TECHNICAL PAPER

ISSN:1047-3289 *J. Air & Waste Manage. Assoc.* **59**:613–618
DOI:10.3155/1047-3289.59.5.613

Seasonal Ammonia Emissions from a Free-Stall Dairy in Central Texas

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ABSTRACT
Studies show that agricultural and animal feeding operations (AFOs) contribute a considerable amount of ammonia (NH_3) to the atmosphere. Agricultural NH_3 emissions are recognized as an important air quality issue. Biological decomposition of manure from dairy operations results in emissions of NH_3 and other gases. There is a need to determine NH_3 emission factors (EFs) to compile annual NH_3 inventories. NH_3 emissions should be estimated from different ground-level area sources (GLAS) including open-lots (cows on earthen corrals), free-stalls (cows in barns), manure composting sites, primary and secondary lagoons, separated solids, and milking parlors. A protocol using flux chambers was used to determine NH_3 EFs from different GLAS of a free-stall dairy in central Texas. Data including NH_3 emissions from GLAS were collected during winter and summer seasons. NH_3 concentration measurements were made using chemiluminescence-based analyzers. The EFs for the free-stall dairy were estimated as 11 ± 4.9 (confidence interval [CI]) kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$ for summer and 4.7 ± 4.9 kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$ for winter. The estimated annual NH_3 EF was 8.4 ± 4.9 kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$ for this free-stall dairy. This seasonal difference was attributed to temperature, loading rate of dairy waste, and manure bacterial activity of GLAS. In winter, composted manure and free-stalls contributed nearly 77% of the total NH_3 emissions for the dairy; however, in summer, two lagoons at the dairy contributed 65% of the overall NH_3 emissions.

IMPLICATIONS
Agricultural and AFOs contribute a considerable amount of NH_3 to the atmosphere. NH_3 is released to the atmosphere from biological decomposition of dairy manure. Measurement of NH_3 emissions from individual GLAS at AFOs to establish EFs is necessary to develop emissions control strategies, determine applicability of emissions control methods, and select appropriate mitigation strategies. It is important to obtain real-time, direct estimates of emissions from different NH_3 emission sources at AFOs to compile emission inventories and to develop abatement strategies.

INTRODUCTION
Ammonia (NH_3) is released to the atmosphere because of the biological decomposition of dairy manure. In both Europe and the United States, agricultural NH_3 emissions from animal feeding operations (AFOs) and fertilizer applications are considered as major contributors (up to 80%) to total NH_3 emissions.[1,2]

Recently, Mukhtar et al.[3] provided a detailed list of dairy NH_3 emission factors (EFs) reported between 1987 and 2007. NH_3 EFs for dairies have generally been reported based on the nitrogen mass balance method. In Europe[4–8] and the United States[9–11] EFs for dairy facilities were estimated to be anywhere from 1.5 to 55.5 kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$. NH_3 emissions to the atmosphere from dairy operations in the United States were reported as 38.1 kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$ in the year 2002 National Emissions Inventory (NEI) by the U.S. Environmental Protection Agency (EPA).[9] Differences in climate, housing, feed, and waste management practices contribute to the differences among the given EF range. However, an exhaustive literature search resulted in no information on NH_3 emissions from the ground-level area sources (GLAS) of free-stall dairies typical for housing lactating dairy cows in the southwestern United States.

The potential for federal air quality regulations accelerates the need for better estimates and effective management practices for reducing NH_3 emissions. It is important to obtain real-time, direct estimates of emissions from different NH_3 emission sources at AFOs. There is a need for an accurate technique to measure NH_3 emissions from AFOs to obtain emission inventories and to develop abatement strategies. A protocol to measure surface gas emissions from GLAS using an isolation flux chamber (FC) has been published by EPA.[12] This measurement technique applies to land surfaces and quiescent liquid surfaces such as lagoons, where surface runoff and process-generated wastewater from AFOs are stored and treated under anaerobic conditions. According to Shah et al.,[13] the closed-dynamic chamber may be the most preferred method for measuring NH_3 fluxes for real-time data on the soil surface and short crops. Isolation FCs have been previously used by Aneja et al.,[14] Mukhtar et al.,[3] and Capareda et al.[15] to measure NH_3 fluxes from different emitting surfaces (i.e., open-lot corrals, lagoon surfaces, and composted manure surfaces).

In our study, this protocol was used to determine NH_3 EFs from different GLAS at a free-stall dairy in central Texas. The objectives of our study were (1) to measure seasonal NH_3 emissions from GLAS of a free-stall dairy using a real-time measurement system, and (2) to evaluate seasonal variations of EFs during two consecutive seasons and develop an annual free-stall dairy EF.

EXPERIMENTAL DETAILS

Sampling Site: Free-Stall Dairy

Free-stalls and open-lot dairies are the most common dairy systems in southern and western parts of the United States.[16] A free-stall dairy in central Texas was chosen to determine NH_3 emissions from different GLAS. An aerial photo of the site showing the sources of NH_3 emissions at the dairy is presented in Figure 1. Approximately 2100 lactating and dry cows were housed at the dairy. The open-lots at this free-stall dairy were provided for dry or low-milk-producing cows and included centralized feeding and watering areas and freestanding shelters for relief from severe weather conditions.

Manure that accumulated in the free-stall barns was removed by flushing four times a day (7:00 a.m., 1:00 p.m., 7:00 p.m., and 1:00 a.m.). Three naturally ventilated free-stall barns with open sides and ends were located at this dairy. Free-stall bedding, feed, non-feed, and drinking water (water tanks) areas were nearly 40, 30, 28, and 2% of the total free-stall area, respectively. Each free-stall was flushed in series from north to south. The flushed slurry was then transported into a solids separator system for liquid-solid separation. Screened solids were composted in windrows, managed with a compost turner on-site, and used as bedding for the free-stall barns. The separated liquid portion was transported to the first cell of the anaerobic lagoon (Lagoon 1). The effluent from the primary lagoon was conveyed to the second cell (Lagoon 2) with a pipe outlet. Lagoon 2 also accepted runoff from two other open-lots. Each open-lot was an unpaved, confined area with access to feed bunkers and water tanks. Manure produced in the open-lot was removed by scraping using tractor-mounted blades. The rate of manure production was generally higher near feed bunkers and water tanks. The scraped manure was stockpiled and either land applied or composted on-site.

Sampling Equipment

Isolation FCs were used to measure real-time NH_3 concentrations from GLAS of the free-stall dairy. The basic design of the FC includes a hemispherical acrylic top (dome) and a cylindrical stainless steel skirt (Figure 2). The dome contained four symmetrical holes with stainless steel fittings. A tubing inlet located at one of the stainless steel fittings allowed for the flow of sweep air into the chamber.[17]

The sweep air was NH_3-free purified air generated from a zero-air generator (Model 737-12, AADCO Instruments). A fitting on the top of the dome allowed for the pollutant stream to be conveyed to a measurement device. Two of these holes were used to connect the FC to low-density polyethylene (LDPE) tubing to convey the contaminant-free zero-grade air to sweep and purge the chamber and to Teflon tubing to convey a sample of the

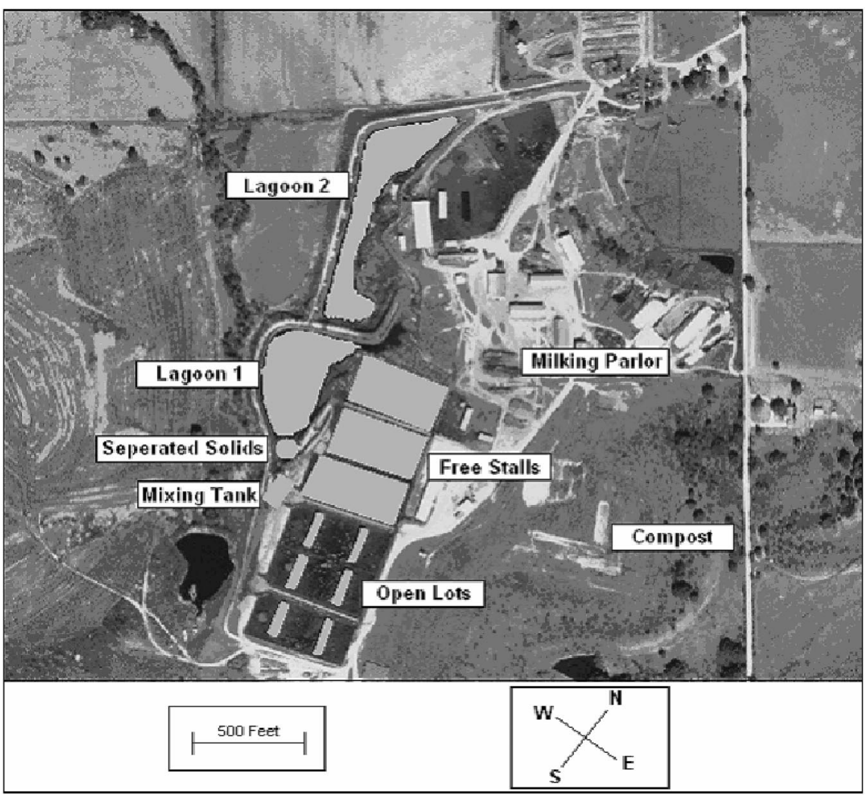

Figure 1. An aerial view of the sampled GLAS at the free-stall dairy.

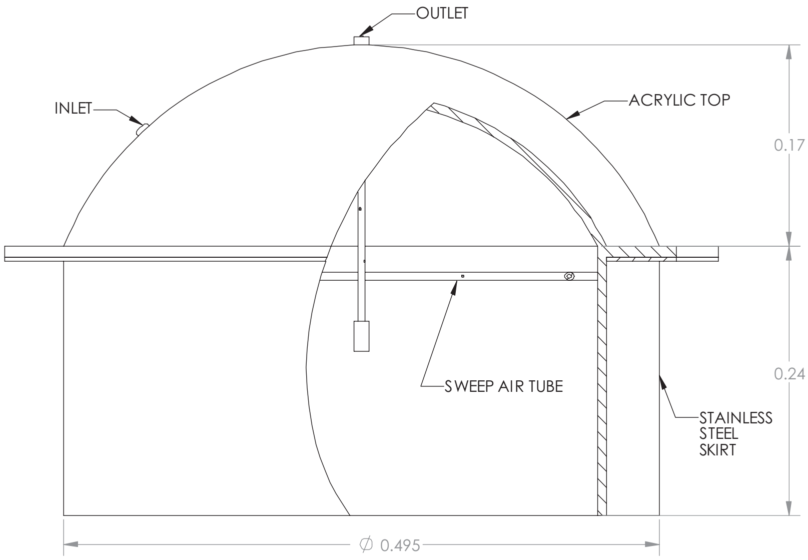

Figure 2. Schematic diagram of the FC (all dimensions are in meters).[20]

polluted air from the chamber to the NH_3 gas analyzer. During summer sampling at the dairy, FCs were covered with cylindrical covers on the sides and on top (Figure 3) to minimize potential overheating of the chamber when exposed to direct sunlight. This insulation kept the inside temperature of the chamber within 7 °C of the ambient temperature. Previous studies[18–20] have provided details of sampling NH_3 using FCs.

Sampling Method

The EPA protocol by Gholson et al.[12] requires three to four volumetric air exchanges in the FC during the sampling process. An NH_3-free sweep airflow rate of 5 $L \cdot min^{-1}$ was used during winter sampling and 7 $L \cdot min^{-1}$ was used during summer sampling. From the FC dimensions in Figure 2, a chamber volume of nearly 64.5 L was calculated. As described below, for a 30-min purging and a 30-min sampling period, 4.5 and 6.5 chamber volume changes were achieved for flow rates of 5 (winter) and 7 $L \cdot min^{-1}$ (summer), respectively. The sampling process began when the FC was placed on a GLAS.

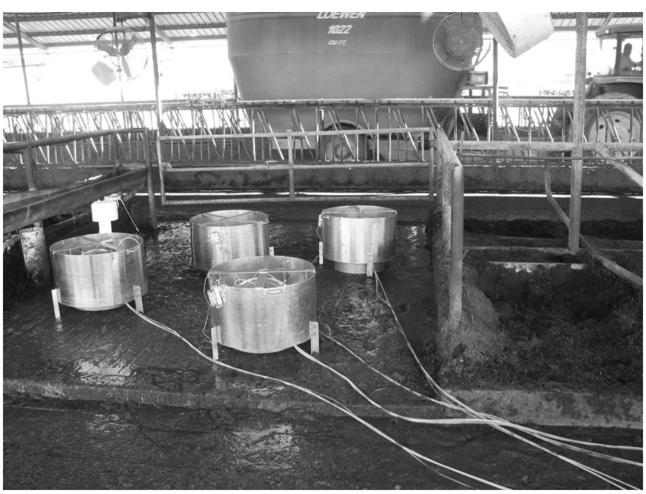

Figure 3. Isolation FCs in a free-stall barn.

Initially, the sweep air from the zero-air generator was pumped into the FC and was purged for 30 min. After purging the FC, actual sampling of polluted air was initiated by conveying the polluted air from the FC to a TEI chemiluminescence analyzer (Model 17C, Thermo Environmental Instruments) to measure NH_3 for an additional 30 min.

The TEI analyzer was calibrated using known concentrations of NH_3, nitrogen dioxide (NO_2) and nitric oxide (NO), certified high-purity standard gases guaranteed by the manufacturer to be within ±2% accuracy (Praxair, Inc.). Details of the principle of chemiluminescence to measure NH_3 have been provided in previous studies.[15–20]

Adsorption studies were conducted earlier to determine losses from the sampling tube (Teflon) and the FC system. Results indicated that an adsorption loss of NH_3 on Teflon tubing was negligible[19] and NH_3 adsorption losses were approximately 8% for the FC.[15] NH_3 concentrations from the analyzer were corrected based on adsorption losses.

Uncertainty analysis was performed on the NH_3 sampling process.[20] The first-order Taylor series technique was used to calculate uncertainty of this sampling procedure. The analysis was performed for the real-time NH_3 measurement system and included the NH_3 analyzer, calibration gases, and the mass flow controllers. The overall uncertainty was found to be in the range of 8–10% for this NH_3 sampling method.

Using the ideal gas law, measured volumetric NH_3 concentrations (parts per million [ppm]) were converted into mass concentration ($C_{mass,}$ $\mu g \cdot m^{-3}$) and eqs 1–3 were used to calculate NH_3 emission fluxes (EFls), emission rates (ERs), and EFs, respectively.

$$EFl_{NH_3} = \frac{C_{mass} \times V_{fc}}{A_{fc}} \quad (1)$$

where EFl_{NH3} is the NH_3 gas EFl ($\mu g \cdot m^{-2} \cdot sec^{-1}$), V_{fc} is the volumetric flow through the FC ($m^3 \cdot sec^{-1}$), and A_{fc} is the area of the FC ("footprint," m^2).

$$ER = EFI_{NH_3} \times A_{sc} \quad (2)$$

where ER is the ER (kg · day^{-1}) and A_{sc} is the area of the source (GLAS, m^2).

$$EF = \left(\frac{ER}{TNA}\right) \times 365 \quad (3)$$

where EF is the EF (kg-NH_3 · yr^{-1} · head^{-1}) and TNA is the total number of animals.

NH_3 emissions data were randomly collected from each of the GLAS for estimating seasonal farm-scale NH_3 emissions. A total of 29 NH_3 flux data were collected in the winter season by using one chamber at a time. The total number of NH_3 samples nearly doubled to 55 by using a multiplexer system in the summer season. This system allowed NH_3 flux sampling using multiple chambers simultaneously. For instance, in winter a total of three and five samples were collected from the composting site and open-lot area, respectively. In contrast, a total of 11 and 8 samples were collected from the composting site and open-lot area, respectively, in the summer season. Overall, more samples were taken from solid surfaces (free-stall, open-lot, etc.) per unit area than from lagoons because lagoon surfaces had fewer NH_3 flux variations as compared with solid surfaces.

RESULTS AND DISCUSSIONS

Winter Measurement

Two consecutive seasonal studies were conducted at the same free-stall dairy. The first study was conducted in the winter season. Twenty-nine samples were collected to determine the EFs of NH_3 from different GLAS of the dairy. The winter NH_3 EFs, area of each GLAS, and ambient and GLAS temperatures are presented in Table 1. During winter sampling, the total area of the composting windrows was nearly 27% greater (Table 1) than that during summer sampling (Table 2). Conversely, areas of both lagoons, measured at the waterline, were lesser in winter (Table 1) than summer (Table 2) by nearly 37 and 6% for Lagoon 1 and 2, respectively.

The highest NH_3 EFs were from the composting area and free-stall barns at 1.7 ± 2.2 and 1.7 ± 1.1 kg-NH_3 · yr^{-1} · head^{-1}, respectively. The lowest EFs were from open-lots and the primary lagoon (Lagoon 1). Each source emitted 0.1 kg-NH_3 · yr^{-1} · head^{-1}. The highly diluted secondary lagoon (Lagoon 2) and the small footprint of the separated solids site contributed little to the overall EFs. The large variation in EFs for the composting area and open-lots (Table 1) resulted from highly variable NH_3 emissions measured from these surfaces. NH_3 emission from compost piles varied with microbial activity in a compost pile. Actively composting piles emitted greater NH_3 as compared with mature piles. As for open-lots, spatially variable distribution of manure on open-lot surfaces contributed to large variations in NH_3 emissions. In a companion study to measure NH_3 emissions from a strictly open-lot dairy, Mukhtar et al.[3] found highly spatially variable emissions from open-lot surfaces because of variable manure loading rates in feeding, dry, and shaded areas of the open-lot. The compost and the free-stall areas contributed nearly 77% to the total NH_3 EF for this facility, whereas the dry open-lot contributed an additional 18%. The overall calculated NH_3 EF was 4.7 ± 4.9 kg-NH_3 · yr^{-1} · head^{-1} for this free-stall dairy. The average ambient temperature during winter sampling was 6.6 °C.

At the same source and ambient temperature (Table 1), the wet areas of open-lots had higher NH_3 concentrations than the dry areas, but because of a much smaller footprint, the EF from wet open-lots was less than that of dry open-lots. The area of free-stalls was less than one-half that of the open-lots, but the much greater NH_3 emissions measured from free-stalls resulted in higher EFs than that from open-lots. This was attributed to a higher density of cows in the free-stall barn, resulting in greater amounts of manure accumulation. Additionally, relatively higher free-stall barn temperatures as compared with those from open-lots contributed to higher NH_3 emissions from waste. The high temperature of actively composting piles resulted in increased NH_3 emissions, and higher ERs resulted from the compost site representing the second largest area at the dairy.

Summer Measurement

The second study at the same free-stall dairy was conducted during the summer season. Fifty-five samples were collected to determine NH_3 emissions from the same sources plus the crowding area (adjacent to the milking parlor) of the dairy. Additionally, for a better understanding of NH_3 emissions from the free-stall barn, NH_3 was measured from the feed and non-feed sides and from

Table 1. Average NH_3 EFs with 95% confidence interval (CI) from different GLAS of the dairy in winter.

GLAS	Number of Samples	GLAS Area (m^2)	Winter EFs (kg-NH_3 · yr^{-1} · head^{-1})	Ambient Temperature (°C)	GLAS Temperature (°C)
Compost	3	21,000	1.7 ± 2.2[a]	8.5	30.1
Free-stall	5	10,000	1.7 ± 1.1	6.3	6.4
Dry open-lots	3	36,100	1.1 ± 1.4	−1.0	−1.1
Wet open-lots	4	1,900	0.1 ± 0.05	−1.0	−1.1
Solid separator	2	110	0.0 ± 0.0	3.7	3.6
Primary lagoon	6	14,000	0.1 ± 0.03	16.7	8.7
Secondary lagoon	6	16,000	0.0 ± 0.02	13.0	9.5
Summation	29	99,110	4.7 ± 4.9[a]		

Notes: [a]CI.

Table 2. Average NH_3 EFs with 95% confidence interval (CI) from different GLAS of the dairy in summer.

GLAS	Number of Samples	GLAS Area (m^2)	Summer EFs ($kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$)	GLAS Temperature (°C)	Chamber Temperature (°C)	Ambient Temperature (°C)
Compost	11	16,600	0.2 ± 0.2[a]	43.2 ± 7.1[a]	39.1 ± 1.8[a]	33.3 ± 1.6[a]
Free-stall Barns						
Non-feed	5	2,700	0.8 ± 0.9	25.8 ± 3.2	30.1 ± 2.0	33.4 ± 1.3
Feed	5	3,090	1.5 ± 1.4	33.9 ± 56.1	33.2 ± 5.4	34.6 ± 0.2
Bedding	2	3,800	0.1 ± 0.0	27.0 ± 2.8	31.1 ± 2.5	33.3 ± 3.1
Watering	2	200	0.0 ± 0.1	23.8 ± 2.1	31.5 ± 4.4	34.5 ± 2.7
Open-lots	8	38,000	1.2 ± 1.0	30.6 ± 3.5	35.3 ± 3.1	33.3 ± 1.4
Crowding area	4	925	0.1 ± 0.0	21.5 ± 1.0	24.2 ± 1.0	25.6 ± 1.0
Solids separator	4	110	0.0 ± 0.0	34.0 ± 5.2	32.7 ± 4.7	N/A
Lagoon 1	8	19,200	4.1 ± 0.9	29.5 ± 1.2	29.7 ± 1.8	29.6 ± 2.3
Lagoon 2	6	17,000	3.1 ± 0.3	28.4 ± 0.7	27.7 ± 2	26.7 ± 1.9
Summation	55	101,625	11.0 ± 4.9			

Notes: [a]CI. N/A = not applicable.

bedding and watering areas of the barn. Ambient air, GLAS, and chamber temperatures were measured simultaneously with NH_3 emission measurements (Table 2).

Results of NH_3 EFs from each individual GLAS are shown in Table 2. NH_3 EFs ranged from nearly zero to 4.1 ± 0.9 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$. Both primary (Lagoon 1) and secondary (Lagoon 2) lagoons were the highest contributors to the overall NH_3 EF in the summer season.

A difference in NH_3 emissions occurred because of temperature variations, nonuniform waste loading rates, and biological activity. For instance, EFs from both lagoons were not significant contributors to the overall EF in the winter season (Table 1). However, summer NH_3 EFs were 4.1 ± 0.9 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$ from Lagoon 1 and 3.1 ± 0.3 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$ from Lagoon 2 (Table 2). This increase in NH_3 emissions from both lagoons was attributed to increased volatilization of NH_3 from higher lagoon temperatures in summer than in winter. Also, greater lagoon surface areas in the summer resulted in greater estimates for summer lagoon EFs. Despite the higher compost pile surface temperature in summer than in winter, NH_3 emissions from compost were lower in summer than those in winter (Table 1). At the time of the summer NH_3 measurements, the compost piles had already gone through an active heating cycle (the differences between pile and ambient temperatures were 9.8 °C during summer sampling as compared with 21.6 °C during winter sampling) and microbial activity of the piles was reduced, resulting in lower NH_3 volatilization. Additionally, the lesser surface area of compost windrows as compared with the winter season also contributed to lower summer EFs from the compost site. The total free-stall NH_3 EF in summer (2.4 ± 2.4 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$) was higher than that from winter (1.7 ± 1.1 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$).

During summer, the feed area of the free-stall had the highest NH_3 concentration, followed by the non-feed side, water area, and bedding (Table 2). The feed side of the barn had the most amount of waste accumulation, resulting in the highest NH_3 emissions. Waste around water tanks was diluted because of water spillage by cows in the vicinity, resulting in lower NH_3 emissions than those from feed and non-feed sides. The free-stall bedding was composted separated solids with most nitrogen tied up in organic matter and very little NH_3 volatilization, hence minimal NH_3 emissions were measured from the bedding area.

The overall calculated summer NH_3 EF was 11 ± 4.9 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$ for this facility. It is noticeable that two lagoons contributed 65% of the overall NH_3 EFs during the summer sampling. The free-stalls contributed an additional 22% to the overall NH_3 EFs.

Compared with the average ambient winter temperature of 6.6 °C (Table 1), the average ambient summer temperature was 31.5 °C (Table 2).

Estimate of Annual EF

The long-term (1963–2007) average ambient air temperature data from a weather station located approximately 15 km from the dairy was downloaded from the National Climatic Data Center[21] Web site. Five months with average temperatures below 16 °C were considered winter months and 7 months with average temperature above 16 °C were considered summer months. On the basis of this assumption, the annualized NH_3 EF for this dairy was estimated to be 8.4 ± 4.9 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$ for this 2000-head dairy.

A similar study was conducted by Mukhtar et al.[3] on an open-lot dairy situated within a few kilometers from this free stall dairy. Both dairies housed nearly the same number of Holstein cows (2000). The estimated annual NH_3 EF was 9.4 ± 5.7 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$ for this open-lot dairy. Additionally, the summer EF of this open-lot dairy (11.6 ± 7.1 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$) was also nearly twice that of (6.2 ± 3.7 $kg\text{-}NH_3 \cdot yr^{-1} \cdot head^{-1}$) the winter EF.

CONCLUSIONS

NH_3 is released to the atmosphere because of biological decomposition of dairy manure. At a dairy operation, free-stalls (cows in the barn), open-lots (cows on earthen corrals), manure composting areas, separated solids from flushed manure, primary and secondary lagoons, and milking parlors are all GLAS of NH_3. Two consecutive seasonal studies were conducted to determine NH_3 EFs at a free-stall dairy in central Texas. The EFs were 11 ± 4.9

kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$ for the summer season and 4.7 ± 4.9 kg-$NH_3 \cdot yr^{-1} \cdot head^{-1}$ for the winter season. In summer, two lagoons at the dairy contributed 65% of the overall NH_3 emissions. However, in winter, composted manure and free-stalls contributed nearly 77% to the total NH_3 emissions at the dairy.

Overall, summer NH_3 emissions were more than twice those of winter emissions. This seasonal difference was due to the temperature, loading rate of dairy waste, and microbial activity of NH_3 emission sources at the dairy. Measuring NH_3 emissions and estimating EFs for individual sources of emissions at a free-stall dairy during winter and summer provide better assessment of the seasonal differences in overall EFs from a dairy operation. This approach also assists with implementation of best management practices (BMPs) to reduce NH_3 emissions from individual waste management components of the dairy for winter and summer seasons. For example, covering or chemically treating lagoons solely for the purpose of controlling NH_3 emissions to the atmosphere may not be an effective BMP in the winter when little or no NH_3 volatilization occurs from lagoons because of low temperatures and microbial activity. On the other hand, reducing the size of the composting operation on-site or moving it off-site will reduce dairy operation NH_3 emissions throughout the year.

The difference in annual NH_3 EFs between the open-lot and free-stall dairy was due to different management practices at each dairy. At the free-stall dairy, composted manure was one of the highest contributors to the overall EF in the winter season, whereas no manure composting was conducted at the open-lot dairy. The primary lagoon was the highest contributor to overall EFs at the free-stall dairy in the summer season. This was attributed to a large fraction of the free-stalls being flushed in to the primary lagoon. In contrast, the primary lagoon of the open-lot dairy only collected wastewater that was conveyed from the crowding area (the area where cows are held temporarily awaiting milking) and the milking parlor. This wastewater was highly diluted, resulting in lower NH_3 emissions from the primary lagoon of the open-lot dairy. Therefore, the primary lagoon had less overall NH_3 contributions to the EFs in summer and winter as compared with the corresponding primary lagoon at the free-stall dairy.

ACKNOWLEDGMENTS

This research was funded by a grant from the U.S. Department of Agriculture-Cooperative State Research, Education, and Extension Service, project no. TS-2006-06009.

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