RESEARCH REPORT
ENVIRONMENT

Title: A Nebraska Odor Footprint Tool for Planning Pork Facilities – **NPB #02-195**

Investigator: Dr. Richard Koelsch

Institution: University of Nebraska

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Abstract:
Pork producers and rural communities are struggling to balance air quality issues (primarily odors) with the presence and growth of the industry. Currently the type of pork facility, odor control measures, prevailing wind direction, atmospheric conditions, and a community's tolerance to some degree of odor are largely ignored in the planning process because scientific tools that incorporate this information are lacking. Without such tools, decisions on setback distances and acceptable type and size of facilities are influenced by a range of arguments, often emotional in nature. In addition, pork producers lack tools to assist in evaluating impact on a rural community for alternative sites for a new or expanding facility.

OFFSET, a tool to assess setback distances needed for minimizing odor impact from livestock facilities, was developed by the University of Minnesota and is currently being applied as a community odor planning tool in several Minnesota counties. Cooperative efforts between the The Universities of Nebraska (UNL) and and Minnesota (UMN) are improving the state-of-the-art for odor modeling. Critical limitations for use of OFFSET in Nebraska include differences in weather conditions, lack of anaerobic lagoon data in OFFSET, and its current prediction of odor emissions without regard for wind direction. In addition, the Minnesota model does not handle odors from multiple swine barns. UNL and UMN have been working together to rectify these shortcomings and, through the use of an improved model, made possible by this NPPA grant, can now more accurately estimate the frequency of exposure to annoying levels of odor. The tasks addressed in this project included:

- integration of Nebraska weather data into an improved odor assessment tool (the Nebraska Odor Footprint tool) for pork industry and community use.
- field evaluation of odor emission rates for anaerobic lagoons, and validation in Nebraska of Minnesota emission rates for other facilities.

The new Nebraska Odor Footprint tool will assist pork producers in gaining approval for construction facilities in Nebraska. It will provide them with an ability to determine the intensity and frequency/infrequency of their odor footprint, based upon the size and type of housing, manure storage and odor control technologies they plan to use. It will also allow producers to compare neighborhood impact of alternative sites for new facilities. In addition, it will give county officials a way to understand the likelihood, magnitude and impacted area of odors for a proposed facility. With this they can then make more informed and better decisions on new and expanded facilities. Finally, producers and community leaders will have a common basis with which to evaluate alternative technology options (odor control, housing type, and manure storage type) for reducing odor and the anticipated odor footprint of these options.

Objectives of Research Project

1. An "initial" Nebraska Odor Footprint tool, which integrates Minnesota odor emissions data with Nebraska weather data and an appropriate odor dispersion model, will be developed.
2. An odor emission rate database will be developed for anaerobic lagoons in Nebraska.

Results – Objective 1

"An initial Nebraska Odor Footprint tool, which integrates Minnesota odor emissions data with Nebraska weather data and an appropriate odor dispersion model, will be developed."

Activity 1: Effect of season, direction of prevailing winds and calm/missing wind speeds on the NE Odor Footprint tool

The influence of different seasons, direction of prevailing winds, missing weather data, and calm wind conditions on the setback distances was studied in detail for the region surrounding Norfolk, NE in an effort to develop this example application for the Nebraska Odor Footprint tool.

Effect of seasons: An analysis has been completed to determine if seasonal weather data or data for an entire year should be used. The results of this analysis are illustrated in Table 1. A ten-year weather data set representing mid-spring to mid-fall produced a 10 to 15% increase in setback for winds out of the West to North (270 to 360°) quadrant and North to East (0 to 90°) quadrants when compared to use of 12-months of data. However, a 20% decrease in recommended setback was observed for the same conditions for the East to South (90 to 180°) and South to West (180 to 270°) quadrants. This occurs because prevailing winds from late-fall through early-spring are from the North-Northwest in that part of Nebraska. People are outdoors more so from early-spring through early-fall than during the winter, thus are exposed to odors more frequently when winds are from the Southwest-Southeast (e.g. early-spring through early-fall). That circumstance is similar to the reasoning in OFFSET tool, which uses historical weather data from April 15 – October 14 to estimate the maximum setback distances. For those reasons the April 15 – October 14 modeling period is recommended for use in Nebraska. That period has been used to address Activity 2.

Setback Distance (m) for OEN=500 at 99% odor free level				
Station	N-W	N-E	S-E	S-W
Jan 1 – Dec 31	1975	1975	2125	1125
Feb 15 – Dec 14	2150	2000	1900	1150
Mar 15 - Nov 14	2175	2050	1800	1100
Apr 15 – Oct 14	2225	2150	1700	975

Table 1. Effect of season from which weather data is used on the directional setback distance for Norfolk, NE from 1981-1990 (calm conditions not processed)

Prevailing wind direction: Two different schemes were analyzed to study the effect of prevailing wind direction on the manner in which setback distances should be determined for various locations in Nebraska. The two schemes were:

1. Scheme A. Quadrants are divided into northeast, northwest, southeast and southwest sectors.
2. Scheme B. Quadrants are divided into north, south, east, and west sectors.

The implications of these choices are both an issue of practical concern and of accuracy in predicting setbacks. From a practical perspective, setback recommendations based upon scheme A may result in substantially different recommendations for individuals living close to one another. Most rural neighbors are located in close proximity to roads running east, west, north, or south. Two neighbors located across the road from one another may have substantially different odor setback recommendations. In the case of neighbors directly north of a livestock operation near Scottsbluff (Table 2) a neighbor on the west side of the road would have a 3175 meter setback while the neighbor on the east side would have only an 825 meter setback (see Figure 8, page 10 for a graphic illustration of this). Practical issues such as this will bear on the appropriate scheme.

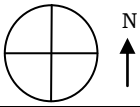
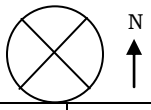
Setback Distance (m) for OEN=500 at 99% odor free level								
	Scheme A 				Scheme B 			
Station	N-W	N-E	S-E	S-W	NW-NE	NE-SE	SE-SW	SW-NW
Omaha, NE	3000	2200	2450	1725	2925	1150	3000	2450
Norfolk, NE	2600	2550	1975	1175	2600	1975	1875	2150
Lincoln, NE	4450	2800	3250	3275	4450	1100	3275	1375
Grand Island, NE	2975	2900	2025	1525	2975	1550	2025	1425
North Platte, NE	3350	2025	2475	2225	2075	2475	1875	3350
Scottsbluff, NE	3175	825	4450	3500	1450	4450	2300	3500
Goodland, KS	2525	2225	2225	1575	2525	2225	1525	1575
Concordia, KS	1925	1625	1125	1200	1925	1000	1200	1750
MN-OFFSET	4600	4600	4600	4600	4600	4600	4600	4600

Table 2. Directional setback distances for two schemes from Apr. 15 – Oct. 14, 1990 (calm conditions not processed)

Prevailing wind direction is also be an important consideration. In Norfolk, the prevailing winds are primarily from the North or South depending on the season. This may suggest that Scheme B would be the preferred solution since setback recommendations may better approximate prevailing winds. In contrast, Scottsbluff with prevailing winds from the northwest and southeast may find scheme A to be the more accurate representation of the impact of these prevailing winds.

Calm and missing wind speeds: The Nebraska Odor Footprint tool is driven by a U.S. Environmental Protection Agency air dispersion model called AERMOD (AMS/EPA Regulatory Model) while the OFFSET tool is driven by an older EPA model called INPUFF-2. Inaccuracies are possible with air dispersion models such as AERMOD and INPUFF-2 when zero wind speed (calm conditions) and missing weather data are allowed to remain in the weather database. Calm conditions typically occur from the evening through mid-morning hours, and are routinely associated observations of high odor levels. The percentage of calm and missing wind conditions encountered in the historical weather data set for various regions in NE varies between 3 and 9%. Thus, ignoring calm conditions, as is done in most meteorological models, would bias the odor footprints

toward under-prediction of odor frequencies. Three corrections were made to address those deficiencies in the weather data files:

1) For data entries of zero wind speed, wind speed is set at 50% of the lowest wind speed measurable by the weather station or 0.5 meters/second.
2) Wind direction during calm conditions is assumed to be the average of the wind direction immediately prior to and following the indication of a zero wind speed observation.
3) Missing readings are filled with average conditions determined by the meteorological data immediately before and after the missing data.

To test those procedures, surface weather data for Norfolk and Scottsbluff, NE were processed with and without the above adjustments. Upper air data from Omaha was used in both cases (upper air data are unaffected by calm conditions, and are needed by AERMOD). The effect of processing calm and missing wind speeds for these two regions on the setback distances is shown in Table 3.

Setback Distance (m) for OER=500 at 99% odor free level				
Station	N-W	N-E	S-E	S-W
Northeast NE– Without Processing	1975	1975	2125	1125
Northeast NE – With Processing	2350	2350	2325	1225
Western NE –Without Processing	1975	750	3975	1975
Western NE –With Processing	2225	800	4300	2225

Table 3. Effect of calm and missing wind speeds on the setback distance for Norfolk and Scottsbluff (weather data from January 1, 1981 to December 31, 1990).

The results in Table 3 clearly demonstrate the need to adjust weather input data files for calm and missing conditions. Depending on the region and direction from the source, setback distances differ from 50 to 375 m, which represents from seven to 19 percent underestimation if calm and missing conditions are ignored. Thus, future footprint development will be done using the procedures outlined above for replacing missing data or calm conditions in weather data files.

Activity 2: Comparison of AERMOD and Minnesota OFFSET Model

AERMOD was run using the Minnesota weather data files to compare results to those from the OFFSET tool based upon INPUFF-2. OFFSET is based on weather data from six regional locations within or near Minnesota and its predicted setback distances are derived from the greatest distance for a point source at various risk levels for those six sites. This worst-case value is then applied statewide.

AERMOD was applied to those same six sites to predict a setback for comparison to the results from OFFSET. The intent was to gain an understanding of the relative differences in predicted setbacks from the two models. Figure 1 shows the maximum setback distances obtained using AERMOD and INPUFF-2. The maximum setback distance was obtained using AERMOD from the nine-year (1984-1992) hourly weather data for International Falls, MN. The weather data set was processed for calm and missing wind conditions (zero wind speed and direction), which has been discussed in the preceding section.

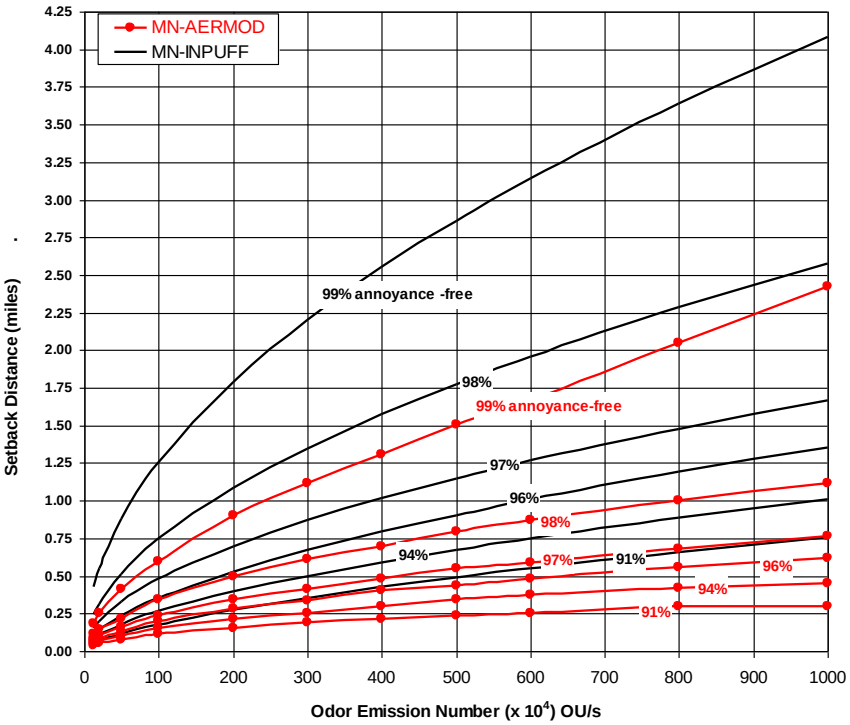


Figure 1. Comparison of maximum setback distance for Minnesota weather stations using INPUFF-2 and AERMOD

Figure 1 suggests that for the same odor emission level and odor risk level, the predicted setback from AERMOD is less than INPUFF-2. This is because, in the development of OFFSET, INPUFF-2 was scaled to produce greater setback distances based on short and long-range validation experiments using odor levels measured by field sniffers. This vital step has yet to be incorporated into the Nebraska Odor Footprint tool. After scaling, setback distances predicted by AERMOD will be more comparable to those from OFFSET. The differences in the mathematical approach used in formulating INPUFF-2 (a puff model), and AERMOD (a plume model) explains some of the disparity.

Activity 3: A sample NE Odor Footprint tool for Northeast (Norfolk), NE

This activity was intended to demonstrate the utility of the Nebraska Odor Footprint tool using weather data from Northeast, NE. Weather data from April 15 – October 14, 1981-1990 for Norfolk, NE was processed for calm wind and missing conditions and subsequently used in AERMOD. A sample odor footprint for $500x10^4$ odor units per second (OU/s) is shown in Figure 2. The isopleths shown in Figure 2 quantify the exposure frequency to a predefined level of odor tolerance (in this case an odor intensity of 2 on a scale of 0 to 5). Thus, the 98 percent isopleth, shown in Figure 2, indicates that 98 percent of the time odor intensities are expected to be a less than 2 on the 0 to 5 scale.

Setback distances needed to accomplish desired frequencies of odor-free conditions in a neighborhood can be obtained in any direction by using footprints such as shown in Figure 2. Thus, Figure 3 was developed by running AERMOD with odor emission rates ranging from 25 to 1000 OU/s in increments of 100, then extracting the resultant maximum separation distance from the source (point source) for the desired frequency isopleths. The AERMOD results from Figure 1 for Minnesota are repeated in Figure 3. Several things are evident from Figures 1 - 3. One is that a non-linear relationship exists between the magnitude of odor emission rates (OU/s) to separation distances. Second is that separation distances are very sensitive to the desired level of odor-free conditions that a community may desire. Where counties

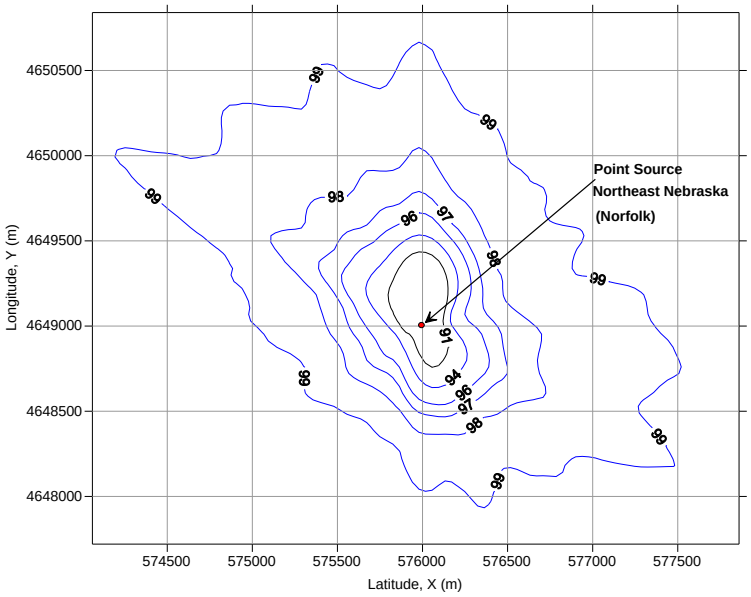


Figure 2. Odor footprint for an Odor Emission Number of 500 x 10^4 OU/s for a facility in Norfolk, NE. (Isopleths represent percent of hourly odor levels ≤ 2 on a 0–5 scale for March-October 1984-1993.)

have implemented OFFSET, odor-free frequencies ranging from 92 to 96% have been chosen. Third is that using the same model and same odor emission rates in Nebraska versus Minnesota produces smaller setback distances. This is likely due to higher wind speeds and greater atmospheric turbulence in Nebraska. The need for further model validation prevents decision makers in Nebraska from using this tool for general or site specific applications. However, the footprint approach has great promise for providing valuable information for assessing the impact of odor reduction strategies by pork producers.

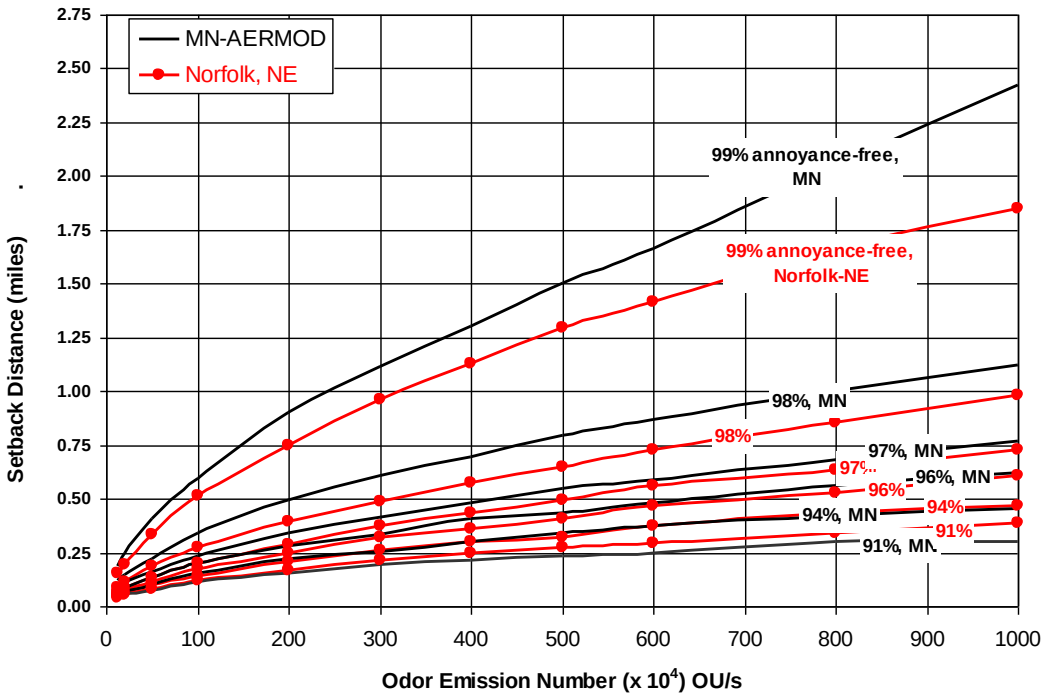


Figure 3. Comparison of maximum setback distance for Minnesota and Northeast (Norfolk), NE weather stations using AERMOD

This first generation of the NE Odor Footprint tool can identify setback distances needed to achieve various odor risk levels in any direction. However, four directions are likely the most practical limits of this approach. For example in Norfolk, one could divide the setback recommendations into those for a north quadrant (315 to 45° for a NW-NE zone where straight North is 0°); an east quadrant (45° to 135° for a NE-SE zone where East is 90°); a south quadrant (135° to 225° or SE-SW zone where South is 180°); and a west quadrant (225° to 315° or SW-NW where West is 270°). The resulting setbacks have been estimated using this procedure for a range of odor emission factors. The resulting data are plotted in four graphs (one for each sector, Figures 4-7) similar to those used by OFFSET to illustrate setback vs. odor emission number for a range of odor nuisance risk levels. It should be noted that the higher odor emission numbers for Figure1 (p. 5) and Figures 4-7, which follow, represent large swine production units (1000 OU/s is the equivalent of approximately 45,000 finishers in deep pit facilities).

The need for converting setback distances in a manner such as shown in Figures 4 through 7 is currently being discussed with stakeholders groups such as the Nebraska Pork Producers Association and interested county planning officials. Their advice regarding the choice of directions will be important considerations in the ultimate appearance of the Nebraska Odor Footprint tool.

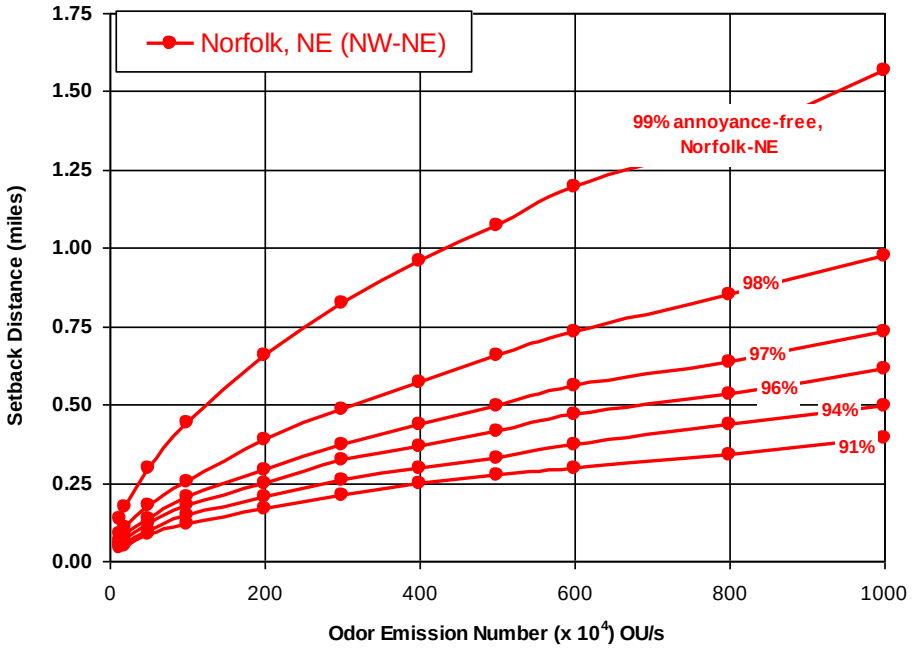


Figure 4. Maximum setback distance in the NW-NE sector for Northeast (Norfolk), NE using AERMOD

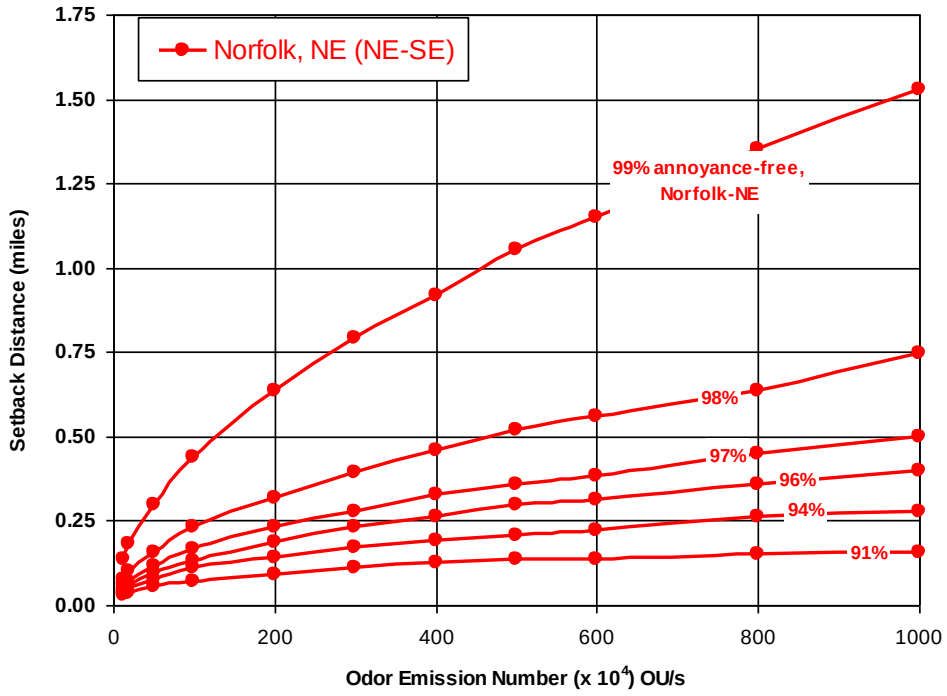


Figure 5. Maximum setback distance in the NE-SE sector for Northeast (Norfolk), NE using AERMOD

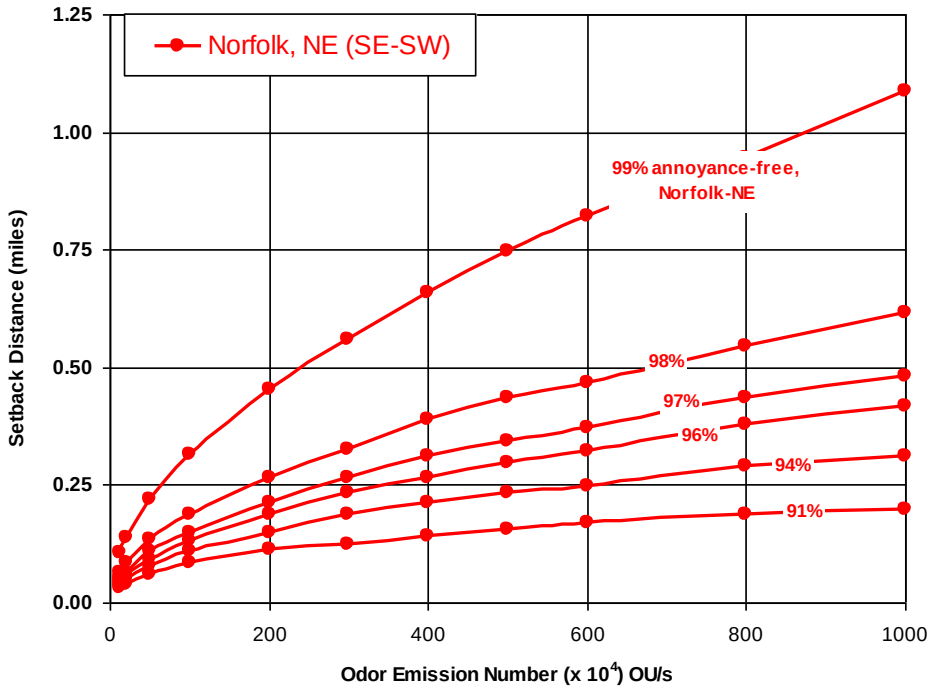


Figure 6. Maximum setback distance in the SE-SW sector for Northeast (Norfolk), NE using AERMOD

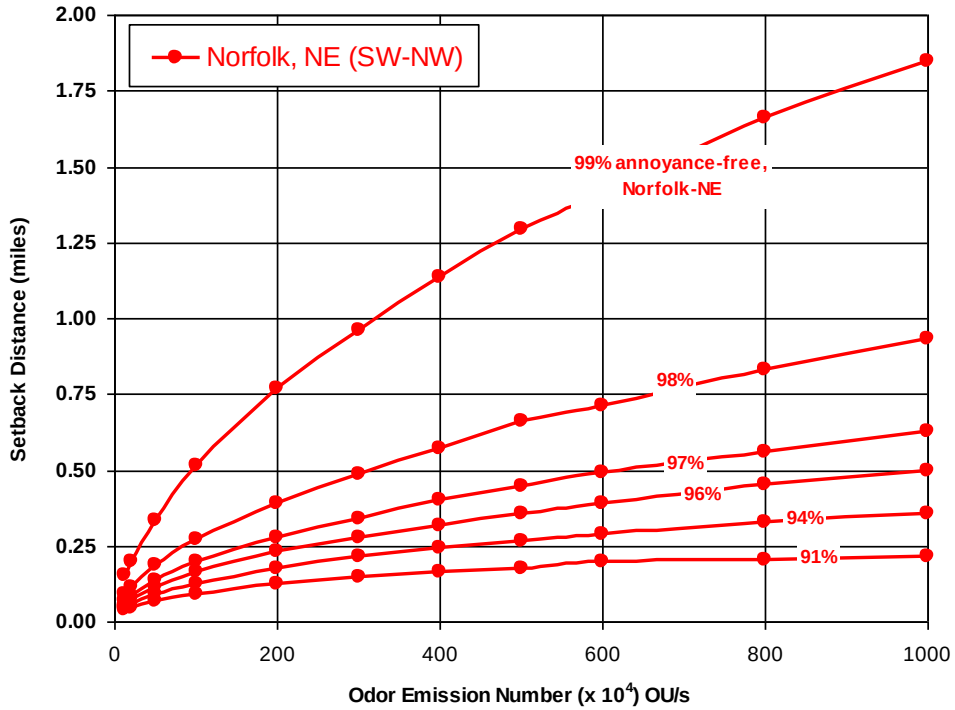


Figure 7. Maximum setback distance in the SW-NW sector for Northeast (Norfolk), NE using AERMOD

Activity 4: Comparison of regional weather patterns (Northeast (Norfolk) vs Western (Scottsbluff)) on the NE Odor Footprint tool

The effect of calm and missing wind conditions was previously shown in Table 3 for ten-year weather data files from both Norfolk and Scottsbluff, NE. This was done using an odor emission rate of 500×10^4 OU/s at both locations. Table 3 only included the 99% odor annoyance free risk level and thus the indicated setback distances were quite large. Figure 8 for those locations includes risk levels as low as 91 percent and shows that the odor footprint for Norfolk is dramatically different than that for Scottsbluff. This reinforces the differences between Minnesota and Norfolk (shown in Figure 3) and emphasizes the need to tailor the Odor Footprint tool to several regions in the state. The percentage of calm and missing wind conditions encountered in the ten-year historical weather data set varies between 3 and 9% depending on where one is in Nebraska.

In addition to a greater frequency of calm conditions, Norfolk has more southerly prevailing wind direction in the summer and a comparatively humid climate to that of Scottsbluff, which is about 400 miles to the west and 705 m higher in elevation. Thus, Figure 8 indicates a substantial shift in the direction of influence of the odor plume for the western NE location compared to northeastern NE. Consequently, separation distances from the source to the 99% odor-free isopleth were nearly 1000 m greater in the westerly direction (and 700 to 900 m less in the northerly and easterly directions, respectively) in Scottsbluff than in Norfolk, NE. It appears that a single, state-wide, separation distance for zoning or county planning would be inappropriate. As a result of this research, and from discussions with the stakeholder groups, five to seven regions are planned for Nebraska.

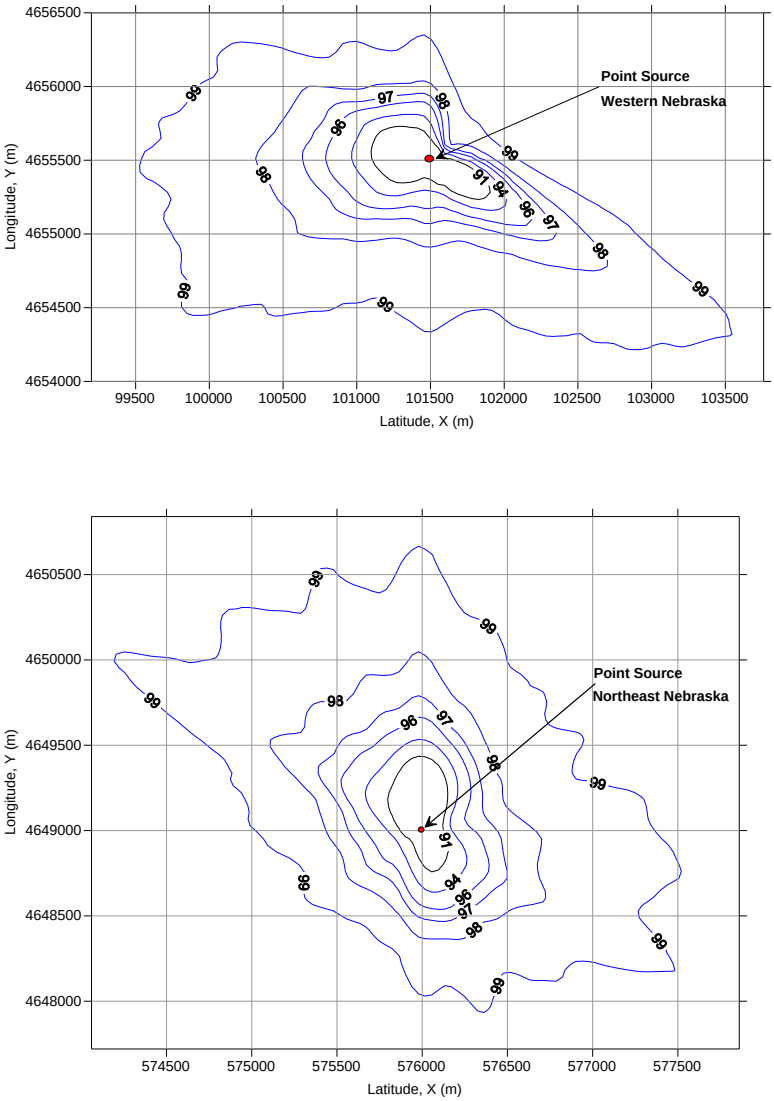


Figure 8. Influence of regional weather patterns on the odor footprints for an Odor Emission Number of 500 x 10^4 OU/s for a facility in Scottsbluff or Norfolk, NE. (Isopleths represent percent of hourly odor levels ≤ 2 on a 0–5 intensity scale for March-October 1984-1993.)

Activity 5: Validation of AERMOD results against field data

The University of Minnesota conducted a short-range verification effort for OFFSET involving a panel of 7 odor sniffers who recorded odor observations at 100-meter intervals between 100 and 400 meters directly downwind of the odor source. These sniffers were trained to recognize odor intensity on a scale of 0 to 5 (based upon an n-butanol) standard and to record those intensities down-wind of 28 livestock facilities. An empirical relationship between odor intensity and an olfactometry-based measure of odor units was developed from those locations and the sniffer data was then compared against INPUFF-2 predictions of odor units. A scaling factor was needed (35 for animal buildings and 10 for manure storage) to adjust the model output to fit the nasal ranger observations. Such scaling is commonly needed, especially when short-term odor measurements (on the order of seconds up to a few minutes) are compared to model predictions, which must be based on hourly intervals that correspond to average meteorological observations. Based upon the results, the model predicted odor units with a high degree of accuracy at shorter distance and declining accuracy at longer distances.

A frequently used procedure, when the time intervals for sampling at the receptors are shorter than that possible for the model, involving "peak to mean ratios" is being investigated. In this procedure modeled concentrations are scaled to match observed data by a power term (Eq. 1).

$$\frac{C_{peak}}{C_{mean}} = \left(\frac{t_{peak}}{t_{mean}} \right)^{-n} \quad (1)$$

where, t_{peak} and t_{mean} are the observation times and n is an exponent.

The power term for Equation 1 is often given as 0.2 regardless of the peak, or mean, averaging times. However, this will need to be adjusted for odors. Previous research indicates that CAFO odor plumes fluctuate widely, especially near ground sources, and that human receptors perceive odors in very short time intervals. Due to such fluctuations and short time intervals the coefficient "n" in Equation 1 may be even greater than 0.4 for dispersion modeling of short-term odor levels.

Six of the 28 data sets mentioned previously were used to compare AERMOD predicted odor levels to field measures of odor intensity and to the calculate peak to mean ratios shown above. The odor sources for these six experiments were earthen basins with emission rates that ranged from 6.5 to 41 OU/(m^2-s) and swine buildings having an average emission rate of 1.7 OU/(m^2-sec). Because these facilities were treated as point sources in the INPUFF-2 validation, they were also assumed to be point sources for comparative purposes to AERMOD.

The peak to mean ratios shown in Table 4 were obtained by dividing the odor levels (C_{peak}) reported by sniffers by predicted concentrations (C_{mean}) from AERMOD and INPUFF-2. Predicted concentrations less than 1% of the highest concentration observed were disregarded for the validation procedure. The peak to mean ratios from AERMOD appear to be substantially greater than for INPUFF-2. More facilities need to be included in this comparison before a reasonable conclusions may be drawn as to why the differences may exist. The models are fundamentally different and agreement is not expected.

Times of 1-hr (t_{mean}) and 1-sec (t_{peak}) were used to calculate the exponent 'n' (Eq. 1) for AERMOD given the C_{peak}/C_{mean} ratios in Table 4. Values of 'n' reported in the literature range between 0.21 for a point source plume and 0.35 for a line source plume and 0.2 to 0.34 for area source odors from wastewater treatment plants. There are few, if any, exponent values reported for area or volume CAFO sources in the literature. Further validation is underway to ascertain the appropriate scaling factors and exponents needed to use AERMOD for accurately predicting ambient odor levels near CAFOs.

Source (area, m^2)	Time of Day	AERMOD		INPUFF-2
		Peak to Mean Exponent 'n'	$\frac{C_{peak}}{C_{mean}}$	$\frac{C_{peak}}{C_{mean}}$
Earthen Basin Trial 1 (4251)	AM	0.35	17.6	10^1
Earthen Basin Trial 2 (7752)	AM	0.35	17.6	
Earthen Basin Trial 3 (7752)	PM	0.28	9.9	
Nursery Barn Trial 4 (580)	AM	0.61	147.7	35^1
Nursery Barn Trial 5 (580)	PM	0.62	160.3	
Finishing BarnTrial 6 (446)	AM	0.65	204.9	

[1] based on 28 datasets

Table 4. Scaling factors and exponent 'n' in the peak-to-mean ratio

Results - Objective 2

"An odor emission rate database will be developed for anaerobic lagoons in Nebraska".

Background.

Anaerobic lagoons have been shown to contribute 70 to 80 percent of odor emissions from swine facilities in Australia (Watts, 2000) but little data is available for lagoons in the U.S. What little data exist in literature on the emission rates from anaerobic lagoons is summarized in Appendix A. 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 portion of the project was to establish 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.

The remainder of the final report 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 5).

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.

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

Table 5. Summary of Lagoon Types: Late spring (Summer)

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 9).

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.

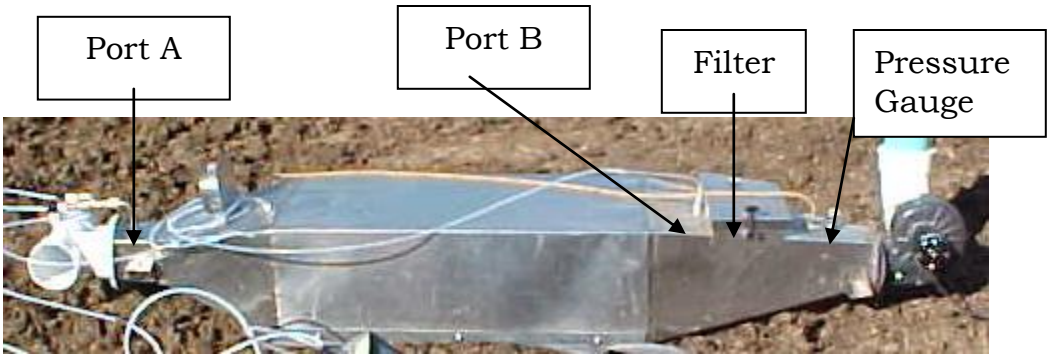


Figure 9. Wind Tunnel

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 10.

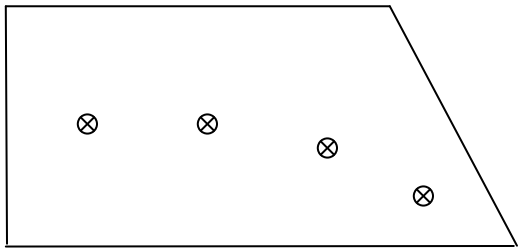


Figure 10. Example locations of sampling distribution on Lagoon A.

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, then was 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. 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. 9) 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 the 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.

Dilutions to threshold (DT) were 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.

Lagoon Characteristics

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 6), these differences were statistically significant ($P<0.0001$).

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

Table 6. Lagoon bacteriochlorophyll *a* and color

Emissions

Odors. 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 7 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.

H_2S. As expected, non-phototrophic lagoons were found to have higher emission rates of hydrogen sulfide than phototrophic lagoons (P<0.0001, Table 7). This is because PSB utilize hydrogen sulfide as a food source. The hydrogen sulfide emission rates were 1.9 and 3.2 μg 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. 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 7). 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

Objective 1

The effects of season of the year, prevailing winds, and calm conditions or missing weather data are now understood and a suitable approach for dealing with these issues is in place. Initial results from the Nebraska Odor Footprint tool show good agreement with those from Minnesota's OFFSET tool, when similar inputs are used. Regional climatic differences between Minnesota and Nebraska, and between regions in Nebraska, dictate that single state-wide setback distances would be inappropriate in Nebraska. In addition, odor footprints differ greatly depending on the direction from a swine facility. A single setback distance for all directions from a facility ignores substantial influence of seasonal prevailing winds. This grant enabled outstanding progress on the initial development of an Odor Footprint tool for Nebraska.

Objective 2

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 μg m^{-2} s^{-1}). The minimum from either type of lagoon was 0.2 μg 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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Table 7. 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= □ g/L H_2S = □ g s^{-1} m^{-2} NH_3 = kg-N ha^{-1} d^{-1} ORP = mV

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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 (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

Modifications of Project From Original Proposal

The long-term objectives in the original proposal were eliminated due to funding of Option 1 only by the NPPA.