Particulate Capture Efficiency of a Vegetative Environmental Buffer Surrounding an Animal Feeding Operatio

William B Willis^{a,*}, William E. Eichinger^a, John H. Prueger^b, Cathleen J. Hapeman^c, Hong Li^d, Michael D. Buser^e, Jerry L. Hatfield^b, John D. Wanjura^f, Gregory A. Holt^f, Alba Torrents^g, Sean J. Plenner^a, Warren Clarida^a, Stephen D. Browne^a, Peter M. Downey^c, and Qi Yao^g

^aIIHR Hydrosience and Engineering, University of Iowa, 300 Riverside Drive, Iowa City, IA, 52242, USA

^bUS Department of Agriculture, Agricultural Research Service (USDA-ARS), National Laboratory for Agriculture and Environment, 2150 Pammel Drive, Ames, IA 50011, USA

^cUS Department of Agriculture, Agricultural Research Service (USDA-ARS), Henry A. Wallace Beltsville Agricultural Research Center, 10300 Baltimore Avenue, Beltsville, MD 20705, USA

^dDepartment of Animal and Food Sciences, University of Delaware, 237 Townsend Hall, Newark, DE 19716, USA

^eBiosystems & Agricultural Engineering Department, Oklahoma State University, 111 Ag Hall, Stillwater, OK 74078, USA

^fUS Department of Agriculture, Agricultural Research Service (USDA-ARS), Cotton Production and Processing Research, 1604 E FM 1294, Lubbock, TX 79403, USA

^gDepartment of Civil and Environmental Engineering, University of Maryland, 1173 Glenn L. Martin Hall, College Park, Maryland, 20742, USA

*Corresponding author. Tel.: +1 708 769 4953. E-mail address: willbranwill@gmail.com

Abstract

Particulate matter emitted from tunnel-ventilated animal feeding operations (AFOs) is known to transport malodorous compounds. As a mitigation strategy, vegetative environmental buffers (VEBs) are often installed surrounding AFOs to capture particulates and induce lofting and dispersion. Currently, point measurements are the primary means by which VEB performance has been investigated. The existing techniques lack spatial and temporal resolution and fail to assign the observed particulate reduction to capture, lofting, or dispersion. This study presents a technique for estimating the capture efficiency of a VEB using lidar and attributes all observed reduction to particulate capture, thereby delineating the effects of capture and lofting. The experiments revealed a capture efficiency ranging from 21-74%. Instantaneous lidar scans showed periodic lofting well above the VEB, but when scans were averaged over several hours, the plumes appeared Gaussian. This paper documents experimental evidence quantifying the capture efficiency of a VEB. It also establishes an experimental framework for future studies on the efficacy of various emissions mitigation strategies.

Key words

Vegetative Environmental Buffer; Shelterbelt; Particulate; Lidar; Emissions; Animal Feeding Operation

1. Introduction

Over the last few decades, advances in mechanical, biological, and chemical technologies have allowed for single farms to manage larger numbers of animals. As a result, many sectors of animal husbandry have shifted toward large-scale production (MacDonald and McBride 2009). This approach increases efficiency and reduces cost, but the practice concentrates animals onto smaller plots of land, concentrating animal-derived pollution. Pollution from animal agriculture

has become a growing concern. Thus, researchers and policy makers are focusing much attention on the measurement, modeling, control, and management of airborne emissions from agricultural sources (Aneja 2009).

Concentrated animal feeding operations (AFOs) emit particulate matter, ammonia, and several other constituents into the atmosphere in high concentrations, and the pollutants travel downwind while dispersing into neighboring communities, causing numerous community health and socioeconomic problems (Donham et al. 2007). In this study, we focus on the transport of particulate matter from poultry houses and its interaction with a mitigation strategy known as vegetative environmental buffers. While AFOs emit numerous constituents which all have their own unique behavior and environmental impacts, only particulate matter emissions were measured in this study. These measurements do, however, reveal the nature of the transport processes for other constituents outside these facilities. The measurement techniques described herein can be directly applied to other constituents in the future.

Particulate matter, which consists of fecal matter, feed particles, and feather and epidermal fragments, is known to cause adverse health effects when inhaled (EPA 2009). In addition, the particulates emitted from AFOs can transport odorous compounds downwind (Burnett 1969; Hammond et al. 1979, 1981; Hammond and Smith, 1981; Yang et al. 2014). Odor creates a burden on communities and induces stress; the complaint of odor is common amongst communities residing near AFOs (Wing et al. 2008; NRC 2003). Odor itself has been shown to cause adverse health effects, including eye, nose, and throat irritation, nausea, cough, shortness of breath, and alterations in mood (Schiffman 2000). A reduction in odor emitted from AFOs can be achieved by reducing particulate matter, since particulate matter is a known odor transport vector. Several post-emission mitigation strategies have been employed to absorb or deflect

particulate emissions (Ni 2015). Vegetative environmental buffers (VEBs) are one technology commonly used.

Vegetative Environmental Buffers (VEBs), also known as shelterbelts, are strategically placed rows of trees and shrubs that help control emissions from agricultural sources to the atmosphere. VEBs are highly regarded for their ability to: (1) enhance vertical mixing in the atmosphere, leading to dispersion and dilution; (2) filter particles mechanically by acting as a porous medium; (3) precipitate particles by reducing wind speed; and (4) improve producer-community relations by providing a visual and noise barrier (Tyndall and Colletti 2007; USDA NRCS, 2007). In addition, a recent survey in Iowa (Tyndall 2009), 52% of producers reported currently-using or expressed an interest in using VEBs specifically to mitigate odor. With this growing demand to use VEBs, it is critical that our understanding of the technology outpace its application, so that extension services can be carried out appropriately (Tyndall 2009). However, our knowledge of VEB efficacy is lacking; a need exists to quantify and document VEB performance, which is difficult due to the complex processes involved in a functioning VEB. Particulate capture efficiency (percent of particulates retained by the VEB) is one measure of VEB efficacy. Capture efficiency measures only the effect of particulate trapping and neglects dispersion, dilution, and psychological effects. In this study, we conducted a field campaign to estimate VEB particulate capture efficiency using lidar.

Estimating the VEB capture efficiency requires that emissions be measured both upwind and downwind of a VEB. Also, the extent of the entire plume needs to be examined. Plumes emitted from animal houses have been shown to exhibit non-Gaussian dispersion and periodic lofting as a result of turbulence fields disrupted by the facilities themselves. In some cases, the plumes reach up to 40 m above the ground surface, well above most sampling towers (Prueger et

al. 2008; Holmén et al. 1998). As a result, only a limited number of experiments have been conducted to quantify VEB capture efficiency (Table 1).

Wind tunnel studies (Laird 1997; Thernelius 1997) have proven useful for examining the entire plume extent, while field campaigns (Parker et al. 2012; Hernandez et al. 2012; Malone et al. 2006a; Lin et al. 2006) have provided data in a more realistic setting. Past field campaigns have used either point sensors or trained human panelists, but these measurements can only help quantify particulate reduction between the specific locations where they are placed. The observed reduction in particulate count may be the result of the combined effects of dispersion, lofting, and VEB capture. Therefore, experiments using point measurements have not precisely estimated capture efficiency. Parker et al. (2012) recognized this deficiency and concluded that investigation into the differences between the various effects is warranted to understand VEB performance more completely.

Lidar (light detection and ranging) has proven to be an effective remote sensing technique for estimating emission rates from AFOs (Bingham et al. 2009; Lewandowski 2009; Holmén et al. 1998). In the lidar technique, a short pulse (10 ns) of infrared light is emitted into the atmosphere. The pulse interacts with particulates in the air; a fraction of the pulse scatters in all directions; and the portion that scatters back to the lidar is collected in a telescope and focused onto a detector. The backscatter intensity is proportional to the number of particulates present in the sampling volume, and the range is proportional to the pulse travel time. The lidar is stepped through a series of vertical angles to measure a cross-section of a particulate plume. The technique provides high spatial resolution of particulate concentration around the facility while automatically capturing and retaining data with minimal labor involved. For a detailed description of lidar methodology, see Kovalev and Eichinger (2004). In this study, we adapted

the lidar technique to estimate VEB particulate capture efficiency. This lidar technique allows for the entire plume to be mapped downwind of the VEB and for the effect of particulate trapping to be delineated from the effects of dispersion and lofting. The alternative method of point sampling can only strictly show the concentration reduction between a single upwind and downwind location. Using this method, the observed reduction may result from the combined effects of particulate trapping, lofting, and dispersion. Thus, the lidar technique provides a more accurate assessment of the particulate capture efficiency of VEBs surrounding animal housing facilities.

2. Methods

2.1. Study site

The study was conducted at the broiler house at the University of Delaware Carvel Research and Education Center (38.64, -75.47) between June 24 and 26, 2013 (Figure 1). The University of Iowa elastic scanning lidar was positioned 410 m from the site so that it could scan vertical planes perpendicular to the prevailing winds and downwind of the VEB.

The multi-row VEB surrounding the facility was established in the Spring of 2003 (Malone et al. 2006b). In this study, we focused on only the northeast section of the VEB (see Figure 1) and conducted experimental runs only when the wind was out of the southwest. The northeast VEB section was planted in sequential rows parallel to the end wall of the broiler house with 12 bald cypresses (*Taxodium distichum*), 13 green giant arborvitaes (*Thuja plicata* x *standishii*), and 14 white pines (*Pinus strobus*). Each tree was 8 to 10 m tall. The closest row was 25 m from the end wall; rows were spaced 3 m apart, and all trees were planted 3 m apart. The

146 dimensions of the VEB were 42 m x 12 m x 9 m (length x width x height) with an optical
147 porosity of 0.18.

148 The selection and arrangement of the trees comprising a VEB is a critical factor dictating
149 the efficacy, cost, and longevity of the VEB. Investigation into optimum tree placement and
150 species arrangement is still in its infancy, but some design considerations are established: (1) The
151 VEB should be planted greater than 10 times the fan diameter away from the fan to protect the
152 trees. (2) Evergreens generally capture more particulates compared to deciduous trees, due to the
153 complex nature of evergreen leaves and the resulting tortuous path. (Malone et al. 2006b) (3)
154 Heights of 5-10 meters are thought to be adequate to capture the entire plume. (4) An optimum
155 porosity exists which is porous enough to allow throughflow and still dense enough to allow
156 adequate contact between the air stream and leaves. (Tyndall and Colletti 2007). (5) Tree species
157 are chosen for having high leaf surface roughness, complex leaf shapes, large leaf areas, and
158 relatively rapid growth rates (6) Deciduous plants are installed on perimeters to protect the
159 coniferous trees. Deciduous plants capture a large load during peak emission times (the summer
160 months, when the leaves are fully bloomed) and drop them during the fall when emission loads
161 are smaller (USDA NRCS 2007). The VEB at the University of Delaware Carvel Education and
162 Research Center was designed using the considerations stated above.

163 2.2. Dust release

164 At the time of this study, the facility contained no chickens. A surrogate particulate,
165 kaolinite dust ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), was released between the facility and the VEB at a known
166 emission rate. The dust had a mass median diameter of approximately 8.11 μm and a density of
167 approximately 2.62 g cm^{-3} (Wang-Li et al. 2013). Particulates in the PM_{10} (particle diameter < 10
168 μm) range have been shown to carry odors in significantly higher concentrations than the rest of

the size spectrum (Yang et al. 2014). The sample released in this experiment contained both the high impact PM_{10} range as well as the remaining size spectrum in the total suspended particulate (TSP) range. The dust was released continuously for six different runs at different distances from the inside boundary of the VEB. Each run ranged 3-6 hrs in duration. Run durations and release distances are provided in the results in Table 2.

2.3. Meteorological measurements

Meteorological measurements were obtained from instruments mounted on a 10-m tower placed 29 m downwind of the VEB equipped with three Campbell Scientific (Logan, UT) CSAT3 3D high frequency sonic anemometers at 2.3, 5.0, and 8.9 m above the ground surface; three Vaisala (Vantaa, Finland) HMP 45C temperature and humidity probes at 2.3, 5.0, and 8.9 m above the ground surface; and one LiCor (Lincoln, NE) 7500 Infrared Gas Analyzer (CO_2 and water vapor) at 2.3 m above the ground surface. All high frequency instruments (sonic and IRGA) were sampled at 20 Hz while temperature and humidity data (low frequency instruments) were sampled at 10-second intervals and output as 10-minute averages.

2.4. Particle collection and analysis

Particulate size distributions (PSDs) were obtained from samplers mounted on two 10-m towers and from six stand-alone sampler units 1.5 m above the ground surface. Each tower held three low-volume (target flow rate = 16.7 liters per minute, lpm) total suspended particulate (LVTSP) sampler heads designed by Texas A&M/USDA-ARS, which were located at 4.5, 7.25, and 10 m above the ground surface (Wanjura et al. 2005). Each stand-alone unit held one LVTSP sampler head positioned at 1.5 m above the ground surface. PSDs were required to obtain mass extinction efficiency, a parameter needed to convert light extinction coefficient obtained from

lidar measurements to mass concentration (Kovalev and Eichinger 2004)Lewandowski et al. 2010).

2.5. Lidar scan data collection and analysis

The lidar continuously scanned two vertical planes of the atmosphere throughout the duration of each experimental run. Two vertical planes, referred to as slice 1 and slice 2, were scanned to provide redundancy in the estimate. The lidar scans provide two-dimensional, spatially-resolved particulate mass concentration data, $C(x, z)$ (mg m^{-3}), where x is the distance from the lidar, and z is the height above the ground surface. For each 3-6 hour run, the lidar produced 170-270 scans for each slice. The scans were then averaged over the entire run duration.

The time-averaged mass flux $\overline{F}(x, z)$ through the VEB is given by:

$$\overline{F}(x, z) = \overline{C(x, z) \cdot u(x, z)}, \quad (1)$$

where $u(x, z)$ is the wind velocity component orthogonal to the (x, z) plane, and overbars denote averaging over all scans performed within the run duration. Wind measurements were only collected at one x location, so the wind profile was assumed horizontally homogeneous, that $u(x, z) = u(z)$. Also, from Reynolds decomposition,

$$\overline{C \cdot u} = \overline{C} \cdot \overline{u} + \overline{C' \cdot u'}, \quad (2)$$

where primes denote fluctuations about the mean. The turbulent transport of mass in the direction of the mean wind is assumed negligible compared to the advection by the mean wind, that $\overline{C} \cdot \overline{u} \gg \overline{C' \cdot u'}$. This assumption is derived from the fact that PM was released continuously, so the gradient $\partial C / \partial y$ is assumed negligible at any (x, z) . This assumption leads to an estimation of the mass flux:

$$\overline{F}(x, z) \approx \overline{C}(x, z) \cdot \overline{u}(x, z) . \quad (3)$$

211 The lidar scanned the atmosphere from the surface to 40 m above the surface, whereas the sonic
 212 anemometers collected data only at heights of 2.3, 5.0, and 8.9 m above the ground surface. For
 213 heights between the anemometer heights, average wind speeds were linearly interpolated
 214 between the corresponding measured values. For heights above 8.9 m, similarity theory (Monin
 215 and Obukhov, 1954) was applied to estimate wind speeds commensurate with the lidar scan
 216 heights:

$$\overline{u}(z) = \frac{\overline{u}^*}{k} \cdot \ln\left(\frac{z - d_0}{\overline{z}_0}\right) \quad (4)$$

217 where $\overline{u}^*$ is the average friction velocity (m s^{-1}), k is von Karman's constant 0.40
 218 (dimensionless), d_0 is the displacement height (m), and $\overline{z}_0$ is the average aerodynamic roughness
 219 height (m). Flux estimates were multiplied by the area in the (x, z) plane of each sample volume
 220 and total run time Δt and then summed to determine the total mass emitted from the VEB
 221 during a run, m_e (g):

$$m_e = \sum_{R=375}^{R=485} \sum_{z=0}^{z=40} \overline{F}(x, z) \cdot \Delta x \cdot \Delta z \cdot \Delta t \quad (5)$$

222 2.6. VEB efficiency calculations

223 VEB efficiency was defined as:

$$\text{Capture Efficiency} = \left(1 - \frac{m_e}{m_r}\right) \times 100\% \quad (6)$$

224 where m_r is the total mass released upwind of the VEB during the run. A summary of the
 225 methodology is provided in Figure 2.

226 3. Results and Discussion

3.1. Particle capture efficiency

The capture efficiencies ranged between 21 and 74% amongst the six runs (Table 2). The performance of the VEB varied based on time of day. The VEB captured a larger fraction of particulates during the night and a smaller fraction during the day (Figure 3). Five of the six runs were performed during the day, while only one was performed at night. Since sampling times were non-uniformly distributed amongst a 24-hour period, the average diurnal capture efficiency was not determined. It is more appropriate to report the range of 21 to 74%. While this range is large, it is consistent with the large range of experimental results reported in the literature. Collectively, Parker et al. (2012), Hernandez et al. (2012), Malone et al. (2006a), Laird (1997) and Thernelius (1997), and Lin et al. (2006) present a range of 35-68% reduction.

3.2. Factor influencing efficiency

Several variables influenced the capture efficiency, including the wind speed and direction, turbulence intensity, and release distance. All of these variables changed between runs. With only six observations and no single variable held constant, it was difficult to precisely quantify the influence of each variable on capture efficiency. However, some general tendencies were observed.

Turbulence has been shown to dominate transport from AFOs to the surrounding atmosphere (Prueger et al. 2008), and it is likely that turbulence contributed to the VEB performance. Turbulent kinetic energy (TKE) is a measure of the energy embedded in the turbulent component of the wind per unit air density ($\text{m}^2 \text{s}^{-2}$):

$$\text{TKE} = \frac{1}{2} \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right), \quad (7)$$

where u, v , and w are the wind velocity components. TKE within the VEB is primarily produced mechanically, and mechanical production is augmented by buoyant processes. As the mean wind

advects over the facility, it encounters bluff-body obstacles which obstruct the flow and induce pressure drag. A range of shear forces develop, and three-dimensional turbulent eddies result. Surface fluxes (sensible and latent heat) also contribute to TKE production. Daytime surface heating creates density inversions in the surface layer, and vertical motion results, enhancing TKE production within the VEB. Conversely, nighttime surface cooling generates a stably stratified layer which degrades TKE.

This study was performed within the roughness elements (the buildings and trees) of the atmospheric surface layer, where mechanical generation of TKE is expected to dominate; there is experimental evidence that supports this expectation. Mechanical TKE production is highest during windy time periods, as greater shear forces develop from larger velocity gradients near the surface. Buoyant production depends only on the surface sensible and latent heat fluxes and not the wind speed. Therefore, in a mechanically dominated regime, a strong relationship between TKE magnitude and wind speed should exist, and the spread should be minimal. Indeed, this study demonstrated such a relationship (Figure 4).

During the daytime runs, the atmosphere within the VEB remained slightly unstable, with the Monin-Obukhov stability parameter (z/L) ranging from -0.12 to -0.02. Similarly, the atmosphere was slightly stable during the nighttime run, with a z/L of +0.17. The observed range of -0.12 to 0.17 z/L represents a near-neutral atmosphere, during which mechanical production of TKE dominates over buoyant production. Still, a slightly negative z/L indicates that surface fluxes are positive, which has some mixing effect. A slightly positive z/L indicates negative surface fluxes, and mixing is suppressed to some degree. In summary, we characterize the turbulence within the VEB as mechanically-dominated and enhanced or suppressed by buoyancy.

The VEB least effectively removed particulates during the daytime runs (capture efficiency = 47 ± 14 %, $n = 9$), when TKE was high—ranging from $1.3 - 1.9 \text{ m}^2 \text{ s}^{-2}$ at 9 m above the surface. The VEB was most effective during the nighttime run (capture efficiency = 73 ± 1.5 %, $n = 2$), when TKE was low ($0.32 \text{ m}^2 \text{ s}^{-2}$). The VEB therefore performed best during times with less turbulence. Since the wind speed was well-correlated with TKE (Figure 4), the VEB also performed best during times of slower wind speeds.

Though turbulence in the direction of flow did not likely contribute significantly to the mass transport, as was discussed in section 2.5, turbulence may have contributed to periodic lofting. A series of instantaneous scans is presented in Figure 5, where plumes are shown to rise well above the 9 m tall VEB. During these events, very little interaction between the plume and VEB was observed, and the lofted particulates could not be captured. Periodic lofting is therefore an undesirable process from the perspective of capturing particulates. However, periodic lofting can enhance dilution and reduce odor concentrations downwind of the source. Thus, a trade-off exists between particulate capture and lofting and dispersion. While this study has presented a range of capture efficiencies, future research may help realize the optimum proportion of capture versus lofting processes. Further, knowledge of these proportions will help engineer future VEBs.

3.3. Effect of Release Distance on Capture Efficiency

VEB design considerations include height, thickness, porosity, tree species, and orientation. Research investigating the effect of each of these variables on capture efficiency is limited. In this study, we varied the release distance from the VEB in an effort to determine a recommended distance VEBs should be installed from the facility. Due to the varying nature of atmospheric conditions throughout the day, it is appropriate to contrast results obtained at the

same time of day under similar atmospheric conditions. Runs 1 and 6 and runs 2 and 4 were examined. The VEB captured 8% more particulate mass in run 6 (9.1 m release distance) than in run 1 (5.2 m release distance). It captured 9% more particulate mass in run 4 (17.4 m release distance) than in run 2 (5.2 m release distance). In both cases, a further distance between the discharge tunnel and the buffer resulted in a higher VEB capture efficiency under the same atmospheric conditions. However, these results are not complete and should be considered preliminary.

3.4. Gaussian plume shape

During each run, between 170-270 lidar scans were collected for each slice. Typical scans are shown in Figure 5. The scans taken throughout this experimental campaign clearly show small individual plume structures intermittently lofting high into the atmosphere, well above the VEB or any ground-based measurement height. These observations are consistent with those reported in Prueger et al. (2008) and Holmén et al. (1998), and they justify the use of lidar to measure the entire plume. However, when scans are averaged over a run duration, they appear Gaussian (Figure 2). These unexpected results have implications in emissions monitoring and future quantification of VEB performance. Given an adequate averaging time, plumes emitted from VEBs converge to a Gaussian shape. With this information, future researchers can deploy arrays of point measurements immediately downwind of VEBs and use inverse Gaussian modeling to determine emission rate.

However, significant questions remain. To the best of our knowledge, this is the first attempt at averaging many lidar scans downwind of an AFO over a few hours. The first question is whether a Gaussian plume results from the presence of a VEB in the flow field, or if it is characteristic of all AFOs. A lidar campaign should be conducted similar to this study, but in the

absence of a VEB, to test this question. The second question is what averaging period is adequate for Gaussian plumes to emerge. The answer to this question will guide future researchers and policy makers in conducting monitoring studies and setting emission guidelines.

4. Conclusions

The results of this study indicate that a VEB can effectively capture between 21 and 74% of PM transported through it, depending on atmospheric conditions. This large range reveals the complexity of the system and the need to understand how variables such as particulate characteristics, wind speed, turbulence, and VEB design all interact and affect the capture efficiency.

Higher capture efficiency is observed at night, during stable atmospheric conditions with low wind speed and turbulence. However, the same conditions seemed to discourage lofting and could cause more odor nuisance to downwind neighbors. Conversely, conditions associated with low capture efficiency (daytime, unstable, and high turbulence) may encourage lofting and dispersion. This presents another interesting trade-off which leads one to conclude that some optimum fraction of lofting exists. A key benefit to the lidar method is that it allows one to separately measure the concentration reduction due to VEB capture versus the reduction due to lofting and dispersion. The only way to discriminate between the two effects is to spatially resolve the entire plume, including particulates that lofted up to 20 m above ground. This is not feasible using point sensors. Therefore, scanning lidar is the tool needed to determine the optimum lofting fraction in the future.

As Tyndall (2009) noted, many farmers are reluctant to invest in VEB technology without tangible, experimental evidence to support claims of their efficacy. Here, we experimentally demonstrated the efficacy of one VEB in-situ. Even during its worst

performance, the VEB captured 21 % of particulates, and at its best, it captured 74 %. The results presented here will hopefully build confidence in producers and extension agents who are interested in, yet still skeptical of VEB technology. We also expect that the lidar methodology presented here will encourage further experimental campaigns examining VEB effects on other constituents such as ammonia. There is still a great deal to learn about VEB design (optimizing porosity, orientation, arrangement). The effect of these design variables on VEB performance should be investigated experimentally in-situ, so that empirical evidence can provide tangible proof to producers and allow us to rationally approach VEB design in the future.

Disclaimer

Mention of specific products is for identification only and does not imply endorsement by the US Department of Agriculture to the exclusion of other suitable products or suppliers.

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Figure 1. Aerial view of the study site. The lidar was positioned 410 m NW of the area of interest (left). Meteorological and particulate instruments were positioned downwind of the VEB, and the lidar scanned two vertical slices immediately downwind of the VEB (right).

Figure 2. Summary of methodology, using run 6, slice 2 as an example. All scans (>200) are averaged over the run duration to produce a two-dimensional, spatially resolved concentration map, $\bar{C}(x,z)$. Concentrations are multiplied by the measured and modeled average perpendicular wind speed, area, and run time— $\bar{u}(z)$, $\Delta x \cdot \Delta z$, and Δt , respectively—to produce a two-dimensional, spatially resolved map of the total mass emitted from the VEB, $m_e(x,z)$. Total mass is summed over all sampling volumes, divided by the mass released, m_r , subtracted from 1, and multiplied by 100%, to obtain capture efficiency.

Figure 3. Capture efficiency varied throughout the day. The capture efficiencies for all runs, both slices, are shown as black lines spanning the entire run duration. The six runs were carried out over 24-26 June, 2013, and all results throughout the time period are combined into one time series in this figure. Shading indicates night time.

Figure 4. Turbulent kinetic energy and wind speed observed during the experimental runs at 2.3 m above the surface. Each point corresponds to a 10 minute period. The relationship is geometric, with a fitted exponent of 1.8.

Figure 5. Progression of vertical lidar scans for run 6. The VEB spans the ranges 410 – 460 m from the lidar, and the wind is blowing orthogonal to the surface, into the page. Each scan took approximately 20 seconds to complete.

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514 *Table 1. Summary of efforts to quantify the effectiveness of vegetative environmental buffers at*
 515 *reducing particulate matter quantities and odor levels.*

Reference	Reduction in Emissions	Methodology
Parker et al. (2012)	66.3% reduction in odor at 15 m downwind	Trained human panelists
Hernandez et al. (2012)	40% reduction in total PM counts; 40-60% reduction in odorous compound concentration	Optical particle counters; Sorbent tubes
Malone et al. (2006a)	49% reduction in PM concentration	Gravimetric filters
Laird (1997) and Thernelius (1997)	35-56% reduction in PM mass	Open-circuit wind tunnel, using digital imaging to relate brightness to dust deposition
Lin et al. (2006)	68% reduction in odor 117m downwind	Trained human panelists

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518 *Table 2. Summary of the experimental runs. Monin-Obukhov stability parameter (M-O z/L) and*
 519 *turbulence kinetic energy (TKE) values are calculated from 20 Hz, 10-minute average statistics,*
 520 *which are averaged over the run period.*

Run	Date	Start	Total Time	Release	M-O	TKE	Capture	
		Time (EDT)	(hours)	Distance (m)	z/L	(m ² s ⁻²)	Efficiency (%)	
							Slice 1	Slice2
1	6/24/2013	10:52	2.95	5.2	-0.12	1.3	42	—
2	6/24/2013	15:20	4.00	5.2	-0.02	1.8	62	46
3	6/25/2013	8:48	4.00	9.1	-0.10	1.6	32	21
4	6/25/2013	13:42	5.97	17.4	-0.05	1.9	64	61
5	6/25/2013	20:23	3.42	9.1	0.17	0.32	74	72
6	6/26/2013	10:45	4.00	9.1	-0.12	1.4	51	48

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