RESEARCHREPORT

ENVIRONMENT

Title: Effectiveness of vegetative environmental buffers to reduce swine facility emissions – **NPB #13-084**

revised

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Industry Summary:

In order to ensure compliance with the current and future air quality regulatory requirements, and to co-exist with increasing numbers of neighbors, practical and cost effective air mitigation options should be available to producers. Vegetative environmental buffers (VEBs) are a potential cost-effective strategy for reducing multiple air pollutants from farms. The VEBs can function as a living bio-filter as well as a windbreak. However, effectiveness of VEBs in reducing air pollutants is highly variable and usually depends on site specific design. Lack of information on performance and technical guidelines are barriers to adoption of VEBs. In this study, the effectiveness of VEBs in reducing multiple air pollutants from a swine facility was tested. Red Cedars were planted to form a line of VEB which is 120-150 feet away from the ventilation fans of the swine barn. Gas concentrations at various downwind distances from the swine facility were monitored with and without the VEBs to determine the effectiveness of VEBs in reducing air pollutants. The following three designs of the VEBs were tested to investigate the effects of height and depth of the VEBs on the results: one row of trees at 8 feet height, one row of trees at 12 feet height, and paralleled three rows of trees at 8 feet height. The results showed that the VEBs were effective in reducing downwind concentrations of hydrogen sulfide (H_2S), ammonia (NH_3), nitrous oxide (N_2O), and methane (CH_4). And the 3-row-8' VEB was most effective as comparing with the other two designs. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB was able to reduce downwind concentrations by up to 60%, 33%, 26%, and 51%, for H_2S, NH_3, N_2O, and CH_4, respectively. No reduction on volatile organic compounds (VOCs) and odor was observed. As expected, how much air pollutants can be reduced depends on the thickness of the VEBs, while the downwind distance from the VEBs within which the reduction is effective depends on the height of the VEBs (the barrier height). For H_2S, the reduction was no longer effective when the downwind distance was beyond 160 feet or 20 times the barrier height from the 3-row-8' VEB. Moreover, the reduction effectiveness for H_2S was sensitive to wind speed. As wind speed increased, the reduction effectiveness decreased. When wind speeds were larger than 3.5 m/s, higher downwind H_2S concentrations were observed with VEBs (especially, for the single-row VEBs) as compared with the control scenario (no VEB), which could be due to unwanted turbulence or downwash effect caused by the VEBs at high wind speeds. The effect of VEBs on downwind PM_{10} concentrations was more complex than expected. On the one hand, 23% PM_{10} reduction across the 3-row-8' VEB was observed; on the other hand, higher downwind PM_{10} concentrations were observed with VEBs as compared with the control scenario (no VEB), which could be due to reduced air movement associated with the VEBs. Further investigation is needed to confirm this observation. It is anticipated that further increasing the thickness of the VEBs could result in further reduced downwind PM_{10} concentrations, and thus could ensure the reduction of downwind PM_{10} concentrations as compared with the control

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scenario (no VEB). In summary, (1) Adequate thickness of the VEBs is very important in order to secure the expected effectiveness of VEBs in reducing air pollutants; and multi-row VEBs are recommended. (2) The downwind distance from the VEBs within which the reduction is effective could be estimated by multiplying the height of VEBs by 20; and reversely, the required height of the VEBs could be estimated when there is a sensitive location downwind of the VEBs needs to be protected. (3) At high wind speed, a single row VEB could result in higher downwind concentrations due to turbulence and downwash effect induced by the VEB. A multi-row design is desired to increase the effectiveness of filtering mechanism and thus overcome this effect. (4) More sophisticated investigation is needed to quantify the effect of VEBs in reducing VOCs and odor.

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Keywords:

Red cedar trees, windbreak, air quality, environment, pig, emission mitigation

Scientific Abstract:

The vegetative environmental buffers (VEBs) has been proposed as a potentially cost effective strategy for reducing multiple air pollutants from livestock facilities. However, effectiveness of VEBs is highly variable and usually depends on site specific design. Lack of information on performance and technical guidelines are barriers to adoption of VEBs. The objective of this study was to investigate the effectiveness of VEBs under various design parameters (such as height and depth of VEBs) for mitigating emissions of multiple air pollutants including NH_3, H_2S, N_2O, CH_4, VOC, odor and PM_{10}, from a research swine barn in northeast Kansas. The long term goal of the study is to establish the overall performance, identify the key design parameters and contribute to the development of guidelines of VEBs for its application in mitigating air emissions from swine production facilities. Four scenarios of VEBs of Red Cedars were established: no VEB as the background, one row of trees at 8 feet height, one row of trees at 12 feet height, and paralleled three rows of trees at 8 feet height. The line of the VEBs was 150 feet long and was 120-150 feet away from the ventilation fans of the swine barn. Six air sampling locations were set up, at 10 feet, 110 feet, 160 feet, 210 feet, 260 feet, and 310 feet away from the ventilation fans of the swine facility respectively. Gas concentrations were measured continuously using an INNOVA1412 photoacoustic multi-gas analyzer and a pulsed fluorescence H_2S analyzer in a sequential manner from sampling points 1 to 6 through a multi-point auto sampling system. For each VEB scenario, at least 10 days of continuous measurements were taken. The PM_{10} concentrations were measured continuously at sampling points 2, 3 and 6 using tapered element oscillating microbalances (TEOM). VOC concentrations were measured using a handheld VOC meter and odors were measured using a nasal ranger at all of the 6 sampling locations. The gas concentration data points at the 6 sampling locations were screened first by precipitation and then by wind direction using hourly local weather data. The data points were included in data analysis only when the sampling locations were at downwind and under influence of the swine facilities. The concentrations at various downwind distances were analyzed to demonstrate the patterns of transport and diffusion of air pollutants from the swine barns and the effect of the VEBs. The results showed that the VEBs were effective in reducing downwind concentrations of H_2S, NH_3, N_2O, and CH_4. And the 3-row-8' VEB was most effective as comparing with the other two designs. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB was able to reduce downwind concentrations by up to 60%, 33%, 26%, and 51%, for H_2S, NH_3, N_2O, and CH_4, respectively. No reduction on VOCs and odor was observed possibly due to the limitation of the measuring instrumentations and approaches. As expected, how much air pollutants can be reduced depends on the thickness of the VEBs, while the downwind distance from the VEBs within which the reduction is effective depends on the height of the VEBs (the barrier height). For H_2S, the reduction was no longer effective when the downwind distance was beyond 160 feet or 20 times the barrier height from the 3-row-8' VEB. Moreover, the reduction effectiveness for H_2S was sensitive to wind speed. As wind speed increased, the reduction effectiveness decreased. When wind speeds were larger than 3.5 m/s, higher downwind H_2S concentrations were observed with VEBs (especially, for the single-row VEBs) as compared with the control scenario (no VEB), which could be due to unwanted turbulence or downwash effect caused by the VEBs at high wind speeds. The

effect of VEBs on downwind PM_{10} concentrations was more complex than expected. On the one hand, 23% PM_{10} reduction across the 3-row-8' VEB was observed; on the other hand, higher downwind PM_{10} concentrations were observed with VEBs as compared with the control scenario (no VEB), which could be due to reduced air movement associated with the VEBs. Further investigation is needed to confirm this observation. It is anticipated that further increasing the thickness of the VEBs could result in further reduced downwind PM_{10} concentrations, and thus could secure the reduction of downwind PM_{10} concentrations as compared with the control scenario (no VEB).

Introduction:

In order to ensure compliance with the current and future air quality regulatory requirements, and to co-exist with increasing number of neighbors, practical and cost effective air mitigation options should be available to producers. Most of currently available air mitigation technologies for swine producers are not economically attractive or have various limitations and need further refinement. Vegetative environmental buffers (VEBs) are potential cost-effective strategy for reducing multiple air pollutants from farms. However, effectiveness of VEBs is highly variable and usually depends on site specific design. Lack of information on performance and technical guidelines are barriers to adoption of VEBs. The long term goal of the study is to establish the overall performance, identify the key design parameters and contribute to the development of guidelines of VEBs for its application in mitigating air emissions from swine production facilities.

The VEBs can function as a living bio-filter as well as a windbreak. As a living bio-filter, the VEBs can reduce air pollutants through (1) interception and retention of dust; and (2) adsorption, absorption and break down of odor components. As a windbreak, the VEBs can reduce air pollutants at ground level through (1) enhancing vertical air mixing and dilution; (2) enhancing deposition of dust by slowing air movement. The waxy leaf surface area (cuticle) has an affinity for N-based chemicals (Walter, 2010), which enable VEBs to adsorb ammonia. Most of dust particles occur in a size range that can be captured by trees. Since odor is often carried on dust particles, odor is reduced when dust is reduced by VEBs.

Other advantages of VEBs include: visual screen (aesthetics value); improved neighbor-relations (highly visible); increased effectiveness over time; potential energy benefits (buffer for extreme temperature fluctuations); snow drift control; soil carbon sequestration; potential soil erosion control; can be planned and utilized by most farms. Published research on the effectiveness of VEBs for mitigating air pollutants from livestock facilities are summarized in Table 1.

Table 1. Effectiveness of VEBs for mitigating air pollutants from livestock facilities

Authors	Farm, location	VEBs	Effectiveness
Hernandez et al., 2012	Swine, Iowa	Single row of Austree willow, 52-100m from house, 9m tall	40-60% reduction in odor compounds; 40% reduction in dust across the VEB
Parker et al., 2012	Swine, Missouri	Five rows, 9-12m from fans, 2.4-3.6m tall	66.3% reduction in odor at 15m; no reduction at 150m & 300m downwind
Burley et al., 2011	Laying hen, Pennsylvania	Four rows, 17.7m from fans, 1.5-2.1m tall, 12.8m in depth, 11m in width	No effect on dust
Nicolai et al., 2010	Swine, South Dakota	One to three rows	Most effective reduction occurs just beyond VEB; little effect after 500m
Patterson et al., 2009	Laying hen, Pennsylvania	Four and five rows, 11.4-17.7m from fans	34% reduction in odor with a 4-row VEB; 46-54% reduction in odor with a 5-row VEB
Adrizal et al., 2008	Poultry, Pennsylvania	Three to twelve rows, 11.4-17.7m from fans	Greater foliar N concentration near the fans suggests entrapment of airborne NH_3 by the plants
Malone, et al., 2004 and 2008	Poultry, Delaware	Three rows, 9m from fans, 4.8m tall, 6.7m in depth	56%, 54%, 26% reduction across VEB in dust, NH_3 and odor, respectively; 19% reduction in aerosol bacteria
Tyndall, 2008	Swine, Iowa	-	6-15% reduction in odor, up to 50% reduction in NH_3 and dust
Lin et al., 2006	Odor generator, Canada	Single row, 15-60m from odor generator, 7.6-18.3m tall	Reduction in odor: 68% at 117m downwind; 3% at 520m downwind
Nicolai et al., 2004	Swine, South Dakota	The mature VEB: 8 rows, 1.8m from manure storage, 9m tall, 42m in depth; the immature VEB: 2 rows	85% reduction in H_2S for the mature VEB; reduction in H_2S was significant only at $V<5$mph for the immature VEB
Laird, 1997	Wind tunnel modeling, Iowa	Three rows	56% reduction in dust

Costs for VEBs include upfront costs (site preparation, tree stock & establishment, 40-70% of total costs) and maintenance costs (Tyndall, 2008). Saucer, et al. (2008) reported costs for site preparation was $53.85 per acre, and costs for tree stock was from $0.75 (15" Austree willow) to $18 (2-3' Eastern red cedar) per tree. Cost per head of swine is estimated to be around 20 cents by IOWA demonstration cooperators.

The general suggestions for establishing a VEB include:

- Greater species diversity and a combination of plant growth rates are recommended to make a robust and mature VEB system (Tyndall, 2008; NRCS, 2007).
- Row spacing of 16 to 20 ft is recommended by NRCS.
- Appropriate site preparation is critical to the long term health of tree plantings and will contribute toward lower tree mortality and faster tree growth. Many VEBs fail (e.g. high tree mortality) because of inadequate site preparation (Tyndall, 2008).
- Design of VEBs should consider air circulation near and through animal houses. Minimum distances of 75 and 100 ft away from house are recommended for mechanical and natural ventilation, respectively (May, 2008).

Some studies indicate effective reduction occurs just beyond the VEB (Parker et al., 2012; Nicolai et al., 2010; Lin et al., 2006). Wind tunnel simulation on barriers at roadside showed that percentage reduction decreases with downwind distance, and they are generally below 50% beyond 15 times the barrier height (Heist, 2009).

However, actual data on how VEBs will affect the transport of various air pollutants from swine facilities is not available. It is not well known how VEBs will affect odor footprint and reduce the needed separation distance from neighbors. More research experiments are needed to determine the key design and management parameters (such as, height, depth, porosity, tree species, etc.) for maximum performance of VEBs with limited costs.

Objectives:

The main objective is to determine the effectiveness of a vegetative environmental buffer (VEB) to mitigate multiple air emission constituents, including NH_3, H_2S, VOC, N_2O, CH_4, odor and dust, from a swine production facility. The specific objectives of the proposed study include:

(1) Measure the concentrations of multiple air emission constituents at various distance from a swine facility with and without the presence of a VEB, and also correlate the mitigation effectiveness of the VEB under various weather conditions;
(2) Determine the effectiveness of the VEB under various design parameters (height and depth) and evaluate how height and depth of the VEB will affect the mitigation effectiveness;
(3) From the study, develop design suggestions and best management procedures to utilize a VEB.

Materials & Methods:

Experiment site

Experiments were conducted at the two swine nursery houses (200 head capacity each; 50’ × 27’ × 8’) at Kansas State Universities Segregated Early Wean Unit (SEW). The SEW facility has pens that are designed with slatted metal floors. A 4 foot deep pit with pit ventilation is located underneath pens.

Establishment of the VEBs

The original plan was to establish VEBs to the north of the swine facility. Due to the difficulties to transplant trees at the original locations (very rocky soils and poor accessibility), the VEBs were established to the west of the swine facility. The NRCS (2007) lists red cedar trees as one of the proven plants for VEBs. In this study, red cedar trees were transplanted to selected locations to establish 4 scenarios of the VEB: (1) control: no VEB; (2) one row of trees at 12 feet height; (3) one row of trees at 8 feet height; and (4) paralleled three rows of trees at 8 feet height. Tree and row spacing was around 12 feet. The line of the VEBs was 150 feet long and was 120-150 feet away from the ventilation fans of the swine barn. A tree spade borrowed from the USDA plant materials center was used for transplanting the trees (Figure 1). The four VEB scenarios were established during September 2014 to April 2015. Six air sampling locations were set up, at 10 feet, 110 feet, 160 feet, 210 feet, 260 feet, and 310 feet away from the ventilation fans of the swine facility respectively. Figure 2 is a picture demonstrating layout of the established VEB (1-row-8’ VEB) and the swine facility. Figure 3 is a picture of the established 3-row-8’ VEB. For the 3-row-8’ VEB, the gaps between trees in the 1-row VEB were filled by the additional second and third rows.

Figure 1. The tree spade used for transplanting trees and establishing the VEBs

Figure 2. The established VEB (1-row-8' VEB) and the swine facility (view from the furthest sampling location)

Figure 3. The established 3-row-8’ VEB (view from the swine facility)

Air sampling protocol

A mobile lab was set up by the swine facility for the air quality field experiment. Concentrations of NH_3, H_2S, N_2O, and CH_4 were measured using a pulsed fluorescence SO_2-H_2S analyzer (TEI Model 450i, Franklin, MA) and an INNOVA 1412 photoacoustic analyzer (Lumasense Technologies, Ballerup, Denmark) that determines CO_2, CH_4, NH_3 and N_2O concentrations. Gas samples were directed to the analyzers in a sequential manner from sampling points 1 to 6 through a multi-point auto sampling system. Gas samples from each sampling location were continuously measured for 30 minutes and before moving to next sampling location. For each measurement of 30 minutes, the first 20 minutes were used for purge of sampling line and stabilization of instruments. Then data was collected for the remaining 10 minutes, and the 10-minute average concentration was reported as one data point. Each measurement cycle through all the six sampling location requires 180 min to complete (6 × 30 min per sampling location). Therefore, for every 24 hours of monitoring, there were eight data points (10-minute average concentrations) from each sampling location. For each VEB scenarios, at least 10 days of continuous measurements were taken. VOC concentrations were measured using a handheld VOC meter (HAL-HVX501, Hal Technology, CA. Range 0 to 2 ppm) and odors were measured using a Nasal Ranger Field Olfactometer (St. Croix Sensory) at the 6 sampling locations. The PM_{10} concentrations were measured continuously at sampling points 2, 3 and 6 (110 feet, 160 feet and 310 feet away from the ventilation fans respectively) using three tapered element oscillating microbalances (TEOM). Due to technical failure of the TEOM at sampling location 2, we have to move the TEOM at sampling location 6 to sampling location 2 to collect PM_{10} data at upwind and downwind of the VEBs simultaneously. The PM_{10} data from sampling location 2 was only available under the 3-row-8' VEB scenario.

Data analysis

Hourly local weather data (wind direction, wind speed, air temperature, relative humidity, solar radiation and precipitation) were compiled and matched with each gas concentration data point according to the time of measurement. The gas concentration data points at the 6 sampling locations were screened first by precipitation and then by wind direction. The data points at raining days were removed. And the data points were included in data analysis only when the sampling locations were at downwind and under influence of the swine facilities. For the control scenario, 1081 data points were obtained; for the 1-row-12' VEB, 658 data points were obtained; for the 1-row-8' VEB, 110 data points were obtained; for the 3-row-8' VEB, 306 data points were obtained.

The gas concentration data points at downwind sampling locations were then analyzed separately at three wind speed levels: wind speed ≤1.5m/s; 1.5m/s< wind speed ≤ 3.5m/s; and wind speed > 3.5m/s. In order to reduce the influence of occasional high concentrations on the results, the median instead of average of concentrations at various downwind distances were plotted to demonstrate the patterns of transport and diffusion of air pollutants from the swine barns and the effect of the VEBs.

I. Results:

(1) H_2S

The average concentration of H_2S concentrations at outside of the ventilation fan was 52.75 ppb with a standard deviation of 128.46 ppb. The H_2S concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels are presented in Table 2 and Figures 4-6. The 3-row-8' VEB resulted in lowest H_2S concentrations comparing with all other scenarios. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB was able to reduce downwind H_2S concentrations by 22% to 60%. But at downwind distance beyond 160 feet or 20 times the barrier height from the VEB, no significant reduction was observed. The reduction effectiveness for H_2S was sensitive for wind speed, and the reduction was more effective when wind speed was lower. When wind speed was between 1.5 and 3.5 m/s, no obvious reduction was observed for all the three VEB scenarios. When wind speeds were larger than 3.5 m/s, higher downwind H_2S concentrations were observed with VEBs (especially, with the single-row VEBs) as compared with the control scenario (no VEB). A possible explanation is that, at high wind speed, when there was no VEB, the air pollutants were dispersed quickly and concentrations on ground surface were very low. When there was VEB, the air speed around the VEB was reduced and thus the dispersion was reduced. And the VEB could generate unwanted turbulence and downwash effect. All these effects could contribute to the observed higher concentrations on ground surface at downwind VEB at high wind speed. The 1-row-12' VEB caused fluctuation of H_2S concentrations at downwind locations and elevated H_2S concentrations right downwind of the VEB (160 feet from the ventilation fan, and 10 feet from the VEB), which increased with increasing wind speed levels (see Figure 7).

Table 2. H_2S concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels

Wind speed	Downwind distances	Median of concentrations (ppb)				Standard deviation of concentrations (ppb)			
		Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB
Calm v≤1.5m/s	110 feet	0.88	0.43	0.65	0.71	0.81	0.53	0.61	0.37
	160 feet	0.36	0.93	0.54	0.28	0.80	1.43	0.47	0.35
	210 feet	0.68	0.46	0.55	0.27	0.57	0.44	0.48	0.27
	260 feet	0.38	0.41	0.90	0.25	0.33	0.63	1.14	0.30
	310 feet	0.39	0.39	0.71	0.46	1.03	0.62	1.40	0.66
1.5<v≤3.5m/s	110 feet	2.42	0.84	0.85	0.81	1.03	0.57	0.55	0.79
	160 feet	0.55	1.38	0.88	0.62	0.70	2.26	0.95	0.44
	210 feet	0.38	0.51	0.45	0.83	0.77	0.57	0.56	0.44
	260 feet	0.92	0.86	0.41	0.36	2.20	0.43	0.24	0.33
	310 feet	0.59	0.65	0.73	0.54	2.95	0.54	0.77	0.70
v>3.5m/s	110 feet	0.52	0.91	1.98	0.70	0.65	0.43	1.76	0.69
	160 feet	0.44	1.66	1.14	0.87	0.33	1.60	0.36	1.13
	210 feet	0.36	0.96	1.09	0.62	0.51	2.48	0.53	0.88

	260 feet	0.57	0.38	0.59	0.79	1.07	0.50	0.84	0.83
	310 feet	0.91	0.60	0.90	0.74	62.05	0.48	0.25	1.54

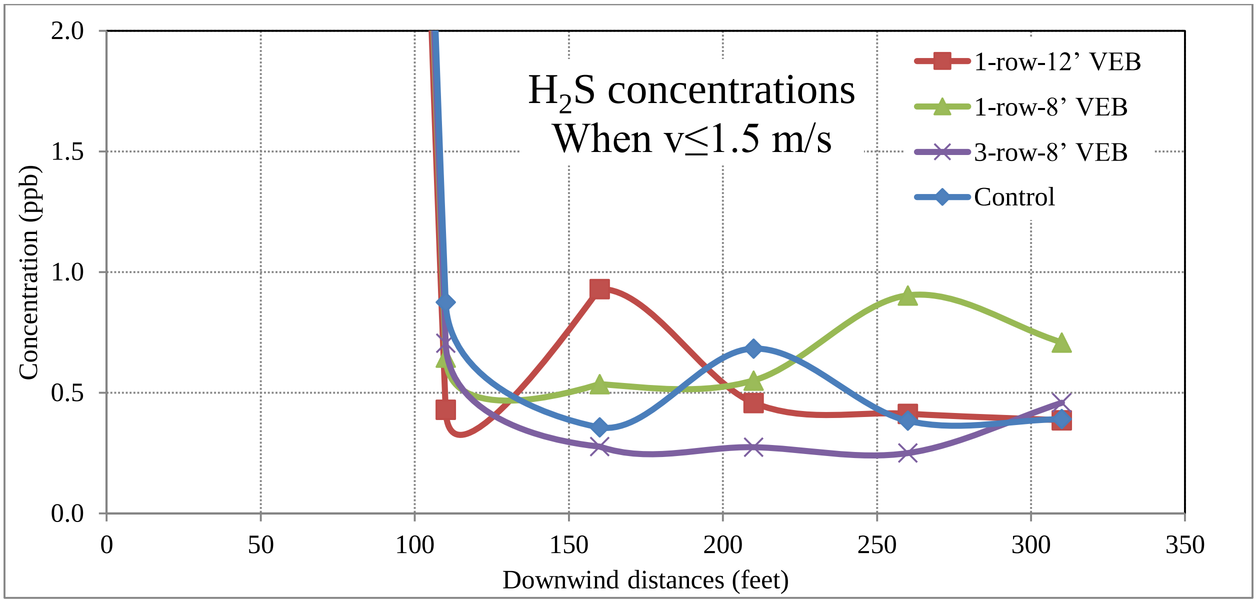

Figure 4. H_2S concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was less than 1.5 m/s

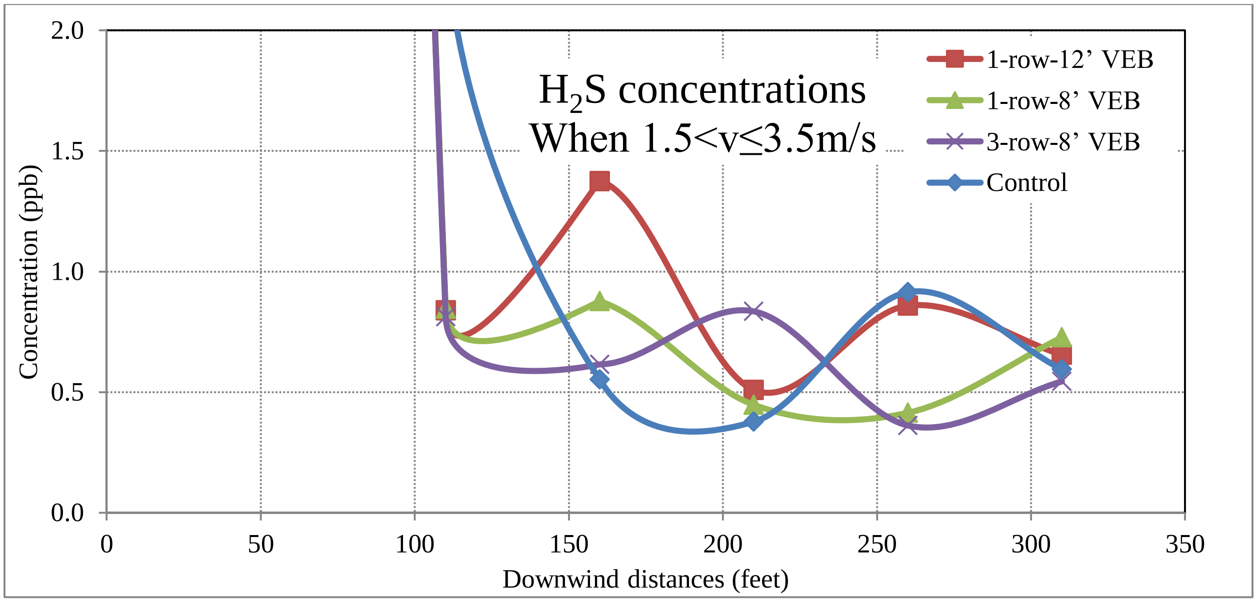

Figure 5. H_2S concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was between 1.5 and 3.5 m/s

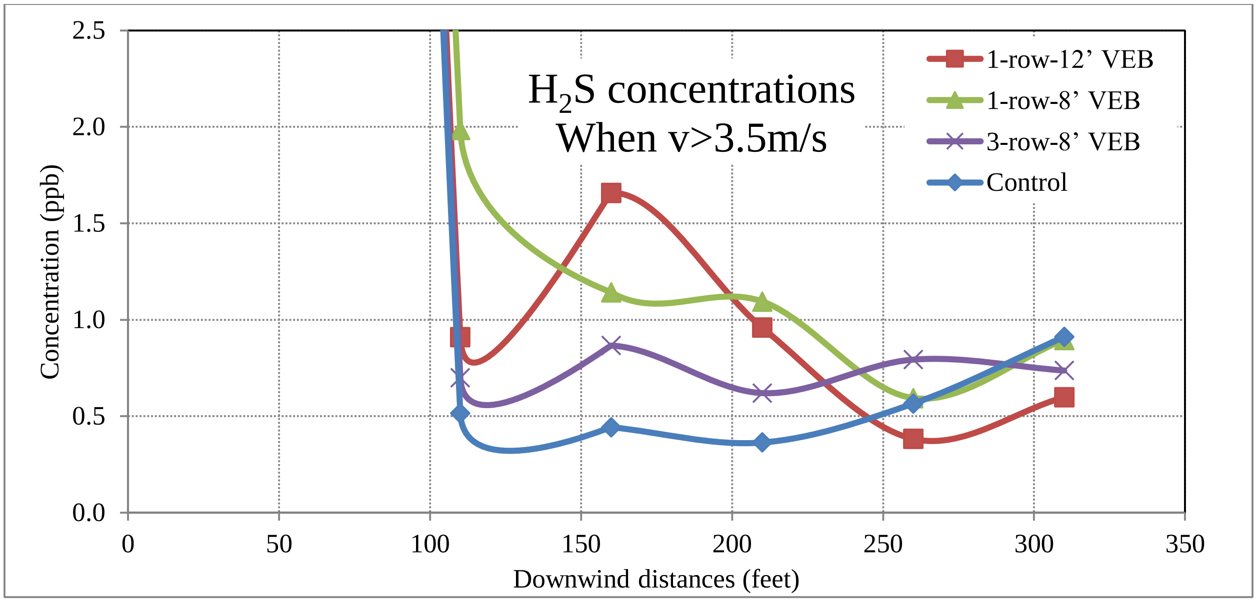

Figure 6. H_2S concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was larger than 3.5 m/s

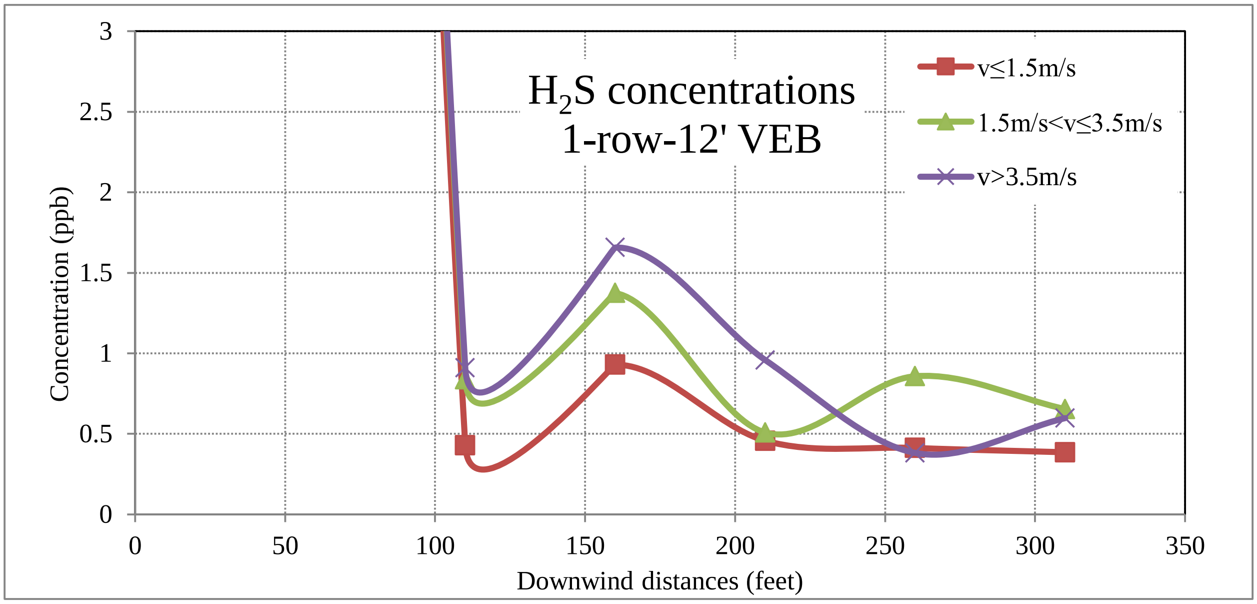

Figure 7. H_2S concentrations at various downwind sampling locations for 1-row-12’ VEB at different wind speed levels

(2) NH_3

The average concentration of NH_3 concentrations at outside of the ventilation fan was 0.97ppm with a standard deviation of 1.67ppm. The NH_3 concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels are presented in Table 3 and Figures 8-10. At all wind speed levels, the 3-row-8’ VEB resulted in lowest NH_3 concentrations comparing with all other scenarios at downwind distances 160, 210, 260 and 310 feet. The reduction effectiveness for NH_3 was also affected by wind speed, although not as sensitive as H_2S. The reduction of NH_3 was more effective and stable when wind speed was lower. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB was able to reduce downwind NH_3 concentrations by 10% to 33%. When wind speeds were larger than 3.5 m/s, higher downwind NH_3 concentrations were observed with single-row VEBs as compared with the control scenario (no VEB).

Table 3. NH_3 concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels

Wind speed	Downwind distances	Median of concentrations (ppm)				Standard deviation of concentrations (ppm)			
		Control	1-row-12’ VEB	1-row-8’ VEB	3-row-8’ VEB	Control	1-row-12’ VEB	1-row-8’ VEB	3-row-8’ VEB
Calm v≤1.5m/s	110 feet	.	0.22	0.24	0.17	.	0.11	0.07	0.23
	160 feet	0.20	0.24	0.20	0.18	0.06	0.16	0.07	0.14
	210 feet	0.19	0.23	0.20	0.15	0.03	0.15	0.05	0.13
	260 feet	0.27	0.23	0.24	0.18	0.02	0.18	0.56	5.23
	310 feet	0.24	0.24	0.24	0.18	0.06	0.17	0.73	0.28
1.5<v≤3.5m/s	110 feet	.	0.22	0.35	0.16	.	0.12	0.16	0.35
	160 feet	0.27	0.23	0.34	0.16	0.07	0.12	0.20	0.39
	210 feet	0.23	0.27	0.35	0.18	0.05	0.11	0.28	0.39
	260 feet	0.29	0.30	0.36	0.18	0.02	0.13	0.16	0.66
	310 feet	.	0.30	0.41	0.17	.	0.13	0.25	0.72
v>3.5m/s	110 feet	0.22	0.33	0.23	0.18	0.03	0.15	0.02	0.20
	160 feet	0.17	0.28	0.20	0.18	0.01	0.15	0.02	0.18
	210 feet	.	0.33	0.22	0.16	.	0.15	0.02	0.16
	260 feet	.	0.31	0.50	0.16	.	0.16	0.43	0.19
	310 feet	0.40	0.35	0.53	0.21	1.25	0.17	0.42	0.20

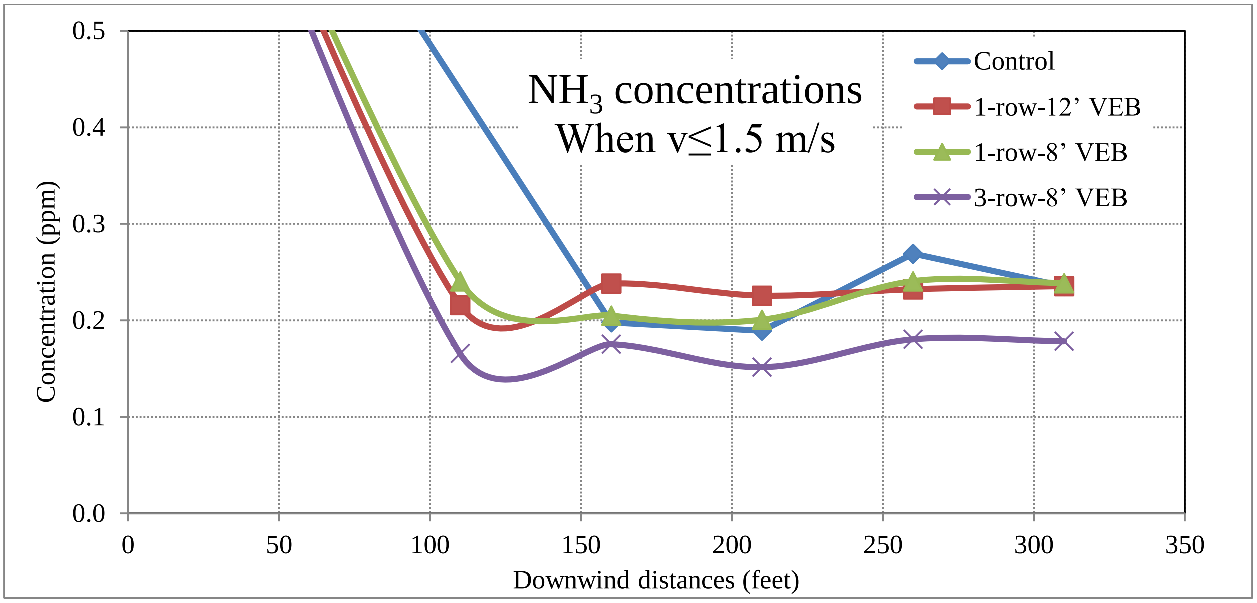

Figure 8. NH_3 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was less than 1.5 m/s

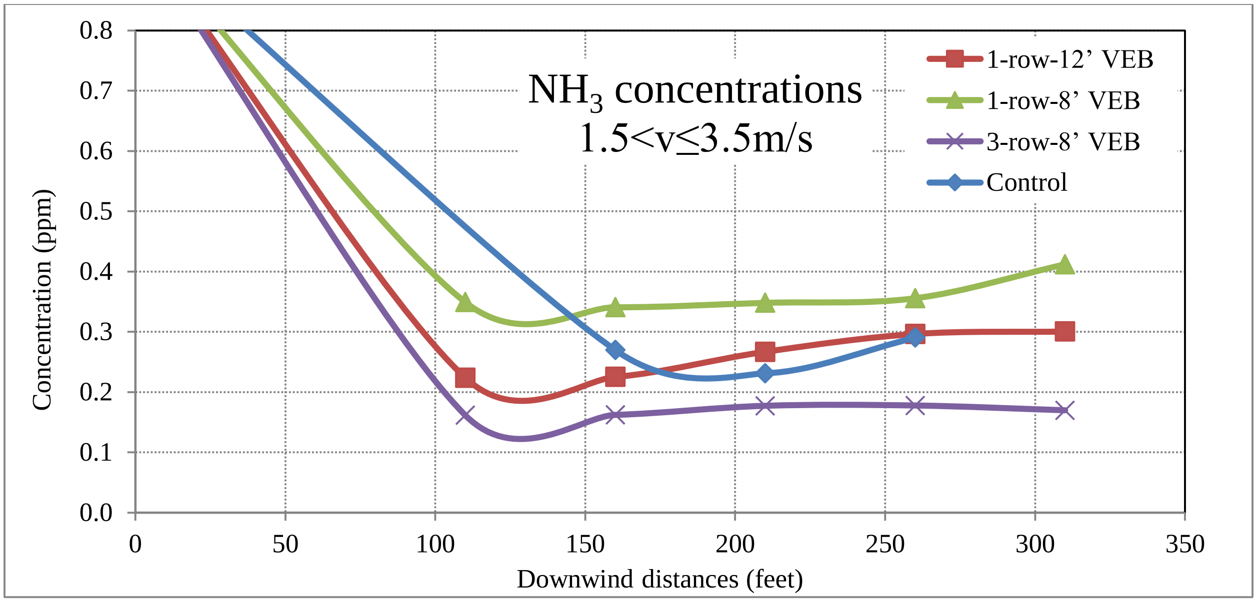

Figure 9. NH$_3$ concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was between 1.5 and 3.5 m/s

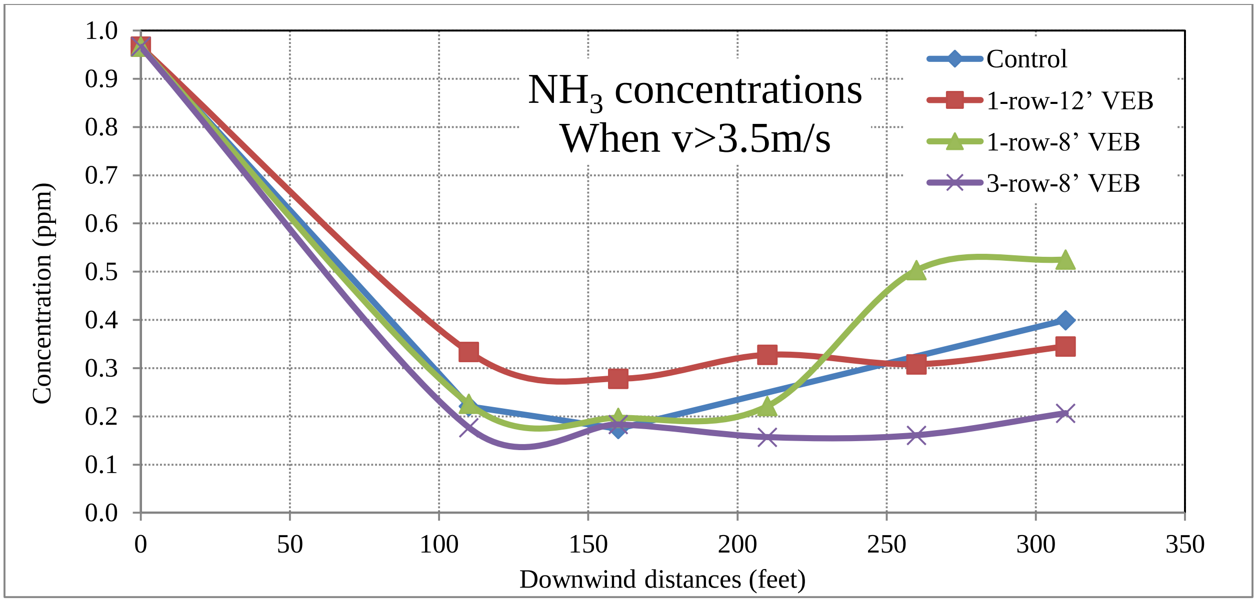

Figure 10. NH$_3$ concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was larger than 3.5 m/s

(3) N$_2$O

The average concentration of N$_2$O concentrations at outside of the ventilation fan was 0.94 ppm with a standard deviation of 0.78 ppm. The N$_2$O concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels are presented in Table 4 and Figures 11-13. At all wind speed levels, the three VEB scenarios all resulted in reduced N$_2$O concentrations comparing with control and no significant difference was observed from the three

VEB scenarios. The reduction effectiveness for N_2O was not sensitive to wind speed. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB was able to reduce downwind N_2O concentrations by 18% to 26%,

Table 4. N_2O concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels

Wind speed	Downwind distances	Median of concentrations (ppm)				Standard deviation of concentrations (ppm)			
		Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB
Calm v≤1.5m/s	110 feet	.	0.60	0.60	0.60	.	0.02	0.03	0.04
	160 feet	0.73	0.59	0.61	0.61	0.06	0.02	0.03	0.03
	210 feet	0.73	0.59	0.61	0.60	0.02	0.02	0.03	0.03
	260 feet	0.82	0.60	0.61	0.61	0.04	0.02	0.07	0.04
	310 feet	0.82	0.60	0.60	0.62	0.06	0.02	0.09	0.04
1.5<v≤3.5m/s	110 feet	.	0.59	0.63	0.59	.	0.03	0.03	0.05
	160 feet	0.73	0.58	0.61	0.58	0.05	0.03	0.04	0.05
	210 feet	0.78	0.58	0.63	0.59	0.06	0.02	0.04	0.05
	260 feet	0.82	0.58	0.63	0.59	0.00	0.02	0.04	0.07
	310 feet	.	0.58	0.63	0.59	.	0.02	0.05	0.08
v>3.5m/s	110 feet	0.77	0.55	0.55	0.57	0.02	0.02	0.00	0.02
	160 feet	0.70	0.57	0.56	0.57	0.02	0.02	0.00	0.02
	210 feet	.	0.58	0.56	0.58	.	0.02	0.00	0.01
	260 feet	.	0.57	0.61	0.58	.	0.02	0.07	0.03
	310 feet	0.79	0.57	0.62	0.58	0.54	0.01	0.06	0.03

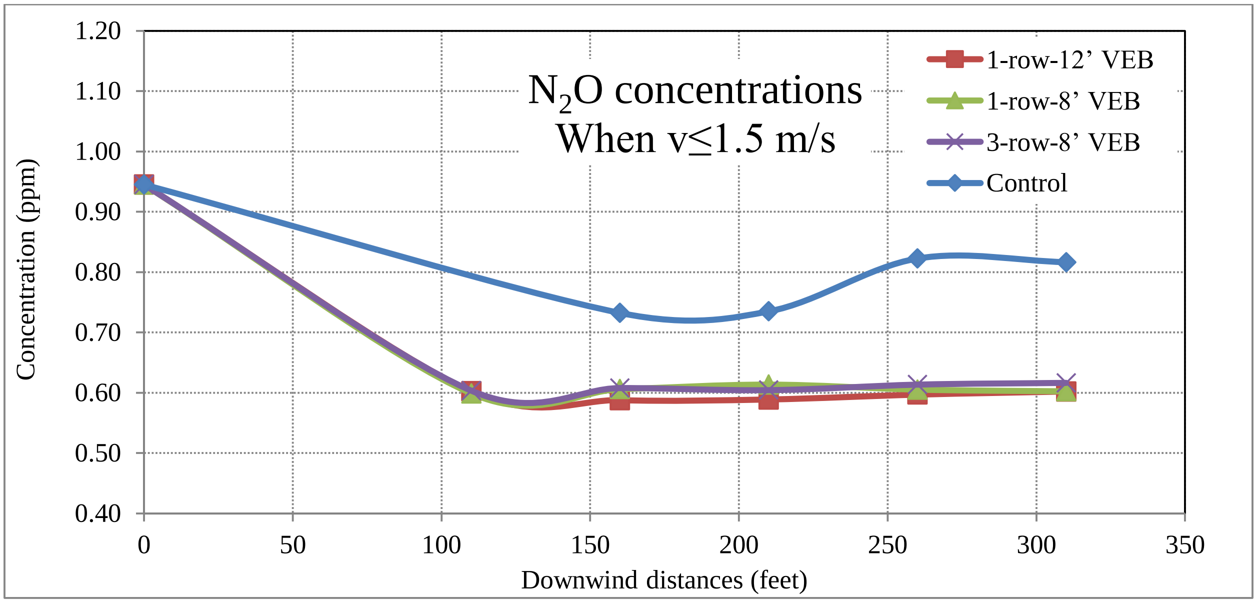

Figure 11. N_2O concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was less than 1.5 m/s

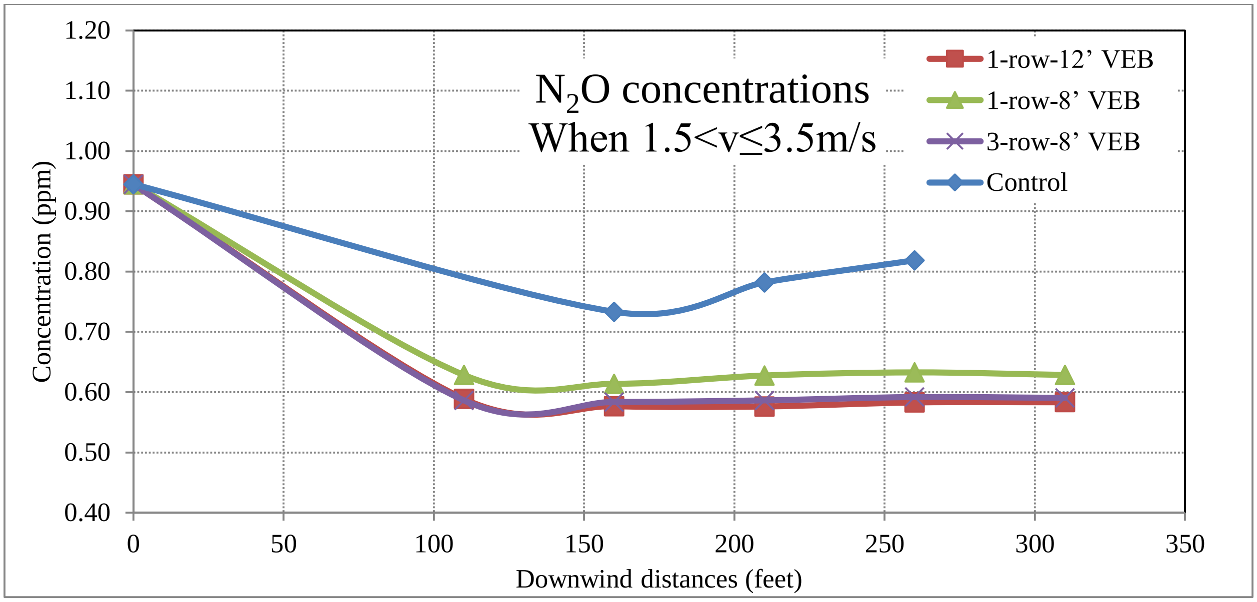

Figure 12. N_2O concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was between 1.5 and 3.5 m/s

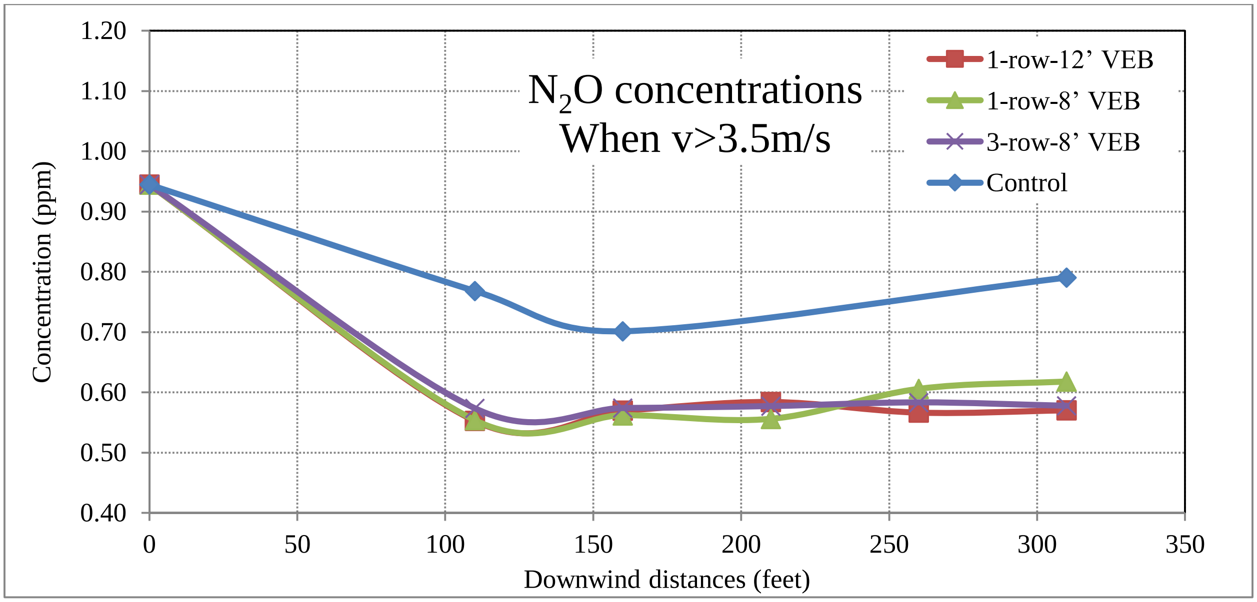

Figure 13. N_2O concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was larger than 3.5 m/s

(4) CH_4

The average concentration of CH_4 concentrations at outside of the ventilation fan was 8.31 ppm with a standard deviation of 6.92 ppm. The CH_4 concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels are presented in Table 5 and Figures 14-16. The CH_4 data for the control scenario was decided invalid based on the results of instrument calibration after the sampling task. At all wind speed levels, the 1-row-8’ VEB scenario resulted in highest CH_4 concentrations comparing with other two VEB scenarios, and the data from the 3-row-8’ VEB scenarios were compared with data from the -row-8’ VEB scenario to estimate the potential reduction effectiveness for CH_4. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB showed potential to reduce downwind CH_4

concentrations by 28% to 51%. It should be noted that the observed high CH_4 concentrations at downwind distances 260 and 310 feet could be due to the contribution of cattle facilities which are located to the southeast of the swine facility.

Table 5. CH_4 concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels

Wind speed	Downwind distances	Median of concentrations (ppm)				Standard deviation of concentrations (ppm)			
		Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB
Calm v≤1.5m/s	110 feet	.	3.85	7.86	4.68	.	2.54	2.98	3.37
	160 feet	.	3.99	6.45	4.65	.	2.04	3.08	1.81
	210 feet	.	4.02	6.88	4.67	.	1.82	2.74	1.69
	260 feet	.	4.09	9.04	4.97	.	2.34	7.14	19.84
	310 feet	.	4.10	9.90	4.83	.	1.98	9.85	4.35
1.5<v≤3.5m/s	110 feet	.	4.37	8.64	5.78	.	2.20	1.56	4.78
	160 feet	.	5.67	8.65	5.71	.	1.62	2.24	5.67
	210 feet	.	6.18	8.49	5.85	.	1.43	3.30	5.95
	260 feet	.	6.34	9.19	5.83	.	1.65	1.05	7.96
	310 feet	.	6.78	10.27	5.98	.	1.50	2.79	10.14
v>3.5m/s	110 feet	.	4.44	9.60	6.30	.	1.63	1.83	1.73
	160 feet	.	4.78	9.34	6.38	.	1.44	1.45	1.69
	210 feet	.	4.99	9.43	6.10	.	1.40	0.60	1.69
	260 feet	.	5.14	12.23	5.80	.	1.36	4.07	1.89
	310 feet	.	5.48	12.49	6.32	.	1.55	4.25	2.48

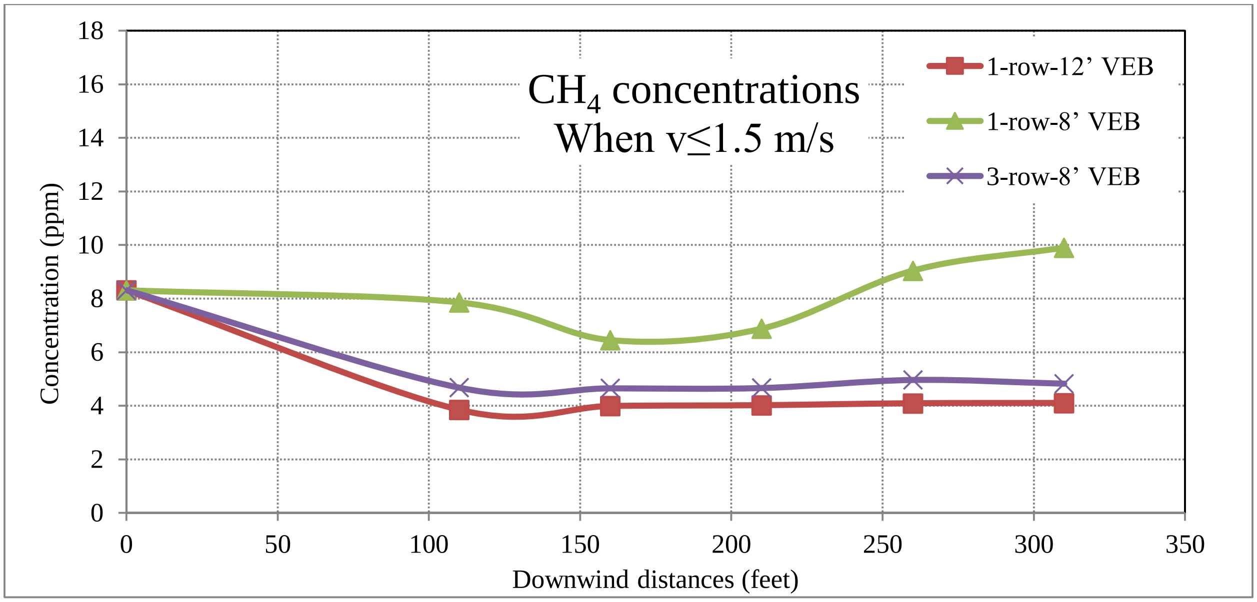

Figure 14. CH_4 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was less than 1.5 m/s

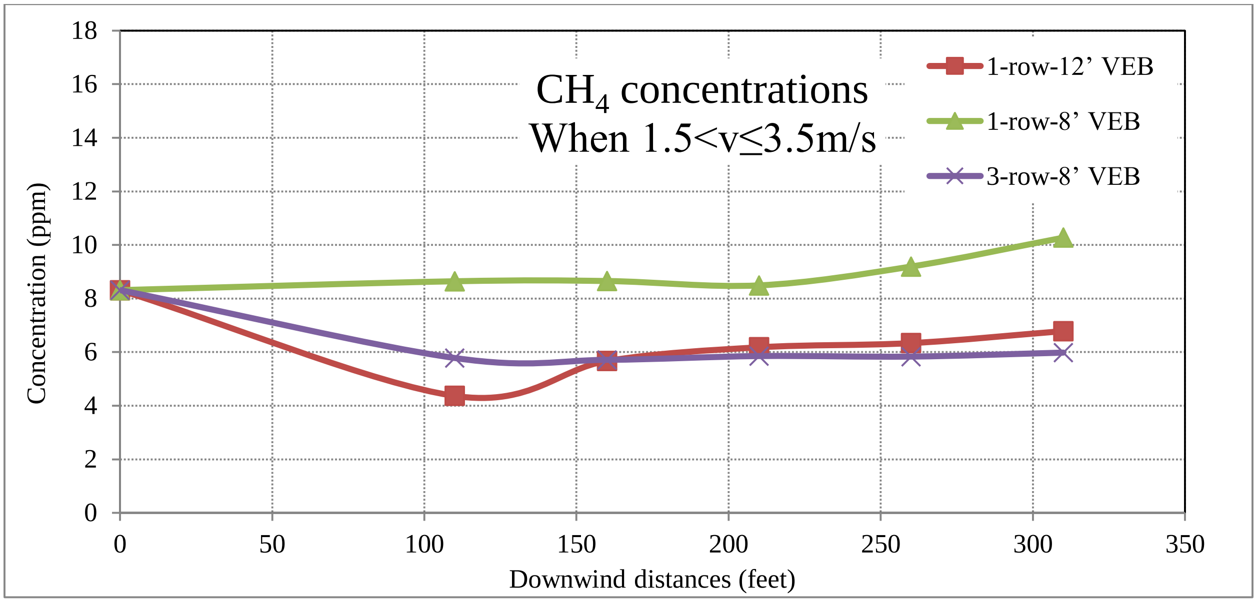

Figure 15. CH_4 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was between 1.5 and 3.5 m/s

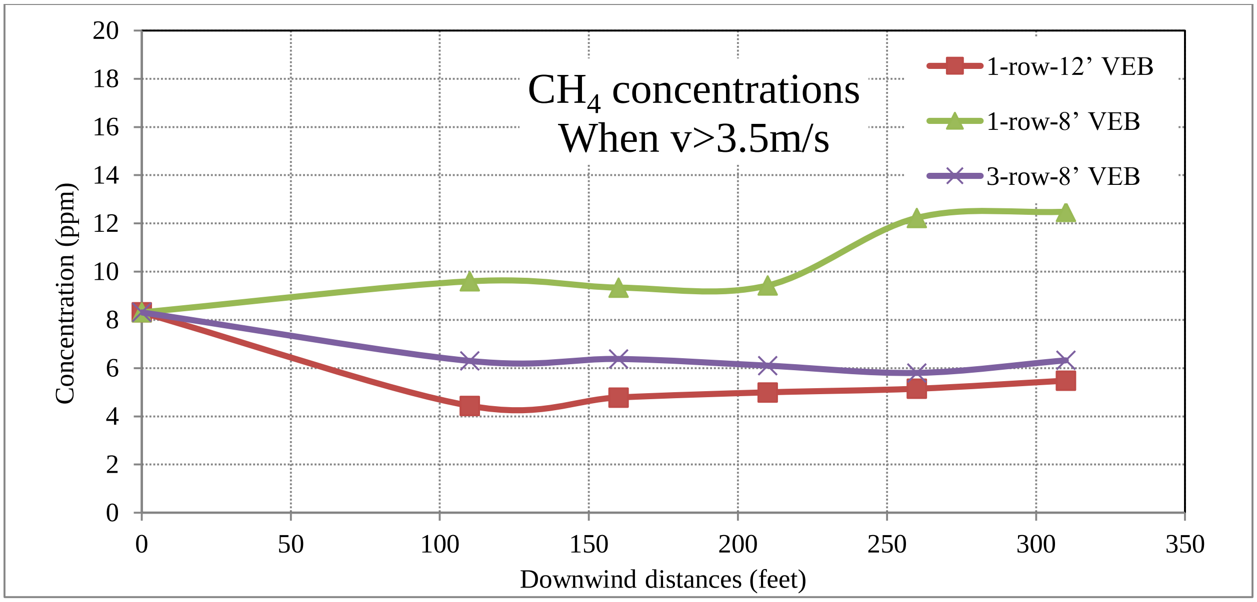

Figure 16. CH_4 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was larger than 3.5 m/s

(5) CO_2

The average concentration of CO_2 concentrations at outside of the ventilation fan was 856 ppm with a standard deviation of 931 ppm. The CO_2 concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels are presented in Table 6 and Figures 17-19. At all wind speed levels, the three VEB scenarios all resulted in reduced CO_2 concentrations comparing with control at downwind distances 260 feet and beyond.

Table 6. CO_2 concentrations at various downwind sampling locations under the three VEB scenarios and three wind speed levels

Wind speed	Downwind distances	Median of concentrations (ppm)				Standard deviation of concentrations (ppm)			
		Control	1-row-12’ VEB	1-row-8’ VEB	3-row-8’ VEB	Control	1-row-12’ VEB	1-row-8’ VEB	3-row-8’ VEB
Calm v≤1.5m/s	110 feet	.	451.27	465.39	450.91	.	22.05	19.99	14.30
	160 feet	443.11	450.05	467.04	450.59	22.87	15.54	18.30	15.52
	210 feet	454.40	455.67	472.21	452.45	8.72	15.06	16.36	13.15
	260 feet	494.20	450.83	461.59	452.59	12.59	25.47	14.38	18.29
	310 feet	496.68	450.46	466.73	454.34	29.84	22.70	14.35	22.52
1.5<v≤3.5m/s	110 feet	.	444.54	450.20	444.08	.	32.81	11.81	12.80
	160 feet	445.24	445.39	451.08	446.20	20.92	38.09	7.14	10.37
	210 feet	478.89	446.54	452.56	446.28	24.19	30.29	33.87	26.76
	260 feet	491.99	446.39	452.38	445.05	1.78	12.95	24.83	16.49
	310 feet	.	448.92	452.68	447.08	.	11.68	17.04	11.52
v>3.5m/s	110 feet	467.12	419.34	434.90	437.21	10.30	11.96	6.41	9.58
	160 feet	427.77	433.79	433.61	436.20	5.06	19.50	3.00	10.76
	210 feet	.	434.77	433.11	436.91	.	15.54	1.66	6.73
	260 feet	.	433.32	439.45	437.90	.	13.38	10.74	6.89
	310 feet	486.57	431.33	438.75	436.59	724.79	12.10	9.53	6.70

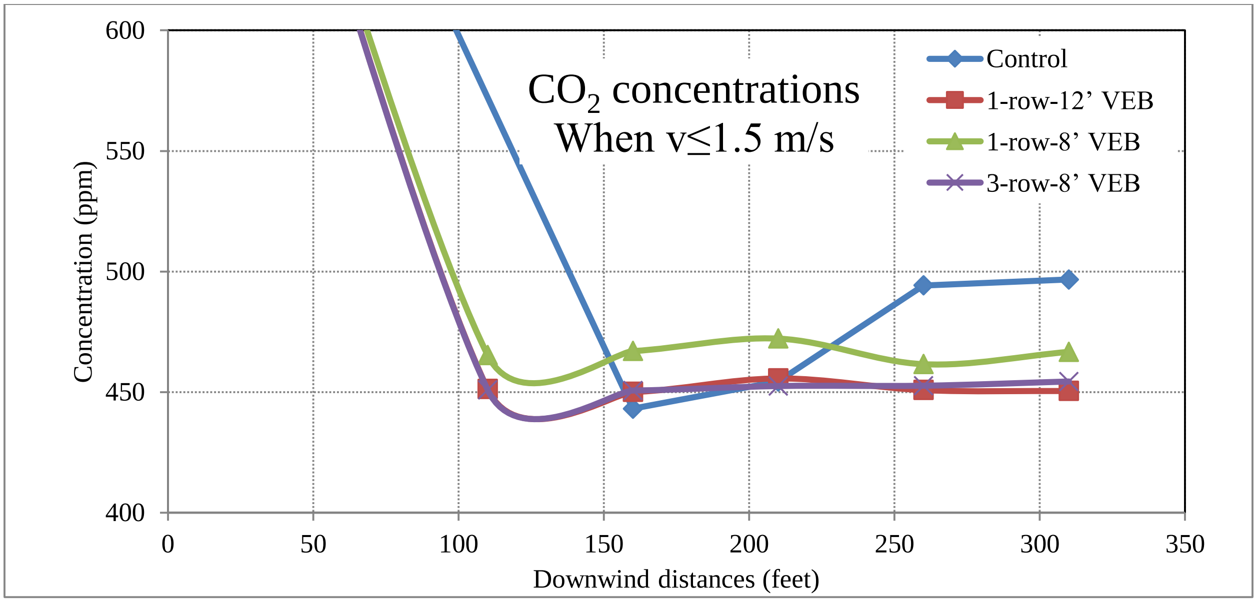

Figure 17. CO_2 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was less than 1.5 m/s

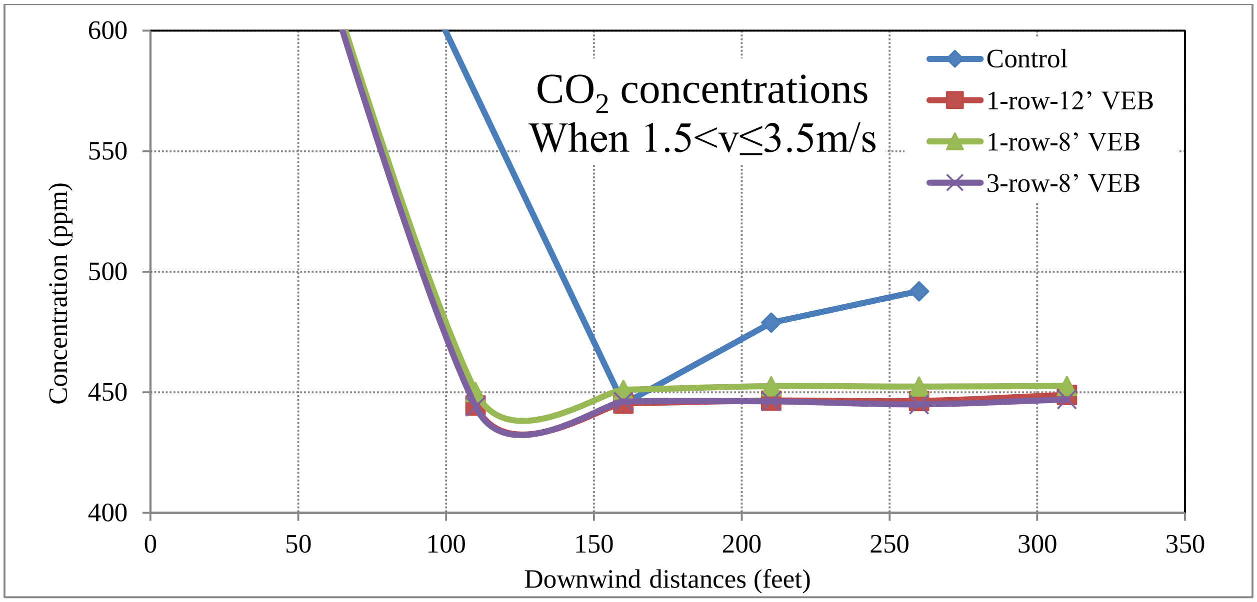

Figure 18. CO_2 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was between 1.5 and 3.5 m/s

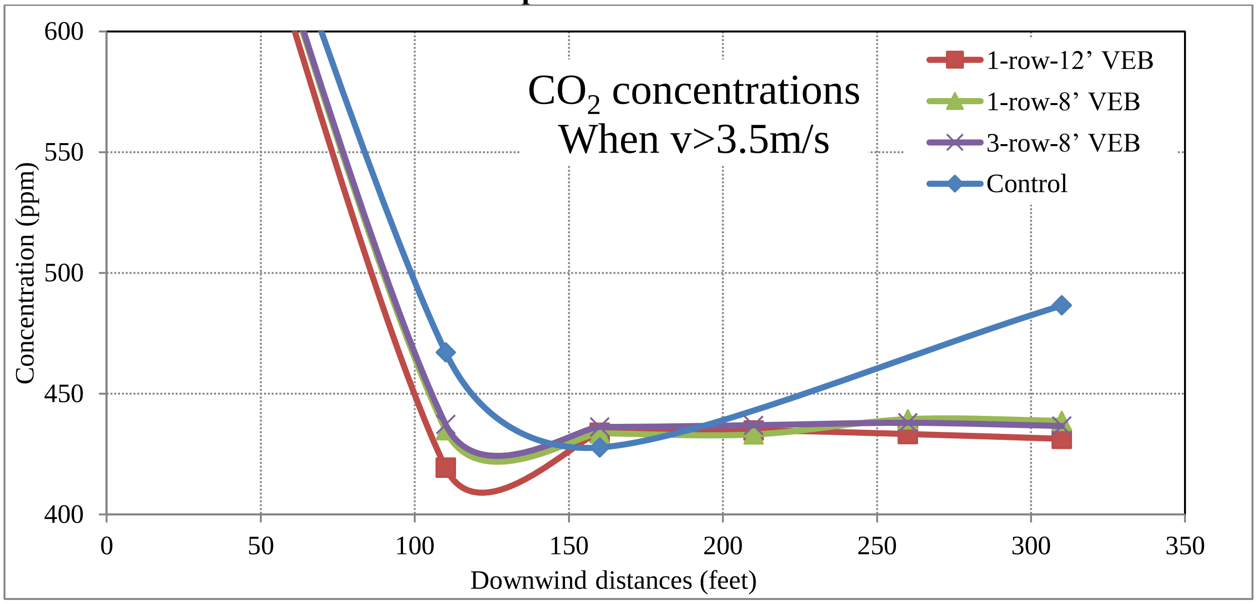

Figure 19. CO_2 concentrations at various downwind sampling locations under the three VEB scenarios when wind speed was larger than 3.5 m/s

(6) PM_{10}

The PM_{10} concentrations at the two downwind sampling locations (sampling locations 3 and 6) under the three VEB scenarios are presented in Table 7-1. Surprisingly, higher downwind PM_{10} concentrations were observed with VEBs as compared with the control scenario (no VEB). And the 1-row-12’ VEB scenario resulted in highest downwind PM_{10} concentrations as comparing with the other two designs. One possible explanation is that the VEB reduced dispersion of PM_{10} by reducing air movement, generating unwanted turbulence, and enhancing deposition of dust, which could result in increased PM_{10} concentration in local environment; and the higher VEB (12 feet) had more influence on air movement than the lower VEB (8 feet). The PM_{10} concentrations at upwind and downwind of the VEB (sampling locations 2 and 3) under the 3-row-8' VEB scenario are compared in Table 7-2. Results of paired t-test showed that the PM_{10} concentrations at downwind of the VEB was 23% lower than that at upwind of the VEB ($P<0.05$). The results indicated that the effect of VEBs on local concentrations of dust or particulate matter could be more complex than expected. It is common sense that dust particles can be captured by trees. However, on the one hand, 23% PM_{10} reduction across the 3-row-8' VEB was observed; on the other hand, higher downwind PM_{10} concentrations were observed with VEBs as compared with the control scenario (no VEB). Further investigation is needed to confirm this observation on the effect of VEBs on downwind PM_{10} concentrations. It is anticipated that further increasing thickness of the VEBs could result in further reduced downwind PM_{10} concentrations, and thus could ensure the reduction of downwind PM_{10} concentrations as compared with the control scenario (no VEB). In Table 7-1, it was observed that the PM_{10} concentrations at the sampling location at downwind distance of 310 feet were generally higher than that right behind the VEB (160 feet from the ventilation fan, and 10 feet from the VEB). This could be due to other fugitive dust sources (there is a small unpaved trail to the south of sampling location 6) and may not be connected to the swine facility.

Table 7-1. PM_{10} concentrations at sampling locations 3 and 6 under the three VEB scenarios

Sampling locations (downwind distances)	Average concentrations (µg/m^3)				Standard deviation of concentrations (µg/m^3)			
	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB
#3 (160 feet)	10.56	30.73	14.40	15.73	14.10	35.91	24.57	6.71
#6 (310 feet)	17.52	36.91	23.34	18.42	15.87	40.19	30.89	17.87

Table 7-2. PM_{10} concentrations at sampling locations 2 and 3 under 3-row-8' VEB scenario

Sampling locations (downwind distances)	Average concentrations (µg/m^3)	Standard deviation of concentrations (µg/m^3)
#2 (110 feet, upwind of the VEB)	15.33	17.32
#3 (160 feet), downwind of the VEB)	11.83	17.24

(7) VOC

VOC measurements were taken only when sampling locations were at downwind of the swine facilities. For each scenario, 15 VOC measurements were taken at each sampling locations. The average concentration of VOC concentrations at outside of the ventilation fan was 0.439 ppm with a standard deviation of 0.574 ppm. The VOC concentrations at various downwind sampling locations under the three VEB scenarios are presented in Table 8 and Figures 20. Due to the high uncertainties observed in VOC measurements, no significant difference was observed for VOC concentrations among different VEB scenarios.

Table 8. VOC concentrations at various downwind sampling locations under the three VEB scenarios

Downwind distances	Median of concentrations (ppm)				Standard deviation of concentrations (ppm)			
	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB	Control	1-row-12' VEB	1-row-8' VEB	3-row-8' VEB
110 feet	0.052	0.032	0.063	0.010	0.027	0.166	0.546	0.169
160 feet	0.039	0.039	0.050	0.018	0.017	0.148	0.579	0.150
210 feet	0.037	0.058	0.030	0.012	0.051	0.168	0.609	0.134
260 feet	0.034	0.063	0.021	0.106	0.008	0.155	0.574	0.117

310 feet	0.032	0.097	0.017	0.100	0.007	0.143	0.520	0.106

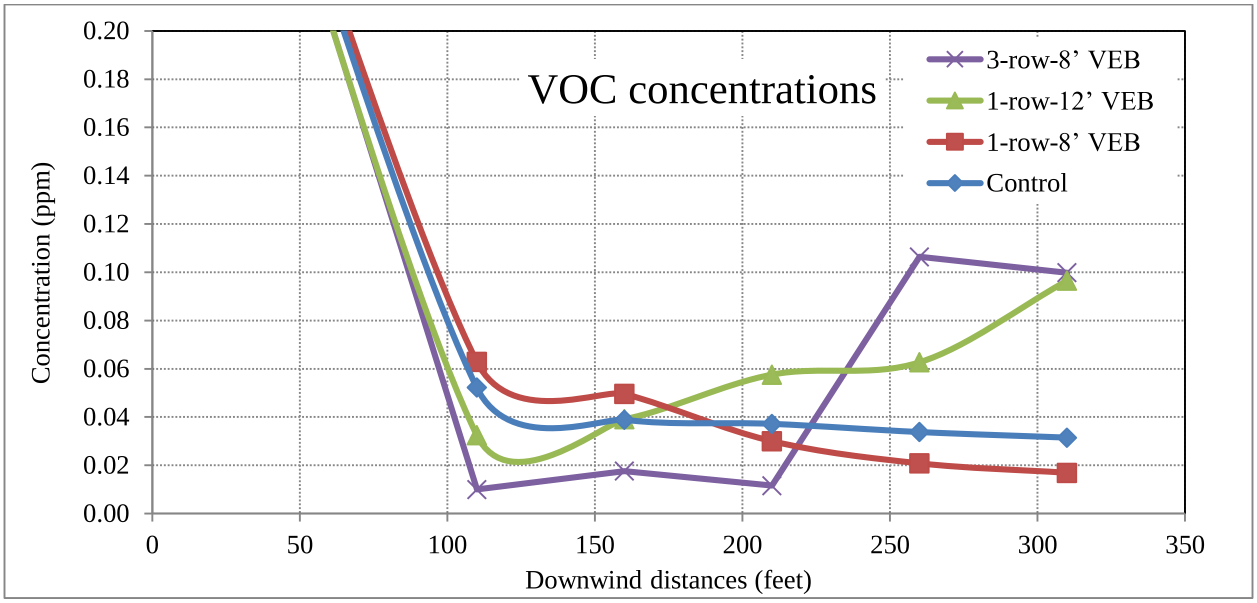

Figure 20. VOC concentrations at various downwind sampling locations under the three VEB scenarios

(8) Odor

Odor measurements were taken only when sampling locations were at downwind of the swine facilities. For each scenario, 15 odor measurements were taken at each sampling locations. The odor dilution ratios measured by nasal ranger at various downwind sampling locations under the three VEB scenarios are presented in Table 9. The percentages of chances that odor can be detected by human nose were also listed. The odor dilution ratios at outside of the ventilation fan were in the range of undetected to more than 60, with a median dilution ratio of 30. At sampling locations equal and more than 160 feet from the ventilation fan, odor dilution ratios were all not detectable using nasal ranger (dilution ratio less than 2), and odor can only be detected by human nose directly. No difference was observed with regard of percentage of odor detection at downwind locations under various VEB scenarios.

Table 9. Odor measurement at various downwind sampling locations under the three VEB scenarios

Downwind distances	Median of odor dilution ratios				Percentage of odor detection (number of odor detection/all)			
	Control	1-row-12’ VEB	1-row-8’ VEB	3-row-8’ VEB	Control	1-row-12’ VEB	1-row-8’ VEB	3-row-8’ VEB
10 feet	30	30	15	4	100%	100%	100%	87%
110 feet	2	2	2	2	100%	100%	100%	66%
160 feet	1	1	1	1	66%	66%	90%	60%
210 feet	1	1	1	1	66%	66%	92%	66%
260 feet	1	1	1	1	66%	66%	82%	66%
310 feet	1	1	1	1	66%	66%	60%	66%

II. Discussion

The 3-row-8' VEB was most effective in reducing downwind concentrations as comparing with the other two designs. When wind speeds were lower than 1.5m/s, the 3-row-8' VEB was able to reduce downwind concentrations by up to 60%, 33%, 26%, and 51%, for H_2S, NH_3, N_2O, and CH_4, respectively. For H_2S, the reduction was no longer effective when the downwind distance was beyond 160 feet or 20 times the barrier height from the 3-row-8' VEB. This result is comparable with finding of Heist (2009) in wind tunnel simulation. But for NH_3 the reduction can be effective beyond 160 feet or 20 times the barrier height from the VEB. The reduction effectiveness for H_2S was sensitive to wind speed, and the reduction was more effective when wind speed was lower. When wind speeds were larger than 3.5 m/s, higher downwind H_2S concentrations were observed with VEBs (especially, with the single-row VEBs) as compared with the control scenario (no VEB). A possible explanation is that, at high wind speed, when there was no VEB, the air pollutants were dispersed quickly and concentrations on ground surface were very low. When there was VEB, the air speed around the VEB was reduced and thus the dispersion was reduced. And the VEB could generate unwanted turbulence and downwash effect. All these effects could contribute to the observed higher concentrations on ground surface at downwind of VEB at high wind speed. The reduction effectiveness for NH_3 was also affected by wind speed, although not as sensitive as H_2S. The reduction of NH_3 was more effective and stable when the wind speed was lower. The reduction effectiveness for N_2O was not sensitive to wind speed. This could be due to different reducing mechanisms for different air pollutants. One major reducing mechanism is adsorption on the VEBs and the VEBs function as a filter for reducing the air pollutants. Another reducing mechanism is the enhanced vertical air mixing and dilution. When the reduction effectiveness is very sensitive to wind speed, it may indicate that the first mechanism may play a less important role in reducing this specific air pollutant (e.g. H_2S), and a thicker VEB may be desirable in order to enhance the filtering mechanism. The effect of VEBs on downwind PM_{10} concentrations was more complex than expected. On the one hand, 23% PM_{10} reduction across the 3-row-8' VEB was observed; on the other hand, higher downwind PM_{10} concentrations were observed with VEBs as compared with the control scenario (no VEB), which could be due to reduced air movement associated with the VEBs. Further investigation is needed to confirm this observation. It is anticipated that further increasing the thickness of the VEBs could result in further reduced downwind PM_{10} concentrations, and thus could ensure the reduction of downwind PM_{10} concentrations as compared with the control scenario (no VEB). No reduction on VOCs and odor was observed in our study. This is possibly due to the limited thickness of the VEBs, and the limited precision of the measuring instrumentations and approaches in this study. Another limitation of our study is that we did not consider the effects of solar radiation or air stability on dispersion of pollutants in our data analysis due to amount of available data.

In summary, (1) Adequate thickness of the VEBs is very important in order to secure the expected effectiveness of VEBs in reducing air pollutants; and multi-row VEBs are recommended. (2) The downwind distance from the VEBs within which the reduction is effective could be estimated by multiplying the height of VEBs by 20; and reversely, the required height of the VEBs could be estimated when there is a sensitive location downwind of the VEBs needs to be protected. (3) At high wind speed, a single row VEB could result in higher downwind concentrations due to turbulence and downwash effect induced by the VEB. A multi-row design is desired to increase the effectiveness of filtering mechanism and thus overcome this effect. (4) More sophisticated investigation is needed to quantify the effect of VEBs in reducing VOCs and odor.

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References

Adrizal, A., P.H. Patterson, R.M. Hulet, R.M. Bates, C.A.B. Myers, G.P. Martin, R.L. Shockey, M. van der Grinten, D.A. Anderson, and J.R. Thompson. 2008. Vegetative buffers for fan emissions from poultry farms: 2. ammonia, dust and foliar nitrogen. Journal of Environmental Science and Health, Part B. 43:1, 96-103.

ATSDR. 2008. Agency for Toxic Substances and Disease Registry. Minimum Risk Levels (MRLs) for hazardous substances. U.S. Department of Health and Human Services. Atlanta, Ga.: ASTDR. Available at: www.atsdr.cdc.gov/mrls/index.html .

Burley H.K., A. Adrizal , P.H. Patterson , R.M. Hulet, H. Lu, R.M. Bates, G.P. Martin, C.A.B. Myers, and H.M. Atkins. 2011. The potential of vegetative buffers to reduce dust and respiratory virus transmission from commercial poultry farms. J. Appl. Poult. Res. 20:210–222.

Guarino M, A. Costa, and M. Porro. 2008. Photocatalytic TiO2 coating—To reduce ammonia and greenhouse gases concentration and emission from animal husbandries. Bioresoure Technol. 99:2650-2658.

Heist, D.K., S.G. Perry, and L.A. Brixey. 2009. Wind tunnel study of the effect of roadway configurations on the dispersion of traffic-related pollution. Atmospheric Environment. 43:5101–5111.

Hernandez, G., S. Trabuea, T. Sauera, R. Pfeiffer, and J. Tyndall. 2012. Odor mitigation with tree buffers: Swine production case study. Agriculture, Ecosystems and Environment. 149:154–163.

Koziel, J., X. Yang, T. Cutler, S. Zhang, J. Zimmerman, S. Hoff, W. Jenks, H. Van Leeuwen, Y. Laor, U. Ravid, and R. Armon. 2008. Mitigation of odor and pathgens from CAFOs with UV/TIO2: exploring cost effectiveness. Proceedings of Mitigating Air Emissions from Animal-Feeding Operations Conference. Des Moines, IA. May 19-21.

Laird, D.J. 1997. Wind tunnel testing of shelterbelt effects on dust emissions from swine production facilities. Thesis (M.S.)--Iowa State University.

Lin, X.J., S. Barrington, J. Nicell, D. Choinie`re, and A. Ve´zina. 2006. Influence of windbreaks on livestock odour dispersion plume in the field. Agriculture, Ecosystems and Environment. 116: 263–272.

Malone, G, G. VanWicklen, and S. Collier. 2008. Efficacy of vegetative environmental buffers to mitigate emissions from tunnel-ventilated poultry houses. Proceedings of Mitigating Air Emissions from Animal-Feeding Operations Conference. Des Moines, IA. May 19-21.

Malone, B. 2004. Using trees to reduce dust and odour emissions from poultry farms. Proceedings 2004 Poultry Information Exchange., Surfers Paradise, Qld, AU. pp. 33-38.

May, J. 2008. Vegetative buffers to control odors on livestock farms. Michigan State University. Available at http://msue.anr.msu.edu/news/vegetative_buffers_to_control_odors_on_livestock_farms. Accessed in 11/2012.

National Research Council (NRC). 2003. Air Emissions from Animal Feeding Operations, Current Knowledge, Future Needs. Washington, D.C.: National Academy Press.

Nicolai, D., J, Ball, and B. hoffer. 2010 Effect of shelterbelts on H2S emissions from swine barns. Air Quality Education in Animal Agriculture Webcast Series. Presented by the Livestock and Poultry Environmental Learning Center.

Nicolai R.E., S.H. Pohl, R. Lefers, and A, Dittbenner. 2004. Natural windbreak effect on livestock hydrogen sulfide reduction and adapting an odor model to South Dakota weather conditions. South Dakota State University. Available at http://www.sdstate.edu/abe/research/structures/upload/Report-to-SDPPA-on-windbreaks-SDOFT.pdf. Accessed in 11/2012.

NRCS. 2007. Windbreak plant species for odor management around poultry production facilities. USDA-NRCS National Plant Materials Center, Beltsville, MD. Maryland Plant Materials Technical Note No. 1.

Parker, D.B., G.W. Malone, and W.D. Walter. 2012. Vegetative environmental buffers and exhaust fan deflectors for reducing downwind odor and VOCs from tunnel-ventilated swine barns. Transactions of the ASABE. 55(1):227-240.

Patterson, P. H., A. Adrizal, R. M. Bates, R. C. Brandt, R. M. Hulet, E. F. Wheeler, D. A. Despot, and P. A. Topper. 2009. The potential for plants to trap odors from farms with laying hens. Poultry Sci. 88(E suppl. 1): 9-10.

Powers, W.J., S.B. Bastyr, J. Harmon, and B.J. Kerr. 2005. Gaseous emissions from swine facilities following feeding of low crude protein diets. Proceedings of the AWMA. Minneapolis, MN, June 21-24.

Sauer, T., F. Haan, Jr., J. Tyndall, G. Hernandez-Ramirez, S. Trabue, R. Pfeiffer, and J. Singer. 2008. Vegetative buffers for swine odor mitigation - wind tunnel evaluation of air flow dynamics. Proceedings of Mitigating Air Emissions from Animal-Feeding Operations Conference. Des Moines, IA. May 19-21.

Tyndall, J. 2008. The use of vegetative environmental buffers for livestock and poultry odor management. Proceedings of Mitigating Air Emissions from Animal-Feeding Operations Conference. Des Moines, IA. May 19-21.

Tyndall, J. 2009. Characterizing pork producer demand for shelterbelts to mitigate odor: an Iowa case study. Agroforest Syst. 77:205–221.

Walter, D. 2010. Vegetative Environmental Buffers: New Technology Benefitting Livestock Farmers. Green Horizons. Vol 14, number 3.