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ESTIMATION OF AMMONIA AND HYDROGEN SULFIDE EMISSIONS FROM CATTLE FEEDLOTS IN TEXAS

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Abstract. *A dynamic flow-through chamber system and continuous analyzers were used for on-site measurements of ammonia-nitrogen (NH₃-N) and hydrogen sulfide-sulfur (H₂S-S) fluxes from commercial feedlot surfaces in northwestern Texas during two week period in the summer of 2002. Manure pack moisture content, pH, and TKN were measured daily to characterize its relation with NH₃-N fluxes. The preliminary average NH₃-N and H₂S-S flux from the feedlot surface were 1,669 ± 1,212 NH₃-N µg/m²/min and 1.884 ± 1.497 H₂S-S µg S/m²/min. Manure pack temperature and TKN was found to have a weak correlation with NH₃-N flux.*

Keywords : Ammonia, air quality, hydrogen sulfide, dynamic flow through surface chamber, flux, continuous emissions monitoring, area source, open dirt cattle feedlots, manure.

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INTRODUCTION

Domestic animals are known to be major source of global tropospheric ammonia. For the U.S. only, it was estimated that the ammonia contributions from cattle account for approximately 44% of the $\text{NH}_3\text{-N}$ budget in 1994 (Battye et al., 1994). More than 40% of the U.S. beef cattle are fed and processed in the High Plains of Texas, New Mexico, Oklahoma, Kansas, and Colorado. To date, little is known about the extend NH_3 and H_2S emissions from cattle feedyards in Texas. Quantification of air emissions from area sources in livestock housing, the manure and wastewater storage systems, and during land application is needed to both document actual emissions and to accurately evaluate control methods. In this research, a dynamic flow-through chamber system was used to estimate $\text{NH}_3\text{-N}$ and $\text{H}_2\text{S-S}$ fluxes from commercial cattle pen surfaces. The physiochemical properties of soil, such as temperature, moisture, and pH, were measured to characterize their relations with $\text{NH}_3\text{-N}$ emissions. The objectives of this research were to (1) design field measurements for NH_3 and H_2S fluxes from commercial cattle pen surfaces using dynamic flow-through chamber, (2) determine typical ranges of $\text{NH}_3\text{-N}$ and $\text{H}_2\text{S-S}$ fluxes from cattle pen surfaces.

METHODOLOGY

SAMPLING SITE

Ammonia-N and $\text{H}_2\text{S-S}$ flux measurements were completed at a 55,000 head cattle feedyard located in the northwestern Texas from August 16th to 30th, 2002. One 30.5 m × 53.3 m (100 ft × 175 ft) pen on the western edge of the feedyard was selected for this study. The selection of the pen was driven by the necessity to have unobstructed access to one side of pen at which the instrument shelter could be parked. The pen housed 112 and 116 steers on the first and the last day of the experiment, respectively. The average weight was 145 kg (320 lb) and 160 kg (353 lb) on the first and last day, respectively. This pen could be considered as representative of the dimensions, surface area, surface type, animal feed, and the stocking density to the rest of pens in this feedyard. The feedyard was similar in size to other commercial yards in this part of Texas.

All of the sampling locations were located along the western fence of the pen. This was because of the access limitations to the entire pen area. Two 3 m (10 ft) portable fence sections were installed to protect the dynamic flow-through chamber which was always placed in the middle of the 3 m × 3 m × 3 m (10 ft × 10 ft × 10 ft) (or 3 m × 3 m × 4.9 m (10 ft × 10 ft × 16 ft) for Days 1, 2, and 3) triangle formed by the portable fence sections and the fence of the pen (Fig. 1). The chamber was moved daily to a new location that was not fenced before with the exception of the first three days and the last three days of the experiment. This was done to assure that measurements were completed on surface similar to the rest of pen. As a result, each new location roughly represented the pen for manure loads, and the weather effects, and also increased the diversity of sampling locations. First three days and last three days were dedicated to measurements on one spot (without moving chamber) to analyze the surface “aging” process (Day 1 to Day 3). During the last three days (Day 12 – Day 14), the chamber was moved daily to three different locations within one fenced area to determine the aging process of feedlot surfaces without new manure loads (Fig. 1).

Manure samples were collected each measurement i.e., three samples from the inside of dynamic flow-through chamber at the end of each 24 hr measurement and three representative samples from the outside of chamber at the beginning of each day. Soil moisture content, pH, and Total Kjeldahl Nitrogen in manure pack samples were determined at the USDA-ARS laboratory in Bushland, Texas.

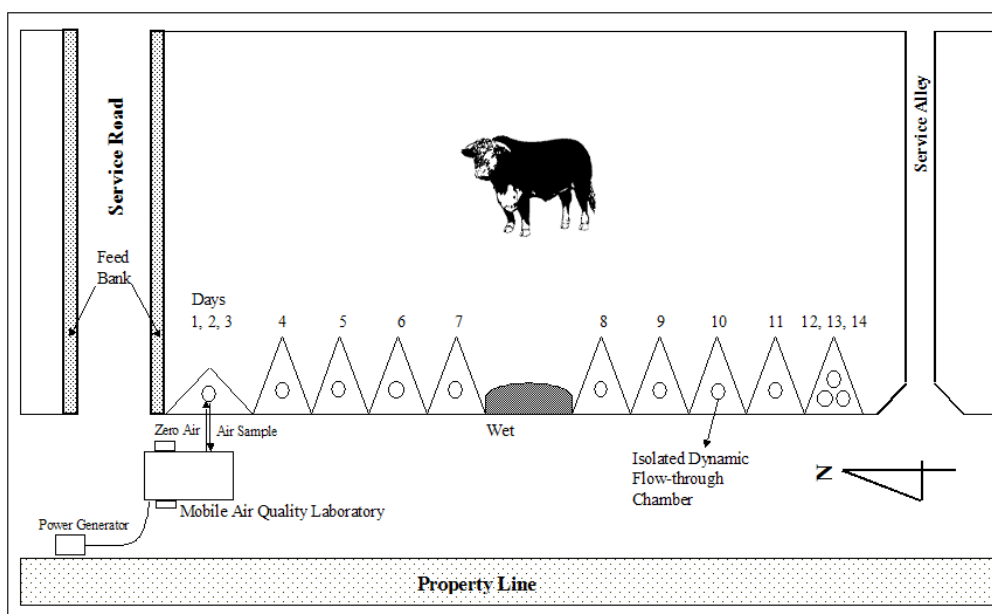


Figure 1. Schematic of the sampling site at a commercial cattle feedyard for the continuous measurements of NH_3 and H_2S flux using a dynamic flow-through chamber system.

Dynamic Flow-Through Chamber

A dynamic flow-through chamber was built from the Lexan translucent tube, 26.5 cm inside diameter and 47.2 cm high, and lined with 0.5 cm thick fluorinated ethylene propylene (FEP) foil (Fig. 2). This chamber was an exact copy of the dynamic flow-through chamber used by Aneja and co-workers (Aneja et al, 2000; Aneja et al., 2001a; and Aneja et al. 2001b). The chamber fitted inside a stainless steel collar which was driven into the manure pack to a depth of approximately 3 to 5 cm, forming a seal with the source surface and the air inside the chamber. Compressed zero-grade air was generated by a Thermo Environment Instrument (TEI) Model 111 (Franklin, MA) generator inside the instrument shelter and directed into the chamber at 6.5 L/min via a 6 mm (1/4 in) PTFE tubing. Flow rate was controlled by 10 L/min rotameter (Gilmont, Barrington, IL). Zero air mixed inside the chamber with the NH_3 , H_2S , and other gases emitted from surface. The chamber maintained a positive pressure throughout the experiment because the influent flow rate of zero-grade air was much higher than the effluent flow rate to the NH_3 and H_2S analyzers. Each analyzer drew 0.5 L/min of sampled air. The well-mixed samples from the chamber were carried to the analyzers in the mobile laboratory through two separate PTFE tubes (6.4 mm (1/4 in) outside diameter, 4 mm (5/32 in) inside diameter) to minimize further chemical reactions with the sample stream. Air from the chamber was analyzed continuously for NH_3 and H_2S concentrations. The remaining 5.5 L/min was exhausted via an exhaust port in the side wall of the chamber. The PTFE impeller was used for mixing of air inside the chamber at constant speed of approximately 50 rpm. Kaplan's experiment (Kaplan et al, 1988) was conducted in this research. It was determined that the chamber reached steady state conditions in approximately 30 minutes after the placement on the surface. This experiment was also conducted to estimate the extent of ammonia loss due to adsorption to walls of chamber and tubing.

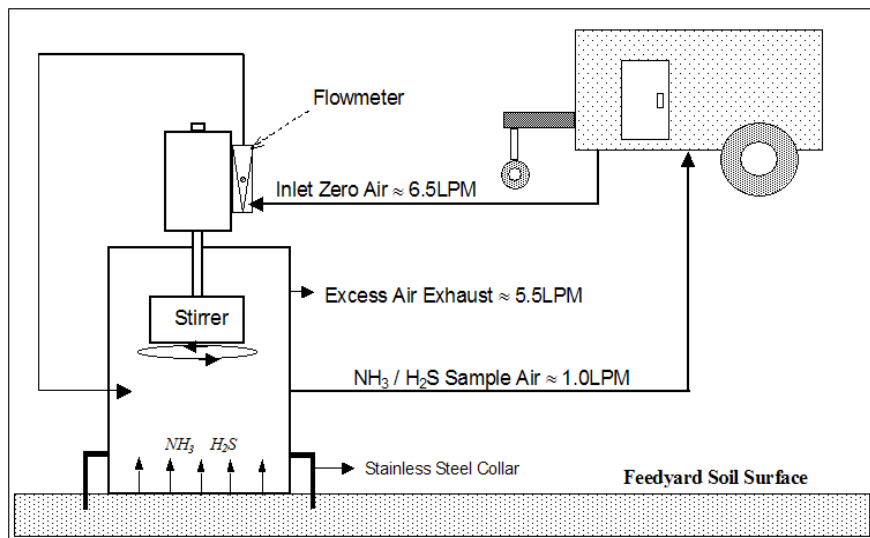


Figure 2. Schematic of the dynamic flow-through chamber used for estimation of ammonia and hydrogen sulfide fluxes from cattle pen.

Measurement of Ammonia and Hydrogen Sulfide Concentrations

The TEI 17C chemiluminescence NH_3 analyzer (Franklin, MA) with 0.5 % precision of full scale and 120 sec of the 0 to 90% response time with 10 sec averaging was used to measure ammonia concentrations inside the chamber. A NH_3 analyzer is a combination of NH_3 converter and an $\text{NO}-\text{NO}_2-\text{NO}_x$ analyzer. The analyzer was calibrated daily using UHP-grade air, certified standard span NH_3 gas in air (50 ppmv) and NO in nitrogen (50 ppmv) (AirGas Southwest, Amarillo, TX).

Hydrogen sulfide concentrations inside the chamber were measured continuously by a TEI 45C $\text{SO}_2/\text{H}_2\text{S}$ analyzer (Franklin, MA) equipped with a pulsed fluorescence SO_2 detector and a high intensity xenon lamp. Instrument precision is 1% of reading or 1 ppbv and its linearity is $\pm 1\%$ of full scale. The analyzer was calibrated daily using UHP-grade air, certified standard H_2S gas in nitrogen (2 ppmv) and SO_2 in nitrogen (1 ppmv) (AirGas Southwest, Amarillo, TX).

Temperature Measurements and Manure Pack Sampling

Two FW3638 thermocouples from ThermoElectric Wire and Cable, L.L.C. (Saddle Brook, NJ) were used to measure the ambient temperature outside of the chamber and inside chamber temperature. Manure pack temperature was measured using a Campbell Scientific (Logan, UT) model 107 soil temperature probe (accuracy $\pm 3\%$) inserted 5 cm into the manure at 45 deg angle inside the chamber. Manure pack samples were collected before and after each measurement. Those samples were analyzed for soil pH, and water content, and total nitrogen.

The in-situ field measurements were conducted using a temperature-controlled instrument shelter. The shelter was a modified 1.5 m \times 2.1 m (5 ft \times 7 ft) size box trailer with a 13,500 BTU air-conditioning unit. A Campbell Scientific data logger 23x was used as an automated data acquisition system. The system recorded 60-s rolling average concentration measurements. Data were downloaded daily.

Estimation of Ammonia and Hydrogen Sulfide Fluxes

The following mass balance equation was used for calculating the flux of NH_3 and H_2S gas from the measured concentration in the chamber:

$$\frac{dC}{dt} = \left(\frac{q[C_{air}]}{V} + \frac{JA}{V} \right) - \left(\frac{LA'}{V} + \frac{q}{V} \right) [C] - R \quad (1)$$

where:

C	=	$\text{NH}_3 / \text{H}_2\text{S}$ concentration in the chamber (mass/volume),
t	=	sampling time (time),
q	=	air flow rate through the chamber (volume/time),
C_{air}	=	$\text{NH}_3 / \text{H}_2\text{S}$ concentration in the air supplied to the chamber (mass/volume),
V	=	volume of the chamber (volume),
J	=	emission flux per unit area (mass/area/time),
A	=	surface area covered by the chamber (area),
L	=	loss term by chamber wall per unit area (length/time),
A'	=	surface area of the chamber walls (area), and
R	=	chemical production/destruction rate in the chamber.

The $[C_{air}]$ $\text{NH}_3 / \text{H}_2\text{S}$ concentration in zero air supplied to the chamber can be assumed to be equal zero, since these gases were filtered out in the zero air generator. This was also confirmed by direct measurement of $\text{NH}_3 / \text{H}_2\text{S}$ concentration in zero air. It is also assumed that there is no chemical production/destruction of target gases inside the chamber. Thus, Equation 1 simplifies to:

$$\frac{dC}{dt} = \frac{JA}{V} - \left(\frac{LA'}{V} + \frac{q}{V} \right) [C] \quad (2)$$

The loss term (L) in Equation 2, the sum of the losses of NH_3 or H_2S through reactions with the chamber walls and chemical reactions with existing oxidants in the carrier gas, was estimated using method developed by Kaplan et al., 1988. This experiment was conducted by reducing the flow rate and allowing the chamber to reach an equilibrium state (Kim et al., 1994; Aneja et al., 1995). The loss term L was derived from Equation 3:

$$-\ln \frac{C_{eq} - C}{C_{eq} - C_o} = \left(\frac{LA'}{V} + \frac{q}{V} \right) t \quad (3)$$

where C_o is the NH_3 or H_2S concentration in the chamber when NH_3 or H_2S concentrations in the chamber reach the first equilibrium state at an initial flow rate and C_{eq} is the NH_3 or H_2S concentrations in the chamber after the flow rate is reduced and the chamber is allowed to reach the second equilibrium. From the linear relationship between the value of $-\ln \frac{C_{eq} - C}{C_{eq} - C_o}$ and time of the

experiment, the slope should be equal to $\left(\frac{LA'}{V} + \frac{q}{V} \right)$. At this study, the experimental mean loss in the chamber was estimated to be 0.000022 m/sec based on two Kaplan experiments during the experimental period. The resulting equation for estimation of the NH_3 and H_2S flux is:

$$J = \left(\frac{LA'}{V} + \frac{q}{V} \right) [C] \left(\frac{V}{A} \right) \quad (4)$$

When the loss term effects are not considered, Equation 4 simplifies to:

$$J = \frac{q[C]}{A} \quad (5)$$

RESULTS AND DISCUSSION

Preliminary Ammonia and Hydrogen Sulfide Fluxes

Table 1 summarizes preliminary daily mean values of ammonia-nitrogen ($\text{NH}_3\text{-N}$, where $\text{NH}_3\text{-N} = 14/17 \times \text{NH}_3$) and hydrogen sulfide-sulfur ($\text{H}_2\text{S-S}$, where $\text{H}_2\text{S-S} = 32/34 \times \text{H}_2\text{S}$) fluxes for the continuous NH_3 and H_2S measurements conducted from August 16th to 30th 2002. Two rainfall events occurred on August 20th and August 29th, 2002. Increases in NH_3 and H_2S fluxes on Day 6 (8/21/2002) and Day 7 (8/22/2002) have been observed.

During the first (8/16/2002 to 8/18/2002) and the second (8/27/2002-8/29/2002) manure pack “aging” process experiments, the mean $\text{NH}_3\text{-N}$ concentrations decreased from Day 1 to Day 3, and from day 14 to Day 15 (Table 1). This is consistent with the fact that the source was limited, i.e., there was only a limited amount of ammonia in manure pack that could be released over time. Preliminary average of $\text{NH}_3\text{-N}$ flux from the feedlot surface including the loss term effects (Equation 4) was $1,669 \pm 1,212$ $\text{NH}_3\text{-N}$ $\mu\text{g}/\text{m}^2/\text{min}$. The same estimate without the loss term (Equation 5) was $1,494 \pm 1,083$ $\text{NH}_3\text{-N}$ $\mu\text{g}/\text{m}^2/\text{min}$. The preliminary average $\text{H}_2\text{S-S}$ flux excluding the loss term was estimated at 1.683 ± 1.334 $\text{H}_2\text{S-S}$ $\mu\text{g}/\text{m}^2/\text{min}$ and 1.884 ± 1.497 $\text{H}_2\text{S-S}$ $\mu\text{g}/\text{m}^2/\text{min}$ when the adsorption losses were accounted.

Table 1. Preliminary daily mean and standard deviation of $\text{NH}_3\text{-N}$ flux, $\text{H}_2\text{S-S}$ flux, manure pack temperature, and manure pack characteristics, such as pH, moisture content, and TKN.

Date	NH ₃ -N Flux w/o Loss Term ($\mu\text{g}/\text{m}^2/\text{min}$) (Equation 5)		NH ₃ -N Flux with Loss Term ($\mu\text{g}/\text{m}^2/\text{min}$) (Equation 4)		H ₂ S-S Flux w/o Loss Term ($\mu\text{g}/\text{m}^2/\text{min}$) (Equation 5)		H ₂ S-S Flux with Loss Term ($\mu\text{g}/\text{m}^2/\text{min}$) (Equation 4)		Soil Temperature (°C)		Manure Pack Characteristics		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	pH	H ₂ O (%)	TKN (ppm)
8/16/02	404	23	448	25	1.849	0.580	2.056	0.648	32.0	13.8	N/A	N/A	N/A
8/17/02	370	38	413	42	1.918	1.355	2.150	1.525	31.4	5.4	N/A	N/A	N/A
8/18/02	340	40	380	45	1.713	1.275	1.919	1.433	31.4	5.7	8.09	6.5	18,414
8/19/02	396	219	441	245	1.108	0.657	1.235	0.736	29.7	3.9	8.08	13.1	18,059
8/20/02	244	27	272	30	1.168	1.912	1.303	2.134	21.5	1.9	7.06	46.6	26,516
8/21/02	823	917	918	1,023	0.562	0.660	0.626	0.736	22.7	1.9	7.54	59.0	25,854
8/22/02	2,271	1,221	2,538	1,368	0.953	0.183	1.062	0.204	28.5	6.3	7.89	48.5	27,451
8/23/02	1,204	1,046	1,347	1,172	1.155	0.470	1.290	0.526	30.1	4.8	8.32	17.6	24,814
8/24/02	751	513	840	575	N/A	N/A	N/A	N/A	30.2	4.0	8.24	20.7	18,396
8/25/02	2,597	2,088	2,904	2,338	N/A	N/A	N/A	N/A	31.5	5.0	8.24	22.3	20,414
8/26/02	2,096	1,343	2,343	1,507	N/A	N/A	N/A	N/A	30.4	4.8	8.38	16.1	18,606
8/27/02	2,293	1,669	2,561	1,866	N/A	N/A	N/A	N/A	28.7	3.1	8.40	10.9	21,499
8/28/02	1,320	949	1,475	1,062	N/A	N/A	N/A	N/A	29.8	4.1	8.22	7.9	23,270
8/29/02	900	712	1,004	795	N/A	N/A	N/A	N/A	24.6	2.1	7.04	65.8	25,493
8/30/02	761	84	847	94	N/A	N/A	N/A	N/A	22.8	0.6	N/A	N/A	N/A

Fig. 3 and 4 show the mean 24-hour profiles of $\text{NH}_3\text{-N}$ during the entire experiment period and $\text{H}_2\text{S-S}$ flux variation during 8/16/2002 – 8/23/2002. Each hourly data point represents mean of hourly $\text{NH}_3\text{-N}$ and $\text{H}_2\text{S-S}$ flux values over the number of observation days and vertical bars represent the ± 1 standard deviation. The dotted line represents the base $\text{NH}_3\text{-N}$ and $\text{H}_2\text{S-S}$ flux values excluding the loss term effects that were estimated using Equation 5. Daytime maximum of $\text{NH}_3\text{-N}$ and $\text{H}_2\text{S-S}$ flux occurred between 2:00 and 4:00 PM, usually the warmest time of the day. A nighttime minimum for both gases developed between 5:00 to 7:00 AM, typically the coolest time of the day. This indicates that surface temperature of the feedlot is one of the major factors regulating the loss of $\text{NH}_3\text{-N}$ and $\text{H}_2\text{S-S}$ from the feedlot surfaces.

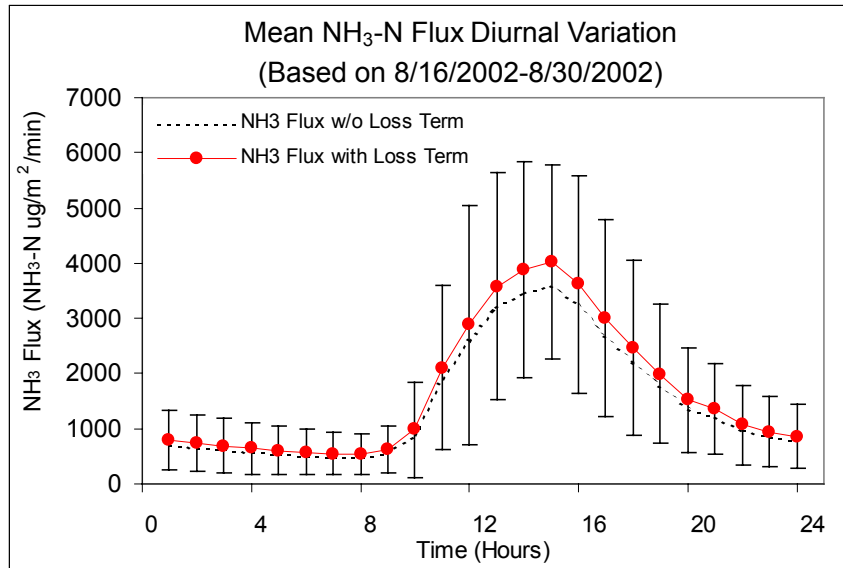


Figure 3. Daily trend of hourly mean NH₃-N flux. Error bars represent standard deviation of each hour mean value during the selected periods.

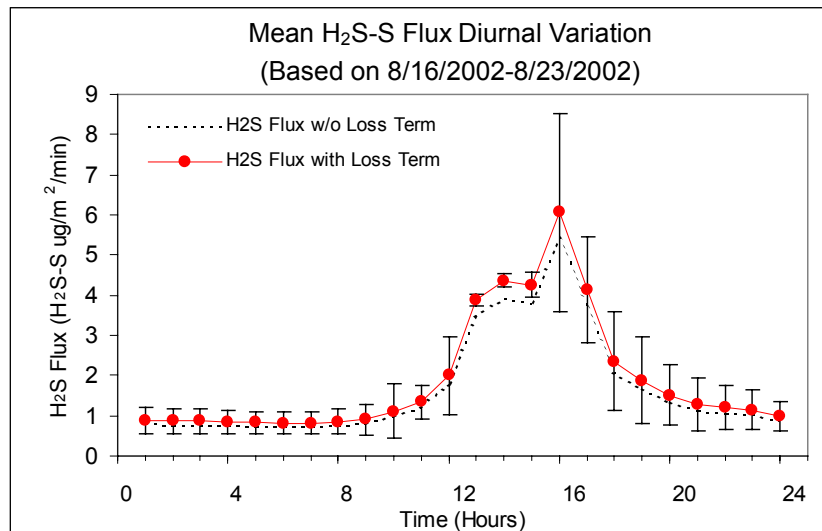


Figure 4. Daily trend of hourly mean H₂S-S flux. Error bars represent standard deviation of each hour mean value during the selected periods.

Table 2 shows comparison of the average NH₃-N flux from other different sources (Aneja et al., 2001; Roelle, 2002). This study showed that the average NH₃-N flux during summer period from the feedlot surfaces is approximately 60% less than NH₃-N flux value during summer period from the swine anaerobic lagoon surfaces estimated by Aneja et al. (2001b).

Relationship between Ammonia Emissions, Manure Pack Temperature and TKN

Previous research (Bunton, 1999; Chauhan, 1999, Dewes, 1996) showed that the temperature of animal waste is a major factor in controlling the release of NH₃ into the atmosphere. Similar observations were made by Roelle (2002) who indicated that NH₃-N flux had a logarithmic dependence with temperature of intensively managed agricultural soils. In this research, manure pack temperature (T_{soil}) was found to have a weak logarithmic relationship with NH₃-N flux [$\text{Log}_{10} \text{NH}_3\text{-N flux } (\mu\text{g N/m}^2/\text{min}) = 0.1308 \times T_{soil}(\text{°C}) + 28.198$, where $R^2 = 0.492$]. Also, the NH₃-N flux was weakly ($R^2 = 0.472$) correlated to the TKN.

Table 2. Comparison of NH₃-N flux from feedyard surface with other studies.

Studies	Measurement Period	Site Description	NH ₃ -N flux
This Study	Summer	Feedlot Surface w/o Loss Term	1,494 ± 1,083 μg NH ₃ -N/m ² /min
		Feedlot Surface with Loss Term	1,669 ± 1,212 μg NH ₃ -N/m ² /min
Roelle, 2002	Spring	Corn Crop, pre-fertilization	0.038 to 0.271 μg N/m ² /sec
	Winter	No Crop Planted	0.003 to 0.026 μg N/m ² /sec
Aneja et al., 2001b	Spring	Anaerobic Lagoon Surface	1,706 ± 552 μg N/m ² /min
	Summer		4,017 ± 987 N/m ² /min
	Fall		8,440 ± 401 μg N/m ² /min
	Winter		3,050 ± 154 μg N/m ² /min

CONCLUSIONS

Ammonia-nitrogen and H₂S-S fluxes from commercial feedlot surfaces in northwestern Texas were monitored with a dynamic flow-through chamber system and continuous analyzers during the experimental period (8/16/2002 – 8/30/2002). Preliminary mean NH₃-N flux from the feedlot surface including the loss term effects was 1,669 ± 1,212 NH₃-N μg/m²/min (1,494 ± 1,083 NH₃-N μg/m²/min excluding the loss due to adsorption to walls of sampling system). Preliminary mean H₂S-S flux was estimated at approximately at 1.884 ± 1.497 H₂S-S μg S/m²/min (1.683 ± 1.334 H₂S-S μg S/m²/min excluding the loss due to adsorption to walls of sampling system). The average NH₃-N flux was approximately 60% less than NH₃-N flux from the swine anaerobic lagoon surfaces estimated by Aneja et al. (2001b). Manure pack temperature and TKN showed weak correlations with the NH₃-N flux.

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REFERENCES

- Aneja, V.P., J.M. Overton, B.P. Malik, Q. Tong, and D. Kang, 2001a, "Measurement and modeling of ammonia emissions at waste treatment lagoon atmospheric interface", *Journal of Water, Air, and Soil Pollution*, 1, 177-188.
- Aneja, V.P., B.J. Bunton, J.T. Walker, and B.P. Malik. 2001b. Measurements and Analysis of Atmospheric Ammonia Emissions from Anaerobic Lagoons, *Atmospheric Environment*, 35, 1949-1958.
- Aneja, V.P., J.P. Chauhan and J.T. Walker. 2000. Characterization of atmospheric ammonia emissions from swine waste storage and treatment lagoons, *Journal of Geophysical Research*, 105, 11,535-11,545.
- Aneja V.P., W.P. Robarge and B.D. Holbrook. 1995. Measurements of nitric oxide flux from an upper coastal plain, North Carolina agricultural soil. *Atmospheric Environment*, 21, 3037-3042.

- Battye, R. W. Battye, C. Overcash and S. Fudge. 1994. Development and selection of ammonia emission factors. EPA Contract Number 68-D3-0034, Work Assign. 0-3, USEPA, RTP, NC.
- Bunton, B. 1999. Measurements and analysis of atmospheric ammonia emissions from anaerobic lagoons. M.S. Thesis, North Carolina State University, Raleigh, NC.
- Chauhan, J.P. 1999. Characterization of ammonia emissions from swine waste storage and treatment lagoons. M.S. Thesis, North Carolina State University, Raleigh, NC.
- Dewes, T. 1996. Effect of pH, temperature, amount of litter and storage density on ammonia emissions from stable manure. *J. Agricultural Science*, 127, 501-509.
- Kaplan, W.A., S.C. Wofsy, M. Keller and J.M.D. Costa. 1988. Emission of NO and deposition of O₃ in a tropical forest system, *Journal of Geophysical Research*, 93, 1389-1395.
- Kim, D.S., V.P. Aneja and W.P. Robarge. 1994. Characterization of nitrogen oxide fluxes from soil of a fallow field in the central piedmont of North Carolina, *Atmospheric Environment*, 28, 1129-1137.
- Roelle, P. A. 2002. Oxidized and Reduced Biogenic Nitrogen Compound Emissions into the Rural Troposphere: Characterization and Modeling. Ph.D. Thesis, North Carolina State University, Raleigh, NC.