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Abstract. *Odor, ammonia and hydrogen sulfide emission data were collected from three phototrophic and three non-phototrophic anaerobic swine lagoons in eastern Nebraska from May 27th to June 18th (late spring) and from July 7th to August 13th (summer). The greatest odor, hydrogen sulfide and ammonia emission rates were from non-phototrophic lagoons during late spring (24.5 OU m^{-2} s^{-1}, 3.2 μg-H_2S m^{-2} s^{-1}, 34.9 kg NH_3-N ha^{-1} d^{-1}, respectively). Non-phototrophic lagoon odor, ammonia and hydrogen sulfide emission rates were much higher in late spring than summer (24.5 vs. 4.8 OU m^{-2} s^{-1}, 34.9 vs. 18.0 kg NH_3-N ha^{-1} d^{-1}, 3.2 vs. 0.3 μg-H_2S m^{-2} s^{-1}, respectively). Odor and ammonia emission rates from phototrophic lagoons were relatively constant from late spring to summer (9.4 vs. 4.0 OU m^{-2} s^{-1} and 23.0 vs. 16.5 kg NH_3-N ha^{-1} d^{-1}, respectively), but hydrogen sulfide emissions were higher in late spring than summer (1.9 vs. 0.1 μg-H_2S m^{-2} s^{-1}).*

Keywords. Lagoons, odor, ammonia, hydrogen sulfide, emissions, phototrophic.

Introduction

Gaseous emissions from swine production represent a significant economic and environmental problem facing modern agriculture (Letson and Gollehon, 1996). Due to the lack of a complete emissions database, there has been little consensus among researchers, producers and regulators concerning the quantity and types of emissions that create decreased air quality, and how to reduce or control those emissions (NPPC, 1997).

There is concern about ammonia (NH_3) emissions from animal feeding operations (EPA, 2001), and hydrogen sulfide (H_2S) and total reduced sulfur (TRS) emissions from livestock systems are increasingly being implicated with community health-related concerns (Koelsch et al., 2004). Low concentrations of H_2S and other gases associated with animal agriculture can potentially impact human health (Schiffman et al., 2001). To date, most research has focused on quantification of ammonia and hydrogen sulfide emissions from animal housing due to the potential health effects to animals and humans in confined spaces, rather than emission rates to ambient air from anaerobic lagoons (Wood et al., 2001). Therefore, little data exist in literature on the emission rates from anaerobic lagoons (Appendix A). However, anaerobic lagoons have been shown to contribute 70 to 80 percent of odor emissions from swine facilities in Australia (Watts, 2000).

It is commonly believed that anaerobic phototrophic lagoons are not as odorous as anaerobic non-phototrophic lagoons. Phototrophic lagoons are characterized by high concentrations of purple sulfur bacteria (Chen et al., 2003). Purple sulfur bacteria have the potential to reduce lagoon odor by oxidizing hydrogen sulfide into elemental sulfur during photosynthesis (McGahan et al., 2001), and by utilizing volatile fatty acids. Purple sulfur bacteria are also known to consume ammonium. When the purple sulfur bacteria are present in high enough concentrations, the lagoon will have a brownish, red or purple color. The presence of purple sulfur bacteria is thought to be an indication of good lagoon function and reduced odor production.

The general purpose of this project was to establish aerial emission rates for anaerobic swine lagoons in Nebraska. Specifically it was to:

1) Determine differences between phototrophic and non-phototrophic lagoons, as defined by bacteriochlorophyll *a* and parameters such as volatile fatty acids, oxidation reduction potential, chemical oxygen demand, pH and electrical conductivity;

2) Establish the differences in odor, H_2S, and NH_3 emission rates between phototrophic and non-phototrophic lagoons and within each lagoon type as a function of season.

This paper focuses on the differences in emission rates of phototrophic and non-phototrophic lagoons.

Materials and Methods

Emissions sampling was conducted 12 times from May 27 to August 20, 2003; six times in late spring (May 27th to June 18th) and six times again in early summer (July 7th to August 13th), approximately from 9:00 am to 1:00 pm. Lagoons that were sampled in the spring were sampled again in the summer. Three of the lagoons were phototrophic and three were non-phototrophic (Table 1).

The non-phototrophic lagoons all appeared black, and more bubbles were observed on the surface than the phototrophic lagoons. The phototrophic lagoons ranged in color from purple-violet to brown-red. Lagoon B was brown-red and lagoons C and E were purple-violet.

The amount of volatile solids (VS) produced by the facility was determined using AMW 2.0.2 (USDA, 2003) and the number, type, and estimated average weight of animals, as provided by the producer. Lagoon volumes were calculated from measured depths, surface areas and slopes. The modified VSLR was then calculated as the ratio of VS to lagoon volume.

Table 1. Summary of Lagoon Types: Late spring (Summer)

Lagoon	Capacity	Type	Depth [m]	Surface Area [ha]	Modified VSLR*
A	4000 Finisher	Non-phototrophic	2.6 (2.7)	1.6 (1.6)	35.2 (33.6)
B	4000 Finisher	Phototrophic	4.1 (4.8)	1.2 (1.3)	30.4 (25.6)
C	1020 Finisher	Phototrophic	0.8 (0.7)	0.7 (0.7)	75.2 (83.2)
D	4000 Finisher 1000 Nursery	Non-phototrophic	2.6 (3.8)	0.8 (0.9)	78.4 (56.0)
E	450 Sows 450 Finisher 400 Nursery	Phototrophic	2.3 (2.4)	0.9 (0.9)	24.0 (24.0)
F	300 Sows 44 Farrow	Non-phototrophic	2.3 (1.2)	0.1 (0.1)	58.5 (58.5)

* g VS day^{-1} m^{-3} of total lagoon volume

A stainless steel wind tunnel, constructed according to plans from Schmidt and Bicudo (2002) originally designed by Jiang (1995), consisted of an inlet PVC stack, blower, expansion chamber, air filter, pressure gauge, tunnel body, mixing chamber, outlet PVC “T” and two gas sampling ports (Figure 1).

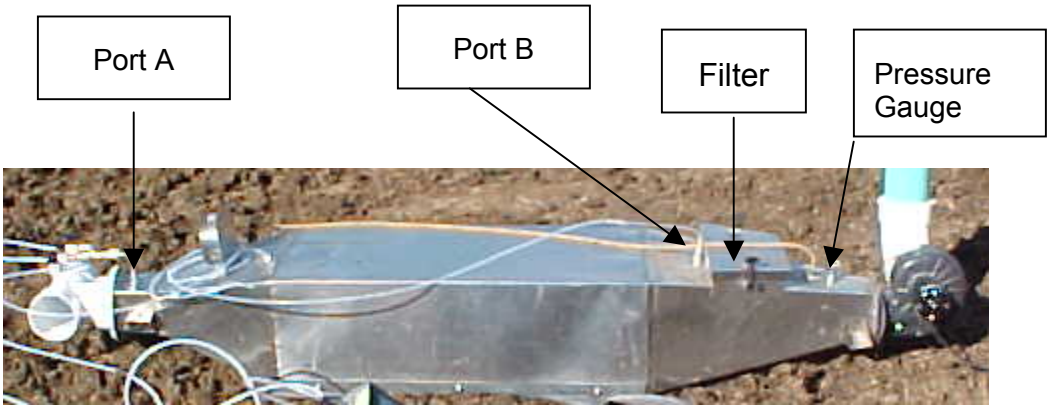

Figure 1. Wind Tunnel

The filter consisted of Purafil® Purakol AM and Purafil® Select CP Blend activated carbon media. Schmidt and Bicudo (2002) showed that this filter removed 99% ammonia, 99% hydrogen sulfide, but only 85% of the odor. Because of the limited empty bed contact time (0.2 to 0.4 seconds) for the activated carbon filter, and based on Schmidt and Bicudo's results, odor samples were collected immediately after the filter (Port B), and after being exposed to the lagoon surface (Port A) enabling net odor emission rates to be calculated using the difference in odor concentrations from these two samples.

A gantry system, based on a design by Galvin et al. (2003), was built to allow sampling equipment to move on a lagoon with minimal disturbance of the lagoon surface. The gantry consisted of rectangular aluminum tubing, 15.2 cm (6 in.) PVC pipe for pontoons, steel cables and an electric winch, and could be disassembled into three parts for transportation. When assembled, it was 3.7 m (12 ft.) long and 1.1 m (3.5 ft.) high. The wind tunnel, having its own pontoons, was raised and lowered to the lagoon surface using the electric winch. Electrical wires and sample collection tubing (Teflon®) ran from the wind tunnel to a boat attached to the structure of the gantry. A plastic toolbox (Craftsman Professional, Sears) was modified to allow for easy connection of the tubing to sampling equipment for NH_3 and H_2S. Teflon® tubing from the wind tunnel connected to ports on the toolbox with Swagelok® quick connects.

Four sampling locations on each lagoon were located approximately along the mid-line of each lagoon and equally spaced along the mid-line. An example, from lagoon A, of the sampling locations is shown in Figure 2.

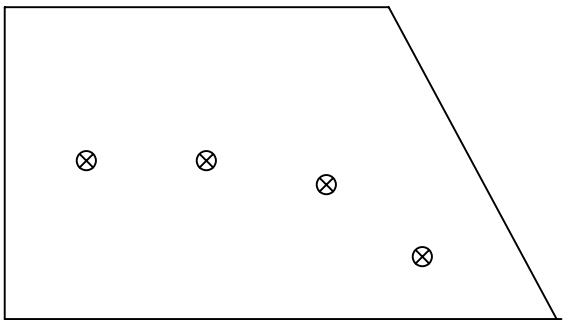

Figure 2. Example locations of sampling distribution on Lagoon A.

After the wind tunnel ran for approximately 15 minutes, sampling was initiated for odor, ammonia, and hydrogen sulfide. One ammonia sample was collected continuously over a 20-minute period at each of the four locations. Odor bag B was allowed to fill once, then purged and filled again. Odor sample B was then completed, and odor sample A was filled, then purged and filled again to complete the odor sampling.

H_2S concentrations were measured simultaneously with odor and ammonia in the outlet air of the wind tunnel using a Model 631-X Jerome Meter. Each H_2S measurement required approximately 30 seconds and 15 measurements were taken at each sampling location.

An SKC air check sampler vacuum pump (Model 224-PCXR8) was used to deliver the ammonia-contaminated air at a rate of 1.0 L min^{-1} to a Supelco midget bubbler that contained 17 mL of 0.2 M sulfuric acid in a removable glass vial (Figure 3.2). A Drierite tube separated the bubbler from the vacuum pump to prevent liquids from damaging the pump. The glass vial was stored on ice until delivered to the University of Nebraska Water Laboratory for analysis.

Odor samples were collected in 10 L Tedlar® bags using a vacuum chamber (Vac-U-Chamber; SKC-West, Inc., Fullerton, CA), and the SKC vacuum pump. Two odor samples were collected, one after the filter and one from the outlet of the wind tunnel. The Tedlar® bags were provided by West Texas A&M University and were prepared for sampling by the method described by Parker et al. (2003). On the lagoon, before sampling, the bags were filled once with sample air, and then purged. The sample from immediately after the activated carbon filter (Port B, Fig. 1) was taken first, and then the outlet sample (Port A) was taken. The bags were then filled to approximately 7 to 8 L to allow for expansion during overnight air transportation to West Texas A&M Olfactometry Laboratory. Once odor sampling was completed at a given location, the wind tunnel was raised and the system was moved to the next sampling location. The sampling process was then repeated.

Odor samples were sent next-day air to the West Texas A&M University Olfactometry Laboratory. DT was measured using triangular forced-choice olfactometry with an AC'Scent International Olfactometer (St. Croix Sensory, Lake Elmo, MN). Panel DTs were calculated following the guidelines of ASTM (1991). The DT for each individual panelist was calculated as the geometric mean of the concentration at which the last incorrect guess occurred and the next higher concentration at which the odor was correctly detected. The panel DT was calculated as the geometric mean of the individual panelist DTs.

Bchl *a* samples were analyzed using the method modified by Austin (1988) and Siefert et al. (1978), which consisted of centrifuging a 50 mL lagoon sample at 2400g for 25 minutes in a Jouan CR422 centrifuge. Then the liquid was decanted from the solid, and 10 mL of boiling methanol was added. After adding the methanol, the pellet was broken up and 3 mL of 0.5% w/v of NaCl solution was added. Then 13 mL of hexane was added, and the sample was mixed. The sample was then centrifuged at 2400g for 10 minutes. The absorbency of the hexane phase was then measured using a Shimadru UV-Visible Recording Spectrophotometer UV-260 at a wavelength of 768 nm, the maximum absorption for Bchl *a* in the hexane phase (Stal et al, 1984). The absorption coefficient used for the hexane phase was 149.5 L g^{-1} cm^{-1}, (Stal et al., 1984).

The data were analyzed using the general linear model for split plot experimental design (SAS, 1996). Fisher's protected LSD was used to determine significant differences in season and phototrophic status when there was an interaction. When no interaction was present, the phototrophic status and season main effects were tested with the appropriate error term to determine differences in phototrophic status or season. The lagoon was the whole plot and season was the subplot.

Results

Supernatant samples were analyzed to confirm which lagoons were phototrophic and non-phototrophic based on Bchl *a* (bacteriochlorophyll a) concentrations. The emission rate data were analyzed to compare emission rates from phototrophic and non-phototrophic lagoons for late spring and again for summer. Changes in emissions within each type of lagoon were also analyzed as a function of season. The May 27th to June 18th results were labeled as "late spring" results, and the July 7th to August 13th data was labeled as "summer."

The lagoon classifications, based on Bchl *a* concentrations were supported by the observed colors. A summary of these data and observations is provided in Table 2, where the highest Bchl *a* concentration for non-phototrophic lagoons is shown to be 669 $\mu g\ L^{-1}$, and the lowest concentration for phototrophic lagoons is 1081 $\mu g\ L^{-1}$. Based on the data in Table 2, lagoons A, D and F were characterized as non-phototrophic, and lagoons B, C and E were characterized as phototrophic. Based on Bchl *a* concentrations (Table 3), these differences were statistically significant ($P<0.0001$).

Table 2. Lagoon bacteriochlorophyll *a* and color

Lagoon	Late spring Average Bchl a (μg/L)	Summer Average Bchl a (μg/L)	Color
A	645	635	Black
B	2020	1081	Brown-Red
C	5038	5303	Purple-Violet
D	318	210	Black
E	4662	3863	Purple-Violet
F	110	669	Black

Odor Emission

Most odor emission studies using wind tunnels have not corrected for the possibility that the activated carbon filter on the tunnel entrance does not remove all odors (Galvin et al., 2003; McGahan et al., 2001; Wood et al., 2001; Bicudo et al., 2002; Schulz and Lim, 1993; Smith et al., 1999). The data from this study showed that, in fact, odors are not completely removed and in a few cases odors level at the inlet were greater than at the outlet. Thus, the method of Lim, et al. (2003) was used to correct for those situations. Thus, the "net odor emission rate with zero values" in Table 3 indicate that the rates reported are based on the difference between inlet and outlet odor levels, corrected to zero if that difference was negative. Table 3 also includes standardized net odor emission rates corrected to an air speed of 1.0 m s^{-1} using the equation of Smith and Watts, 1994).

No statistical difference was found for net odor emission rates with zero values between phototrophic and non-phototrophic lagoons in the summer (P=0.85). This may indicate when the two types of lagoons are operating under more ideal conditions, i.e. summer, the odor emission rates are similar. Results from McGahan et al. (2001), support the finding in this study in that there were no differences between phototrophic and non-phototrophic lagoon odor emission rates during summer. McGahan et al. found no relationship between odor emission rates and Bchl *a* concentrations during summer, however only one of the lagoons in that study were actually deemed to be phototrophic. The maximum Bchl *a* found in the lagoons used by McGahan et al. was 695 μg/L, while the minimum found for phototrophic lagoons in this study was 1081 μg/L.

Table 3. Summary of Emission Rate and other Parameters

Phototrophic

	Net Odor Emission Rate with Zero Values	Standardized Net Odor Emission Rate	Odor Intensity	Bchl a	VFA	H_2S Emission Rate	NH_3 Emission Rate	TAN	pH	ORP
Late spring	9.4	17.1	2.0	3907	2.86	1.9	23	550	7.8	-239
Summer	4.0	7.3	1.7	3438	0.31	0.07	16.5	414	8.1	-193
P Value	0.2014	0.2014	0.022	0.0007	0.0318	<0.0001	0.3509	0.0002	<0.0001	0.0061

Non-phototrophic

	Net Odor Emission Rate with Zero Values	Standardized Net Odor Emission Rate	Odor Intensity	Bchl a	VFA	H_2S Emission Rate	NH_3 Emission Rate	TAN	pH	ORP
Late spring	24.5	44.7	2.5	397	65.4	3.2	34.9	1609	7.4	-311
Summer	4.8	8.7	2.1	488	13.4	0.32	18	1583	7.7	-313
P Value	0.0006	0.0006	0.022	0.5326	<0.0001	<0.0001	0.0401	0.497	<0.0001	0.9318

Late spring

	Net Odor Emission Rate with Zero Values	Standardized Net Odor Emission Rate	Odor Intensity	Bchl a	VFA	H_2S Emission Rate	NH_3 Emission Rate	TAN	pH	ORP
Phototrophic	9.4	17.1	2.0	3907	2.86	1.9	23	550	7.8	-239
Non-Phototrophic	24.5	44.7	2.5	397	65.4	3.2	34.9	1609	7.4	-311
P Value	0.0109	0.0109	0.016	<0.0001	<0.0001	<0.0001	0.107	<0.0001	<0.0001	0.0001

Summer

	Net Odor Emission Rate with Zero Values	Standardized Net Odor Emission Rate	Odor Intensity	Bchl a	VFA	H_2S Emission Rate	NH_3 Emission Rate	TAN	pH	ORP
Phototrophic	4.0	7.3	1.7	3438	0.31	0.07	16.5	414	8.1	-193
Non-Phototrophic	4.8	8.7	2.1	488	13.4	0.32	18	1583	7.7	-313
P Value	0.8448	0.8448	0.016	<0.0001	<0.0001	0.3111	0.8498	<0.0001	<0.0001	<0.0001

Odor = OU m^{-2} s^{-1} VFA = mM TAN = ppm-N

Bchl a= µg/L H_2S = µg s^{-1} m^{-2} NH_3 = kg-N ha^{-1} d^{-1} ORP = mV

H_2S Emission

As expected, non-phototrophic lagoons were found to have higher emission rates of hydrogen sulfide than phototrophic lagoons (P<0.0001, Table 3). This is because PSB utilize hydrogen sulfide as a food source. The hydrogen sulfide emission rates were 1.9 and 3.2 $\mu g\ m^{-2}\ s^{-1}$ for phototrophic and non-phototrophic lagoons, respectively. Zahn et al. (2001a) found that hydrogen sulfide emissions were lower from phototrophic lagoons than non-phototrophic lagoons, which is consistent with the results from this study.

No statistical difference was found for hydrogen sulfide emission rates between phototrophic and non-phototrophic lagoons in the summer (P=0.31). However, the emission rate was numerically lower for phototrophic lagoons than non-phototrophic, which was expected because PSB are known to consume H_2S.

NH_3 Emission

Statistical differences were not found for ammonia emissions in the late spring between phototrophic and non-phototrophic lagoons (P=0.11), but the phototrophic NH_3 emission rate was numerically lower (Table 3). Zahn et al. (2001a) also found ammonia emission rates to be lower from phototrophic than non-phototrophic lagoons. The pH for phototrophic lagoons was statistically higher than in non-phototrophic lagoons (P<0.0001). Higher pH results in a greater fraction of TAN being in the ammonia form. However, TAN was statistically lower for phototrophic lagoons than non-phototrophic lagoons (P<0.0001), which would decrease the amount of ammonia available for volatilization. Phototrophic lagoons should have lower concentrations of TAN because PSB are known to consume ammonium.

No statistical difference was found for ammonia emission rates during summer between phototrophic and non-phototrophic lagoons (P=0.85). This follows the trend in odor and H_2S emission rates for both kinds of lagoons during summer. Lower emissions are expected from anaerobic lagoons in summer and differences between lagoon types may not be significant. However, the emission rate for phototrophic lagoons was numerically less than that of the non-phototrophic lagoons.

Conclusions

The greatest odor, ammonia and hydrogen sulfide emission rates came from non-phototrophic lagoons during late spring. Non-phototrophic lagoon odor emission rates were nearly twice as high in the late spring as in summer. Significant differences were found for net odor emission rates between phototrophic and non-phototrophic anaerobic swine lagoons during late spring, with phototrophic lagoons emitting less odor (P=0.01) but odor emission rates from phototrophic lagoons were relatively constant from late spring to summer. The maximum net odor emission rate (24.5 OU $m^{-2}\ s^{-1}$) was from non-phototrophic lagoons during late spring, and the minimum (4.0 OU $m^{-2}\ s^{-1}$) was from phototrophic lagoons during summer.

H_2S emission rates were higher in late spring than summer, with emissions 10 and 16-fold greater in late spring for phototrophic and non-phototrophic lagoons, respectively. Significant differences were found for H_2S emission rates between phototrophic and non-phototrophic anaerobic swine lagoons during late spring, with lower emissions from phototrophic lagoons (P<0.0001). The maximum H_2S emission rate was from non-phototrophic lagoons during late spring (3.2 $\mu g\ m^{-2}\ s^{-1}$). The minimum from either type of lagoon was 0.2 $\mu g\ m^{-2}\ s^{-1}$ in summer.

Ammonia emission rates were relatively constant from phototrophic lagoons from late spring to summer, but were nearly twice as high in late spring as in summer from non-phototrophic lagoons.

Significant differences were found for NH_3 emission rates between late spring and summer from non-phototrophic anaerobic swine lagoons, with lower emissions in summer (P=0.04). The maximum NH_3 emission rate was from non-phototrophic lagoons in late spring (35 kg NH_3-N ha^{-1} d^{-1}) and the minimum (16.5 kg NH_3-N ha^{-1} d^{-1}) was from phototrophic lagoons in summer.

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Appendix

Table A.1. Summary of Lagoon Ammonia Emission Rates in the Literature

Lagoon Type	Measurement Method	Season	pH	TAN ppm-N	Wind Velocity (m s-1)	Ammonia-N Emission Rate (kg ha-1 d-1)	Reference
P	Ambient		7.1		0.9	769	Zahn et al. (2001a)
NP	Ambient		7.3		1.6	1192	
NP	Wind Tunnel		8.1	853 [a]		87.3	Lim et al. (2003)
NP	Wind Tunnel					95	Wood et al. (2001)
NP	Ambient		8.1 - 8.2	917 - 935		1350	Zahn et al. (2001b)
NP	Ambient		8.1	922	1.0 [b]	155 - 217	Zahn et al. (2002)
NP	Ambient		8.2	934	1.0 [b]	164	
NP						3.0 - 90	Arogo et al. (2001)
NP	Ambient	Spring	7.7 - 8.0	235		3.2 - 40	Harper et al. (2000)*
NP	Ambient	Summer	7.5 - 7.6	285		3.1 - 9.8	
NP	Ambient	Spring	7.8	741		5.2 - 15.4	Harper and Sharpe (2000)*
NP	Ambient	Spring	7.7	227		3.0 - 6.6	
NP	Ambient	Summer	8.1	574		15.4 - 22	
NP	Ambient	Summer	8.3	193		2.9 - 8.4	
NP	Wind Tunnel	Spring	7.6-7.8	540-720		12.3-52	Aneja et al. (2000)*
NP	Wind Tunnel	Summer	7.1 - 7.8	587-695		34 - 123	
NP	Wind Tunnel	Spring	7.9-8.1	326-387		39	Heber et al. (2001)*

[a] TKN ppm-N

[b] normalized to 1.0 m s^{-1}

* from Liang et al. (2002), NRC (2003), and Arogo et al. (2002)

P – Phototrophic

NP - Non-phototrophic

Table A.2. Summary of Lagoon H_2S Emission Rates in the Literature

Lagoon Type	Measurement Method	Wind Velocity ($m\ s^{-1}$)	Emission Rate ($\mu g\ m^{-2}\ s^{-1}$)	Reference
P	Ambient	0.9	2.4	Zahn et al. (2001a)
NP	Ambient	1.6	7.1	Zahn et al. (2001a)
NP	Ambient	1	16	Zahn et al. (2002)
NP	Wind Tunnel	1	5.7	Lim et al. (2003)
NP	Wind Tunnel	0.2	45.7	Wood et al. (2001)

P- Phototrophic

NP - Non-phototrophic

Table A.3. Summary of Lagoon Odor Emission Rates in the Literature

Measurement Method	Season	Air Velocity	Measured Emission Rate ($OU\ m^{-2}\ s^{-1}$)	Normalized Emission Rate* ($OU\ m^{-2}\ s^{-1}$)	Corrected for Inlet Odor	Reference
Wind Tunnel	Summer	0.3 – 0.5		7.1-24.5	no	Galvin et al. (2003)
Wind Tunnel	Summer	0.3	5.3 -10.9	8.7 - 17.3	no	McGahan et al. (2001)
Wind Tunnel		1.0	1.5 [1]	1.5 [1]	yes	Lim et al. (2003)
Wind Tunnel		0.2	16.7 [1]	37.3 [1]	no	Wood et al. (2001)
Wind Tunnel	Apr - Oct	0.3	14	25.6	no	Bicudo et al. (2002)
Wind Tunnel		0.2 –0.4		18.9 -38		Schulz and Lim (1993)
Ambient		1.3 – 3.5	18.0 - 131	14.1 - 58.1		Smith et al. (1999)
Wind Tunnel		1.0 – 3.0	18.0 - 80.4	18.0 - 39.4		Smith et al. (1999)

[1] - geometric mean

* adjusted to 1 m s-1 by the authors