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Measuring gas emissions from animal waste lagoons with an inverse-dispersion technique

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ABSTRACT

Measuring gas emissions from treatment lagoons and storage ponds poses challenging conditions for existing micrometeorological techniques. This is due to non-ideal wind conditions, such as those induced by trees and crops surrounding the lagoons, and lagoons with dimensions too small to establish equilibrated microclimate conditions within the water boundary. This study evaluated the accuracy of an emerging backward Lagrangian stochastic (bLS) inverse-dispersion technique to measure lagoon emissions. It used a fabricated floating emission source with known emission rates from an irrigation pond that resembled typical treatment lagoon environments. The measured parameters were wind statistics and downwind path-integrated concentrations. Anemometers were located on the upwind, downwind, or side berm parallel to wind. Additionally, the berm surface was deliberately roughened during the summer by placing pine straw bales along the berms to simulate vegetation growth. Regardless of the surface roughness, when the surrounding vegetation (i.e. corn field) was short during spring and fall, using an anemometer located on the upwind berm produced the most accurate results (0.93 ± 0.19). However, during the summer, the adjacent corn crop grew more than 2 m high. Consequently, the anemometer had to be moved to the side berm. This resulted in a decrease in accuracy to 0.81 ± 0.18. Yet, even with less than idealized conditions, the bLS inverse-dispersion technique still produced reasonably accurate emission rates. This demonstrated the robustness of this easy-to-use bLS inverse-dispersion technique for complex agricultural emission measurements.

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1. Introduction

Animal waste lagoons and storage ponds consisting of excavated earthen basins have been widely utilized for storage prior to land application and as a partial treatment technology for wastewater from concentrated animal feeding operations (CAFOs) in the U.S. (Ham and DeSutter, 2000). Typically flushed or pit-emptied manure from animal houses is discharged into these lagoons for storage and partial stabilization. These lagoons have been the point sources for odor, ammonia, and greenhouse gas emissions due to biochemical transformation of manures (Liang et al., 2002; Ro et al., 2008; Vanotti et al., 2009). Accurate assessment of these trace gas emissions is vital for proper planning and management of animal wastes. Unfortunately, measuring gas emissions from waste lagoons is not trivial, and reported values of emission rates vary widely with different methods (Arogo et al., 2003; Harper, 2005; Harper et al., 2011). For instance, ammonia emissions from a swine lagoon measured by the flux gradient method ranged from 15.4 to 22 kg NH_3-N ha^{-1} d^{-1}; however, a chamber method yielded emission rates of 34 to 123 kg NH_3-N ha^{-1} d^{-1} from the same lagoon (Table 5 of Arogo et al., 2003). This illustrates the need for a technique with proven accuracy for measuring emissions from lagoon environments.

The bLS inverse-dispersion technique is an emerging micrometeorological method for measuring gas emission from distributed sources (Flesch et al., 1995, 2004, 2005b; Gao et al., 2009, 2010; Harper et al., 2010a; McBain and Desjardins, 2005; Ro et al., 2011). In this technique one measures the concentration rise downwind of a source, and with the aid of an atmospheric dispersion model (and wind information) one infers the

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source emission rate. The main advantages of the technique are the limited number of measurement requirements and the flexibility of measurement locations. The main disadvantage is that for practical calculations one must assume idealized wind flow over the measurement site (i.e., flat and homogeneous terrain) – an assumption violated at many sites. There are many examples where the bLS inverse-dispersion technique has been implemented to study emissions from agricultural sources, including feedlots (Flesch et al., 2007; Todd et al., 2008, 2011), barns (Harper et al., 2009), pastures (Laubach and Kelliher, 2005), and whole-farms (Flesch et al., 2005b). In examining the "bLS technique", Harper et al. (2009, 2010a) compiled a list of validation studies conducted in a variety of settings and concluded that with proper instrument locations the technique has a nominal accuracy of $\pm$10%.

While the advantages of the bLS inverse-dispersion technique – simplicity and flexibility – make it attractive for lagoon measurements, the physical settings of typical lagoons are problematic. For instance, as recommended by the ASAE Engineering Practice 403.3 (ASAE, 1998), many waste lagoons are surrounded by trees and natural barriers which enhance the dispersion and dilution of odors from nearby residences. This complicates the wind flow environment around the lagoon: moving from the upwind to the downwind side of the lagoon will see a transition from a highly turbulent zone with light wind speeds (due to the shelter of the trees) to a less turbulent zone with higher wind speeds over the lagoon, and then back to a more turbulent zone over the downwind berm. This complexity could lead to significant errors in a method assuming idealized windflow.[1]

One suggestion for dealing with this type of complexity is to move the sensors well downwind of the lagoon and away from the complications of trees and berms to an environment where the wind has been re-established to a more idealized flow (Flesch et al., 2005a). However in many lagoon situations the only convenient measurement location is on the berm beside the lagoon. Given the practical advantages of the bLS inverse-dispersion technique, an assessment of its accuracy in a lagoon environment would be a valuable contribution.

There have been few systematic bLS inverse-dispersion validation studies in a lagoon-like setting. Wilson et al. (2001) conducted a modeling study to examine this problem in a theoretical context. They used a complex wind flow model to calculate the evolution of winds passing from the land over a lagoon (which was variously warmer/cooler, rougher/smoother, and with a different atmospheric stratification than over the land). The surface change induced an inhomogeneous wind flow over the lagoon, and led to errors in a theoretical inverse-dispersion calculation. They found the error in the bLS inverse-dispersion deduced emission rate was typically less than 25%. However, this theoretical study did not take into account the complications introduced by a berm or surrounding trees. Furthermore, it did not consider the situation where concentration measurements were made on the downwind berm – the most practical field measurement situation.

The objectives of this study were to evaluate: (1) the accuracy of the bLS inverse-dispersion technique in a lagoon environment using concentration data obtained on the downwind berm; and (2) the optimal location for wind measurements.

[1] The potential for inaccuracy in complex wind environments is not unique to the inverse-dispersion technique, but is a concern for all micrometeorological techniques (e.g., flux gradient, eddy-covariance, eddy accumulation, integrated horizontal flux, etc.).

2. Materials and methods

2.1. Study site

The study was conducted on a 59 m $\times$ 68.5 m rectangular irrigation pond at the USDA-ARS Coastal Plains Soil, Water and Plant Research Center in Florence, SC (N 34°14.741′ and W 79°48.605′) from March to October 2011. The interior of the pond was lined from the bottom to the top of the berm with a rubber liner which provided smooth side slopes. The pond had side slopes of approximately 30% and a maximum depth of 2.7 m. The pond was bordered by pine trees on two sides and open cropland on the remaining two sides. A small pump house was located along one side. The irrigation pond was filled with water from an adjacent well. This site was selected because its boundary conditions (tree lines, buildings, cropland, etc.) were similar to those typically encountered in animal wastewater treatment lagoons (Fig. 1).

The experiment required the use of a distributed area methane source from the water surface. To accomplish this, a synthetic distributed area source was constructed of 1.3 cm schedule 40 PVC pipe. It was assembled into a 45 m square grid. The grid was setup with an "I" shaped manifold connected via polyethylene tubing to a cylinder of compressed chemically pure (CP) grade 99% methane (Airgas, Inc., Florence, SC). The methane gas was used as a test gas. Laterals were connected at 3 m intervals along the manifold. Each lateral had forty-four 1.59 mm holes drilled at 1 m intervals along the entire length. A total of 16 laterals were used. Circular foam floats were threaded onto each section of the laterals as well as the manifold. The floating distributed area source was secured in the center of the pond such that the laterals were in the Northwest–Southeast plane.

The test gas release rate was controlled using a pressure regulator and a flowmeter. The weight of the gas cylinder was measured with a 100 kg digital scale (Ohaus Champ platform scale with CW11-2EO indicator, Pine Brook, NJ). Both the flow rate and weight of the gas cylinder were continuously recorded using a video camera. The actual emission rate was calculated by the change in mass over time and accounting for the gas purity. The controlled methane emission rates for all experiments ranged from 0.7 to 1.4 g s^{-1}.

The experimental layout was designed for winds in the Southwest–Northeast plane. The predominant wind direction was from the southwest for all but one test. The one exception was on 3/29/2011 when the wind direction was northeast in the morning but changed to southwest in the afternoon. All experiments were conducted during the daytime hours. Experiments were conducted with both "smooth" and "rough" upwind and downwind side slopes. The spring tests (March and April, 2011) and the tests on 9/15/2011 and 10/17/2011 were conducted with "smooth" side slopes. The summer (July, August, and September, 2011) and fall (October, 2011) tests were conducted with "rough" side slopes. Bales of pine straw ($H \times L \times W$, 0.25 $\times$ 0.4 $\times$ 0.7 m) were secured midway up the side slopes along the upwind and downwind berms to create an artificial "rough" side slope to simulate berms frequently found with heavy vegetation growth in warm climate regions. A total of 50 bales, 25 on each berm, were equally spaced approximately 1.5 m apart along the length of the two berms.

A 3-dimensional sonic anemometer (CSAT3, Campbell Scientific, Inc.) was used to measure wind statistics at 20 Hz. During the spring tests (March and April, 2011), the anemometer was installed at the edge of the newly planted corn field approximately 10 m upwind of the pond at a height of 2 m above the ground. The corn field was clear with little crop growth during spring tests. However, at the start of the summer tests (July, August, and September, 2011)

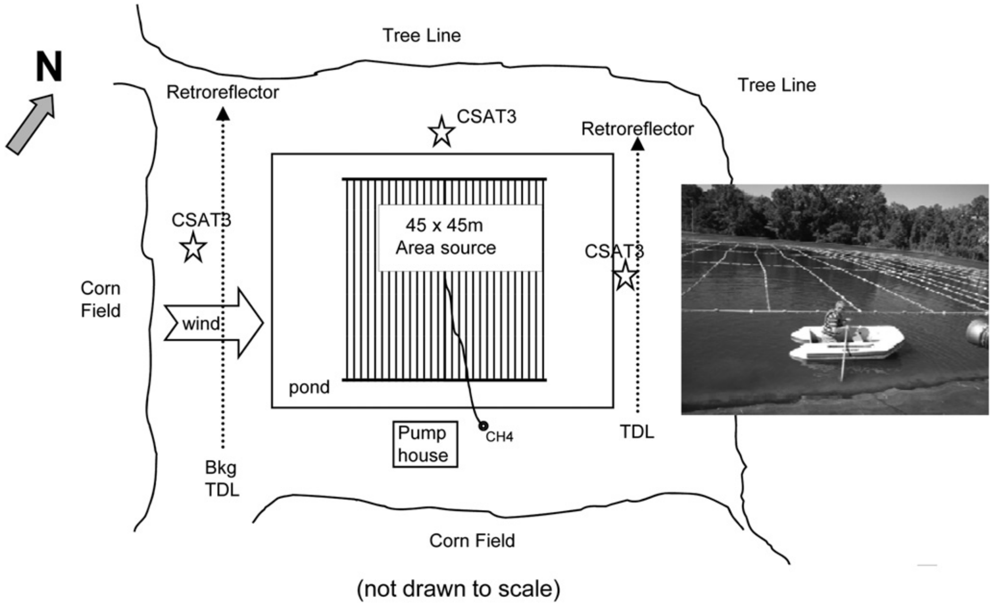

Fig. 1. Experimental layout of the pond, distributed source, and instrument locations (☆ 3D sonic anemometer, CSAT3).

the corn had grown to over 2 m. Obtaining wind flow data from the upwind anemometer directly facing the tall corn was not feasible; therefore, the anemometer was moved to the side berm or the downwind berm at a height of 2 m above the ground. This provided a clear fetch of at least 40 m downwind of the corn. After the corn was harvested, additional experiments were conducted to evaluate the impact of surface roughness on the accuracy of the inverse-dispersion technique. These employed the wind data obtained from one of two anemometers simultaneously located on the upwind and either the side or the downwind berms of the pond (September and October, 2011).

During the spring and fall experiments, the mean air temperature and wind speed measured at 2 m above the ground ranged from 15 to 29 °C and 1.1–4.9 m s^{-1}, respectively. During the summer experiments, the mean air temperature and wind speed ranged from 29 to 34 °C and 0.3 to 2.1 m s^{-1}, respectively. The berm height (relative to the water level) during the study ranged from 0.43 to 1.42 m above the water level.

2.2. Instrumentation

An open-path tuneable diode laser absorption spectrometer (TDL, GasFinder2.0 for CH_4, Boreal Laser Inc., Spruce Grove, Canada) and retroreflector were used to measure path-integrated concentrations (PIC) along the downwind berm. The TDL and retroreflector were located approximately 1 m above the berm. Its path length was approximately 63 m. The TDL was setup for a sample rate of approximately 1 Hz. It had continuous calibration updates every 40 samples using its internal reference cell. Prior to the field tests, the TDLs were calibrated using an external calibration tube and a standard methane gas of known concentration. The calibration tube consisted of a 5 cm i.d. pvc pipe 6.25 m in length. The standard CH_4 gas was mixed with N_2 gas using a Horibastec SGD-710C gas divider (Horiba Instruments, Ann Arbor, MI) to create three concentration levels of methane gas. The average TDL data corresponding to the three concentration levels was regressed against the actual concentrations to determine a correction multiplier for each TDL. The calibration multiplier for a specific TDL was applied to all of its data.

The background methane concentration was measured using a second TDL and retroreflector. These were located upwind of the distributed area source for both the spring and summer tests. In contrast, during later tests in September and October, the average background methane concentration was determined from the data collected prior to and after the CH_4 gas release using a single TDL located on downwind berm. Methane PIC data was averaged at 15 min intervals. For each 15 min period, the background concentrations were subtracted from the downwind concentrations. This net PIC data along with the wind statistic data collected by the anemometers were used as inputs to the windows-based inverse-dispersion computer model, WindTrax 2.0 (Thunder Beach Scientific, http://www.thunderbeachscientific.com/, accessed on October 3, 2008). The sensor heights used in the WindTrax 2.0 were referenced from the ground surface.

Table A
Site and weather conditions during emission rate experiments (weather data from nearby weather station).

Date of tests	Time of CH_4 release	Berm height (m)	Mean wind speed (m s^{-1})	Mean wind direction (°)	Mean temperature (°C)
3/21/11	13:00–17:30	0.92	4.7	237	23.2
3/22/11	10:00–14:30	0.92	3.0	266	25.5
3/29/11	11:00–17:00	0.43	1.1	152	15.0
4/4/11	10:00–15:30	0.43	4.9	221	24.3
7/19/11	11:30–14:30	1.41	0.6	218	32.6
7/20/11	10:30–13:00	1.41	0.3	176	33.5
7/21/11	10:30–14:30	1.42	1.1	239	34.4
7/28/11	9:30–14:00	1.34	1.4	208	29.4
8/3/11	9:00–13:30	1.35	1.3	237	30.5
8/4/11	9:30–12:00	1.36	0.7	208	32.4
9/15/11	9:00–15:00	1.42	2.1	219	29.5
10/17/11	13:30–16:30	1.42	2.6	236	29.2
10/26/11	14:00–16:30	1.42	3.2	245	25.0

2.3. Post-data processing

The software WindTrax 2.0 combines an interface where sources and sensors are mapped with a bLS inverse-dispersion model (Flesch et al., 2004). For each study configuration, a map of emission source, wind and concentration sensors was created. WindTrax used the time series of concentration and wind measurements to determine a time series of emissions. For each measurement period, the bLS model calculated the upwind trajectory of 50,000 gas "particles" that passed through the TDL path. These trajectories determined the relationship between downwind concentration and the lagoon emission rate. The criteria used to avoid error-prone observation periods were (Ro et al., 2011):

- footprint (FP) $\geq 50\%$
- Obukhov stability length scale, $|L| \geq 10$ m
- frictional wind speed, $u^* \geq 0.15\ \mathrm{m\,s^{-1}}$.

The accuracy of the inverse-dispersion technique was calculated as:

$$\text{accuracy} = Q_{\mathrm{bLS}}/Q \qquad (1)$$

where Q is the actual emission rate ($\mathrm{g\,s^{-1}}$), Q_{bLS}, calculated emission rate via inverse-dispersion technique ($\mathrm{g\,s^{-1}}$). The central tendency and its precision of the accuracy were represented with arithmetic averages and standard deviations (given as ± values in the subsequent accuracy summaries). Statistical tests were performed using GraphPad Prism 5.04 (GraphPad Software, Inc., La Jolla, CA).

3. Results and discussion

3.1. Overall accuracy

The average accuracies (Q_{bLS}/Q) of all the runs conducted during the spring and fall were 0.94 ± 0.23 and 0.91 ± 0.13, respectively. In the summer, the average accuracy decreased to 0.81 ± 0.18. These runs included situations where the sonic anemometer was located at the upwind, side, and downwind berms, and where the berm was either "smooth" or "rough". For the entire year, the overall accuracy was 0.88 ± 0.20. This is an encouraging result for the complex lagoon environment – this level of accuracy is not dramatically different from those validation studies conducted over ideally homogeneous landscapes (Harper et al., 2009, 2010b).

We suspect that the lower summer accuracy was partially due to the greater proportion of unstable atmospheric periods (due to higher sensible heat flues and lower wind speeds) A reduction in accuracy during unstable periods has been seen in other studies: Gao et al. (2009) found the accuracy of the inverse-dispersion technique was lower in unstable conditions (i.e., when $1/L < -0.033$). In Fig. 2 we see that unstable conditions were associated with greater uncertainty in Q_{bLS}.

Lower summer accuracies may also be explained by an increase in aerodynamic complexity caused by the corn that had grown up around the lagoon. This adds an additional layer of aerodynamic discontinuity to the lagoon environment (transition between corn-berm-lagoon surface conditions). This discontinuity should (at least in theory) decrease the accuracy of an idealized inverse-dispersion technique. The situation where a lagoon is a "hole" in the corn-tree landscape has similarities to the situation studied by Flesch et al. (2005b). In that study, a synthetic surface area source was surrounded by a windbreak fence, and it induced a complex wind flow over the source. Subsequent inverse-dispersion calculations were made using wind and concentrations measured inside the fenced plot. They found that the calculations tended to underestimate emissions – similar to the underprediction error found in the current summer study.

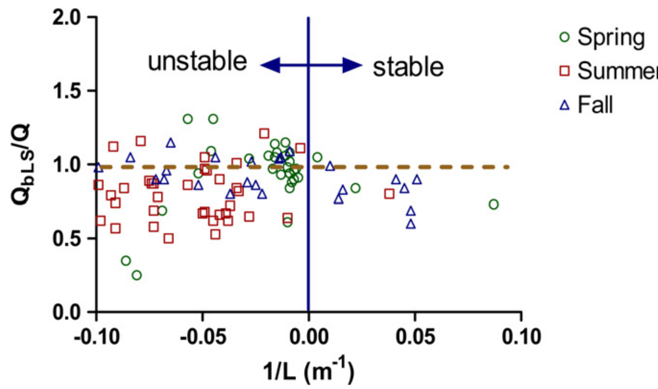

Fig. 2. Accuracies at different atmospheric stabilities.

3.2. Effects of 3D sonic anemometer location

When using the inverse-dispersion technique in a complex wind environment, it is assumed that wind flow is horizontally homogeneous across the landscape. Thus, the location of the wind measurements is critically important in these situations. For example, in the square windbreak plot studied by (Flesch et al., 2005a), there were large differences in the inverse-dispersion calculation depending on whether the wind was measured inside or outside the sheltered plot.

Accordingly, three wind measurement locations were examined in the current experiment: the upwind, side, and downwind berms. The upwind berm location yielded the best results (Table 1). For both the "rough" and "smooth" berm conditions the bLS accuracy was very good: There was no statistical difference in the accuracy levels between the two roughness states. When the sonic anemometer location was on the side berm, accuracy declined to about 0.8. Again, there was no significant difference in accuracy for the rough and smooth berm surfaces. However, when the sonic anemometer location was on the downwind berm, the accuracy of the inverse-dispersion technique depended on whether the berm surface was rough or smooth. The accuracy was good in the smooth configuration ($Q_{\mathrm{bLS}}/Q = 0.92$). It was lower in the rough configuration ($Q_{\mathrm{bLS}}/Q = 0.79$, Table 2).

There were two interesting results to consider regarding the berm roughness trials: (1) there was little difference in Q_{bLS}/Q for rough and smooth berms when using the upwind and side berm sonic; and (2) there was a difference in Q_{bLS}/Q between the rough and smooth berms when using the downwind sonic. For the first result to be true, the concentration at the downwind laser must be insensitive to berm roughness. For the second point to be true, the wind flow on the downwind berm must be sensitive to the berm roughness. In other words, the berm roughness impacted the wind flow at the downwind berm; however, it did not impact the concentration of gas emitted by the lagoon. Accordingly, this

Table 1
Accuracies (Q_{bLS}/Q) associated with various 3D sonic anemometer locations and surface condition.

Location of 3D Sonic anemometer	Surface condition		Are means significantly different? ($P < 0.05$)[a]
	Smooth	Rough	
Upwind berm	0.95 ± 0.23 ($N = 29$)	1.0 ± 0.09 ($N = 8$)	No ($P = 0.20$)
Side berm	0.75 ± 0.15 ($N = 7$)	0.82 ± 0.19 ($N = 30$)	No ($P = 0.34$)
Downwind berm	0.92 ± 0.11 ($N = 9$)	0.79 ± 0.09 ($N = 9$)	Yes ($P = 0.02$)

[a] Using the unpaired t test with Welch's correction.

Table 2
Statistical comparison of the accuracies associated with anemometer location and surface condition – are means significantly different? ($P < 0.05$)[a]

3D Sonic anemometer location	Surface condition	
	Smooth	Rough
Upwind berm vs. side berm	Yes	Yes
Upwind berm vs. downwind berm	No	Yes
Side berm vs. downwind berm	Yes	No

[a] Using the unpaired *t* test with Weltch's correction.

suggested that the downwind berm was not the ideal location for a sonic anemometer because its bLS accuracy would then depend on the roughness of the berm. In contrast, Q_{bLS} would be insensitive to berm roughness if the anemometer were on the upwind berm or side berm. However, any recommendation that the wind be measured on the upwind berm of a lagoon would be subject to a caveat that the measurement not be made in the immediate leeward of any surrounding vegetation (where the anemometer would be located within a highly complex wind region).

3.3. Data filtering criteria

The goal of the post-data filtering process is to eliminate error-prone data while maximizing the number of valid datasets. The effects of the three post-data filtering criteria (i.e., FP, $|L|$, and u^*) on Q_{bLS} accuracy and uncertainty (standard deviation) were evaluated (Table 3 and Fig. 3). Surprisingly, there was a small drop in accuracy as we imposed more restrictive criteria for footprint coverage (FP) of the downwind laser (from no requirement to a threshold of 65%). More significantly, there was a large decrease in Q_{bLS} uncertainty with an increasing FP threshold, particularly as we went from no threshold to 20%. A similar result was found as we imposed a set of $|L|$ thresholds, with a significant decrease in Q_{bLS} uncertainty as we changed the threshold from $|L| = 2–5$ m, (with little change as the threshold became more restrictive). For friction velocity, a threshold value of $u^* = 0.22\ \mathrm{m\ s^{-1}}$ was very effective at reducing the uncertainty in the Q_{bLS} observations.

Using these threshold values as new data filtering criteria (i.e., FP $\geq$ 20%, $|L| \geq 5$ m, $u^* \geq 0.22\ \mathrm{m\ s^{-1}}$), Q_{bLS} accuracy was compared with that using the criteria (FP $\geq$ 50%, $|L| \geq 10$ m, $u^* \geq 0.15\ \mathrm{m\ s^{-1}}$) used by Ro et al. (2011) and Flesch et al. (2005a). While the accuracies were not statistically different (unpaired *t* test with Welch's correction at $P < 0.05$), the number of valid datasets increased from

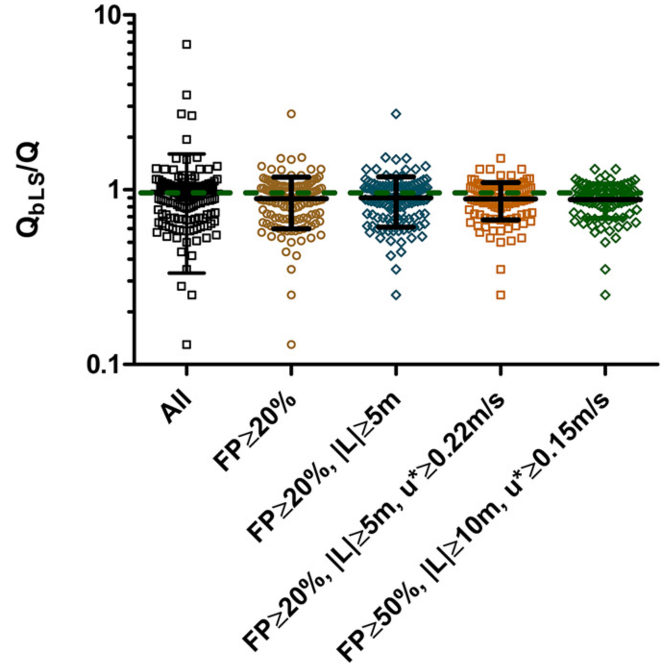

Fig. 3. Accuracy vs. filtering criteria.

91 to 104. Therefore, the new data filtering criteria are recommended for emission measurements from lagoons with similar environments as tested in this study.

4. Conclusions

A fabricated floating emission source was floated on an irrigation pond to simulate lagoon environments during spring, summer, and fall seasons. Subsequently, the accuracy of the inverse-dispersion technique in conjunction with the backward Lagrangian stochastic (bLS) model was evaluated. The overall accuracy of the inverse-dispersion technique with $Q_{bLS}/Q = 0.88 \pm 0.20$ was good. This was especially good given the site's non-ideal complexities; trees and tall corn field surrounding the lagoon, and rough berm surfaces. The accuracy was generally lower in the summer due to more frequent unstable atmospheric

Table 3
Data lost as filtering criteria are narrowed.

	All	FP $\geq$ 20%	FP $\geq$ 35%	FP $\geq$ 50%	FP $\geq$ 65%
Q_{bLS}/Q	0.97	0.92	0.90	0.88	0.88
Standard deviation	0.63	0.34	0.30	0.26	0.24
N	143	140	134	132	128
	All	$\|L\| \geq 2$ m	$\|L\| \geq 5$ m	$\|L\| \geq 7$ m	$\|L\| \geq 10$ m
Q_{bLS}/Q	0.97	0.97	0.92	0.93	0.91
Standard deviation	0.63	0.64	0.37	0.37	0.33
N	143	137	126	111	84
	All	$u^* \geq 0.15\ \mathrm{m\ s^{-1}}$	$u^* \geq 0.20\ \mathrm{m\ s^{-1}}$	$u^* \geq 0.22\ \mathrm{m\ s^{-1}}$	$u^* \geq 0.25\ \mathrm{m\ s^{-1}}$
Q_{bLS}/Q	0.97	0.97	0.94	0.89	0.90
Standard deviation	0.63	0.60	0.59	0.21	0.20
N	143	136	121	105	89
	FP $\geq$ 50%, $\|L\| \geq 10$ m, $u^* \geq 0.15\ \mathrm{m\ s^{-1}}$ [a]			FP $\geq$ 20%, $\|L\| \geq 5$ m, $u^* \geq 0.22\ \mathrm{m\ s^{-1}}$	
Q_{bLS}/Q	0.88			0.88	
Standard deviation	0.20			0.21	
N	91			104	

[a] Data filtering criteria used in Ro et al. (2011).

conditions. The increased wind disturbance caused in part by the tall corn crop that was contiguous to the lagoon.

The accuracy of the inverse-dispersion technique was affected by the location of the 3D sonic anemometers. Using an anemometer located on the upwind berm produced the most accurate results (0.93 ± 0.19). However, this location was used only when the surrounding vegetation (i.e. corn) was short during the spring and fall. During the summer, when the adjacent corn crop grew more than 2 m in height, the anemometer had to be moved to the side berm. In this case, the accuracy decreased to 0.81 ± 0.18. Our results suggest that the preferred location for an anemometer in a lagoon study is on the upwind berm provided that the fetch is free from tall vegetation.

For this particular site and landscape conditions, we found that an alternative data filtering criteria (i.e., FP $\geq$ 20%, $|L| \geq 5$ m, $u^* \geq 0.22$ m s^{-1}) yielded statistically equivalent accuracy with a larger number of valid datasets.

In summary, a lagoon environment is a challenging location in which to apply an inverse-dispersion technique, given the clear violation of the assumptions made in the idealized dispersion calculations. Nonetheless, this lagoon study showed an accuracy level not very different from environments that do meet the ideal assumptions of the inverse-dispersion model. This documents the robustness of the inverse-dispersion technique even in non-ideal settings. This is particularly encouraging for researchers and regulatory agencies in measuring lagoon gas emissions. The bLS inverse-dispersion technique provides a simple and economical measurement tool that can be used in these challenging environments.

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References

Arogo, J., Westerman, P.W., Heber, A.J., 2003. A review of ammonia emissions from confined swine feeding operations. Trans. ASABE 46 (3), 805–817.
ASAE, 1998. ASAE Engineering Practices 403.3 Design of Anaerobic Lagoons for Animal Waste Management. ASAE, St. Joseph, MI.
Flesch, T.K., Wilson, J.D., Yee, E., 1995. Backward-time lagrangian stochastic dispersion models and their application to estimate gaseous emissions. J. Appl. Meteorol. 34, 1320–1332.
Flesch, T.K., Wilson, J.D., Harper, L.A., Crenna, B.P., Sharpe, R.R., 2004. Deducing ground-to-air emissions from observed trace gas concentrations: a field trial. J. Appl. Meteorol. 43, 487–502.
Flesch, T.K., Wilson, J.D., Harper, L.A., 2005a. Deducing ground-to-air emissions from observed trace gas concentrations: a field trial with wind disturbance. J. Appl. Meteorol. 44, 475–484.
Flesch, T.K., Wilson, J.D., Harper, L.A., Brian, P.C., 2005b. Estimating gas emissions from a farm with an inverse-despersion technique. Atmos. Environ. 39, 4863–4874.
Flesch, T.K., Wilson, J.D., Harper, L.A., Todd, R.W., Cole, N.A., 2007. Determining ammonia emissions from a cattle feedlot with an inverse dispersion technique. Agric. For. Meteorol. 144, 139–155.
Gao, Z., Desjardins, R.L., Flesch, T.K., 2009. Comparison of a simplified micrometeorological mass difference technique and an inverse dispersion technique for estimating methane emissions from small area sources. Agric. For. Meteorol. 149, 891–898.
Gao, Z., Desjardins, R.L., Flesch, T.K., 2010. Assessment of the uncertainty of using an inverse-dispersion technique to measure methane emissions from animals in a barn and in a small pen. Atmos. Environ. 44, 3128–3134.
Ham, J.M., DeSutter, T.M., 2000. Toward site-specific design standards for animal-waste lagoons: protecting ground water quality. J. Environ. Qual. 29, 1721–1732.
Harper, L.A., 2005. Micrometerological measurements in agricutural systems. Agron. Monogr. ASA-CSSA-SSSA, Madison, WI.
Harper, L.A., Flesch, T.K., Powell, J.M., Coblentz, W.K., Jokela, W.E., Martin, N.P., 2009. Ammonia emissions from dairy production in Wisconsin. J. Dairy Sci. 92, 2326–2337.
Harper, L.A., Flesch, T.K., Weaver, K.H., Wilson, J.D., 2010a. The effect of biofuel production on swine farm ammonia and methane emissions. J. Environ. Qual. 39, 1984–1992.
Harper, L.A., Flesch, T.K., Wilson, J.D., 2010b. Ammonia emissions from broiler production in the San Joaquin valley. Poultry Sci. 89, 1802–1814.
Harper, L.A., Denmead, O.T., Flesch, T.K., 2011. Micrometeorological techniques for measurement of greenhouse gas emissions from ruminant animal production. Animal Feed Sci. Tech. 166, 167, 227–239.
Laubach, J., Kelliher, F.M., 2005. Methane emissions from dairy cows: comparing open-path laser measurements to profile-base techniques. Agric. For. Meteorol. 135, 340–345.
Liang, Z.S., Westerman, P.W., Arogo, J., 2002. Modeling ammonia emission from swine anaerobic lagoons. Trans. ASABE 45 (3), 787–798.
McBain, M.C., Desjardins, R.L., 2005. The evaluation of a backward Lagrangian stochastic (BLS) model to estimate greenhouse gas emissions from agricultural sources using a synthetic tracer source. Agric. For. Meteorol. 135, 61–72.
Ro, K.S., Sozgi, A.A., Vanotti, M.B., Stone, K.C., 2008. Process model for ammonia volatilization from anaerobic swine lagoons incorporating varying wind speeds and gas bubbling. Trans. ASABE 51 (1), 259–270.
Ro, K.S., Johnson, M.H., Hunt, P.G., Flesch, T.K., 2011. Measuring trace gas emission from multi-distributed sources using vertical radial plume mapping (VRPM) and backward Lagrangian stochastic (BLS) techniques. Atmosphere 2, 553–566.
Todd, R.W., Cole, N.A., Clark, R.N., Flesch, T.K., Harper, L.A., Baek, B.-H., 2008. Ammonia emissions from a beef cattle feedyard on the Outhern high plains. Atmos. Environ. 42, 6297–6805.
Todd, R.W., Cole, N.A., Rhoades, M.B., Parker, D.B., Casey, K.D., 2011. Daily, monthly, seasonal and annual ammonia emissions from southern high plains cattle feedyards. J. Environ. Qual. 40, 1–6.
Vanotti, M.B., Szogi, A.A., Millner, P.D., Loughrin, J.H., 2009. Development of a second-generation environmentally superior technology for treatment of swine manure in the USA. Bioresour. Technol. 100, 5406–5416.
Wilson, J.D., Flesch, T.K., Harper, L.A., 2001. Micro-meteorological methods for estimating surface exchange with a disturbed windflow. Agric. For. Meteorol. 107, 207–225.