MEASUREMENT OF ATMOSPHERIC AMMONIA, METHANE, AND NITROUS OXIDE AT A CONCENTRATED DAIRY PRODUCTION FACILITY IN SOUTHERN IDAHO USING OPEN-PATH FTIR SPECTROMETRY

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ABSTRACT. *The number of dairy cows in Idaho has increased by approximately 80% in the last decade, with the majority of these facilities located in southern Idaho, causing air quality concerns in this region. To determine the potential air quality impacts of these facilities, we measured ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O) concentrations over the pens, wastewater storage pond, and composting area on a 700-cow open-lot dairy using open-path Fourier transform infrared spectrometry (OP/FTIR). Concentrations were measured for one or two days at each location during January, March, June, and September. Median NH_3 concentrations over the pens, storage pond, and composting area ranged from 0.14 to 0.39 ppmv, 0.04 to 0.17 ppmv, and 0.06 to 0.22 ppmv, respectively, with concentrations tending to be lower in January. Average CH_4 concentrations over the pens, storage pond, and composting area ranged from 2.07 to 2.80 ppmv, 1.87 to 2.15 ppmv, and 1.71 to 1.76 ppmv, respectively. Average N_2O concentrations ranged from 0.31 to 0.33 ppmv for all areas, which was similar to global background N_2O concentrations. Combined ammonia emissions for the pen and storage pond areas, calculated with a backward Lagrangian stochastic inverse-dispersion technique, were 0.04, 0.25, 0.19, and 0.15 kg NH_3 cow^{-1} d^{-1} for January, March, June, and September, respectively, and methane emissions were 0.34, 0.55, 0.21, and 0.20 kg CH_4 cow^{-1} d^{-1} for the same months. Assuming this limited monitoring was representative of the entire year, annual emissions from the pens and storage pond were 57 kg NH_3 cow^{-1} and 120 kg CH_4 cow^{-1}. These emission rates were similar to the limited number of comparable studies that have been published. However, more extensive monitoring is needed to better quantify variations in emissions throughout the year and among locations.*

Keywords. Ammonia, Dairy, Emissions, FTIR, Methane.

The state of Idaho has experienced rapid growth of the dairy industry in the past decade, with the number of milk cows increasing approximately 80% and milk production increasing 110% (USDA-NASS, 2007). Idaho is the second largest milk producer in the twelve western U.S. states and has become the third largest milk-producing state in the U.S. In 2006, there were 477,193 milking cows in Idaho, with 71% of these located in the Magic Valley region of southern Idaho (UDI, 2007). While this region has benefited economically from the growth of the dairy industry, there is concern regarding the impact of concentrated dairy production facilities on the environment, particularly emissions of ammonia, methane, and nitrous oxide. Ammonia (NH_3) has the potential to generate secondary particulates that could be a human health risk, and methane (CH_4) and nitrous oxide (N_2O) are potent greenhouse gasses.

Research evaluating the emissions of NH_3 and other trace gases has been requested by both dairy producers and the community. Monitoring atmospheric emissions from concentrated dairy production facilities is challenging, particularly in the case of open-lot dairies where cows are concentrated in a series of large pens. One technique that is amenable to monitoring large-area sources is open-path Fourier transform infrared (OP/FTIR) spectrometry. This technique is capable of measuring the concentrations of multiple gases in real time over relatively long (several hundred meter) paths without altering ambient conditions (Russwurm and Childers, 2002). OP/FTIR spectrometry has been used successfully to monitor pollutants, greenhouse gases, and other emission products at large-area sources, such as landfills (Weber et al., 1996) and industrial sites (Lamp et al., 1995), as well as animal production facilities and manure application sites (Childers et al., 2001; Galle et al., 2000). Independent studies have shown that the concentrations of target gases reported by OP/FTIR methods are comparable to those values determined by more conventional point monitoring methods (Russwurm et al., 1991; Hommrich et al., 1992; Carter et al., 1992).

Emission data for dairy farms are quite limited. Ammonia emission rates of 7 to 16 g NH_3-N m^{-2} d^{-1} were measured from outdoor concrete pens in the U.K. (Misselbrook et al., 2001; Misselbrook et al., 2006). Cassel et al. (2005a) estimated emissions of 50 g cow^{-1} d^{-1} from a free-stall dairy in California during February. They estimated 100 g NH_3 cow^{-1} d^{-1} on a second dairy with both free stalls and open lots, based on five measurement periods made during one day in March (Cassel et al., 2005b). Mukhtar et al. (2008) estimated an annual NH_3 emission factor of 9.4 kg cow^{-1} (25 g cow^{-1} d^{-1}) using an EPA-approved flux chamber measurement protocol for five days in winter and summer on an open-lot dairy in Texas. Rumburg et al. (2008) used a theoretical model to estimate ammonia emissions of 10 kg d^{-1} in winter and 80 kg d^{-1} in summer from a free-stall dairy near Pullman, Washington. The emission rates equal 54 g cow^{-1} d^{-1} in winter and 430 g cow^{-1} d^{-1} in summer for the 185 milk cows.

While there are some published data for NH_3 emissions from dairies, very little concentration and emission rate information is available for open-lot dairies that are typical of southern Idaho. The primary objective of this study was to determine the concentration ranges of NH_3, CH_4, and N_2O over four seasons (spring, summer, fall, winter) at an open-lot dairy in southern Idaho. A secondary objective was to calculate emission rates from the cattle pens and the wastewater storage pond.

MATERIALS AND METHODS

The dairy used in this study was a privately owned commercial dairy in a rural location in southern Idaho, with approximately 700 milking cows and 80 dry cows with a stocking density of approximately 60 m^2 cow^{-1} (fig. 1). This dairy was similar in configuration to most open-lot production facilities in southern Idaho. The operation consisted of six main cattle pens (one of which was divided into two sections, for a total of seven pens), milking parlor, hospital barn, gravity manure separator, wastewater storage pond, and compost area. Wash water from the milking parlor and runoff from the cattle pens were retained in the storage pond, while solid manure from the pens was applied to fields or composted in an area southeast of the facility. Manure was collected daily from feed alleys with a vacuum tanker (Loewen Honey-Vac, Loewen Welding and Mfg., Ltd., Matsqui, B.C., Canada) and applied to the compost windrows. The cattle pens were harrowed daily unless the surface was frozen or muddy. The facility was surrounded by crop land, and the nearest livestock facility was more than 20 km away.

GAS CONCENTRATION MEASUREMENT

Concentrations of NH_3, CH_4, and N_2O were measured using the OP/FTIR spectrometer in January, March, June, and September. Three locations (pens, storage pond, and compost area) were monitored on the dairy to determine relative gas concentrations from the various sources on the farm (fig. 1). Background concentrations were measured at the upwind property line in January and June and at an off-site agricultural field in March. In September, measurements were only made at three locations on the dairy because the instrument was only available for a limited time.

Approximate monitoring paths are shown in figure 1. Path 1 was located at the west property line and represented an upwind point of measurement to detect NH_3, CH_4, and N_2O concentrations entering the farm. Path 2 was located over the cattle pens, traversing two of the pens perpendicular to the prevailing west wind. This path was set up on the west
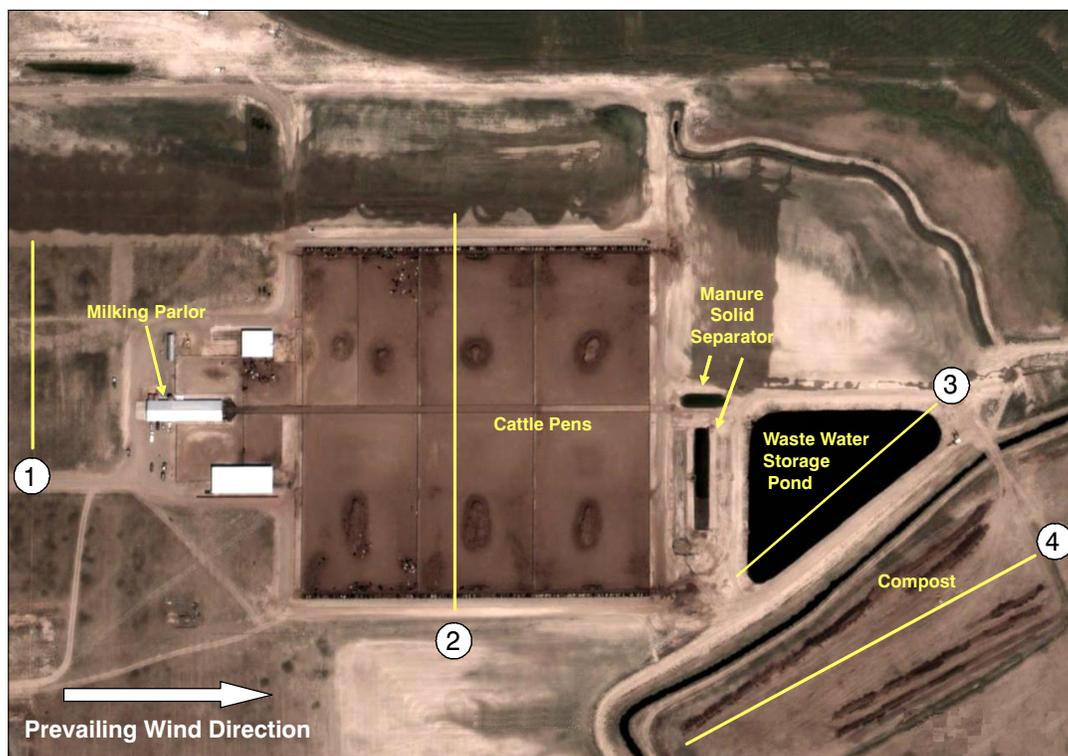

Figure 1. Aerial image of the dairy farm and approximate measurement paths used for the open-path FTIR.

side of the manure piles that were in the pens in January and March. Monitoring equipment was placed in nearly same position (within 3 m) each month for paths 1 and 2. Path 3 was located diagonally across the wastewater storage pond to have a longer path length. Path 3 was shorter in March (table 1). The equipment in the southwest corner was moved north because we did not have access to the southwest corner of the storage pond. Path 4 was located across the compost area and varied each month depending on the size and location of the compost windrows. The average height of the OP/FTIR beam was 2 m for paths 1, 3, and 4, while the height of the OP/FTIR beam across the cattle pens was approximately 3 m in order to avoid fences and cattle.

Only one OP/FTIR system was available for this study, so measurements were made sequentially at the different locations on the dairy, starting with the pens, then the storage pond, and then the compost. All measurements were made using a commercial open-path FTIR spectrometer manufactured by MDA (Atlanta, Ga.) operating in the monostatic mode (Russwurm and Childers, 2002). In this instrument, radiation from a Globar (incandescent silicon carbide) source was collimated and passed into a Bomem Michelson 100 interferometer. The exit beam from the interferometer was passed onto an external beamsplitter, so half the radiation was passed into a 25 cm telescope that expanded the beam in order to increase its collimation. The diameter of the expanded beam at a distance of 50 m from the telescope was less than 40 cm. A cube-corner array retroreflector was mounted at an appropriate distance from the telescope (usually between 150 and 250 m) and was aligned so that the reflected beam was returned to the telescope. The telescope reduced the beam back to a diameter of about 4 cm. The beam was passed from the telescope to the external beamsplitter, which passed approximately 50% of the beam to a Sterling-engine-cooled mercury cadmium telluride detector.

Interferograms were measured at approximately 70 s intervals. Any interferogram that either had a low signal-to-noise ratio (SNR) or was otherwise unacceptable was rejected by the procedure reported by Shao et al. (2007). The remaining interferograms were first preprocessed with high-pass filtering to remove the embedded DC offset. The DC offset was a straight, nonzero baseline in the interferogram, and resulted in a sinusoidal interference in the corresponding single beam spectrum. A second preprocessing procedure was carried out to correct for the nonlinear response of the MCT detector by adjusting the values of the three largest data points in the interferogram in the region of the centerburst (Griffiths et al., 2009).

Quantitative determinations of NH_3, CH_4, and N_2O concentrations were performed by partial least squares (PLS) regression of the OP/FTIR spectra. PLS was used in preference to the more commonly applied classical least squares (CLS) regression because it is both more easily automated and more accurate than CLS (Hart and Griffiths, 1998, 2000; Hart et al., 2000). As NH_3 concentrations are very low in pristine air, the PLS calibration data set was prepared with simulated OP/FTIR spectra synthesized from a total of 54 interferograms measured at several different pathlengths, temperatures, and relative and absolute humidities over a field upwind of the cattle pens, so that the range of background conditions likely to be encountered during the subsequent analytical measurements was represented. Unlike NH_3, CH_4 and N_2O are always present in air. The global average concentrations for CH_4 and

N_2O are 1.7 ppm and 0.32 ppm, respectively (Childers et al., 2001). Therefore, in preparing the PLS calibration data set of CH_4 or N_2O, the above 54 OP/FTIR spectra were used directly and the path-integrated concentrations were obtained from multiplying the global average by the path lengths of these OP/FTIR spectra.

EMISSION RATE SIMULATION

Emission rates were calculated using a backward Lagrangian stochastic (bLS) inverse-dispersion technique (WindTrax 2.0, Thunder Beach Scientific, www.thunderbeach scientific.com). The WindTrax model requires the following input: gas concentration, surface roughness length (z_o), friction velocity (u^*), a measure of atmospheric stability, and mean horizontal wind direction. Additional details about this model can be found in Flesch et al. (2004, 2005) and Flesch and Wilson (2005).

A portable meteorological station was located on site to record the wind speed and direction at 2 m, air temperature, relative humidity, solar radiation, and barometric pressure. Instruments were measured at 2 s intervals with average values stored every 10 min. Air temperature and barometric pressure were used in the WindTrax model to convert gas concentrations from volume (ppmv) to a mass basis.

Atmospheric stability was defined by Pasquill-Gifford stability class, which categorized atmospheric stability into seven classes from very unstable (A) to very stable (F), according to the matrix used by Mohan and Siddiqui (1998). Daytime stability classes were determined by wind speed and solar radiation, with incoming solar radiation defined as slight when <300 W m^{-2} and strong when >600 W m^{-2} (table 1). Wind speed and solar radiation were measured by the on-site meteorological station. Nighttime stability classes were determined by wind speed and cloud cover (table 1). Cloud cover was determined from a National Weather Service site located 35 km from the dairy. A matrix similar to table 1 is used by NOAA and EPA in atmospheric dispersion/assessment tools (e.g., www.arl.noaa.gov/READYpgclass.php).

The model calculated friction velocity from measured wind speed. Surface roughness of 15 cm was selected from the descriptive list in WindTrax. This is the maximum value allowed in the model and our best estimate of an appropriate value. More research is needed to identify surface roughness for these conditions. Because only one OP/FTIR was used for this study, background gas concentrations could not be measured at the west property line at the same time as the source areas. Background gas concentrations for WindTrax simulations were set to the minimum concentration recorded during each measurement interval at a particular source location. These minimum concentrations were comparable to con–

Table 1. Matrix for determining Pasquill-Gifford stability class (adapted from Mohan and Siddiqui, 1998).

Wind Speed (m s^{-1})	Daytime Solar Radiation (W m^{-2})			Nighttime Cloud Cover	
	Strong >600	Moderate 300-600	Slight <300	Cloudy/ Overcast	Clear/Partly Cloudy
<2	A	B	B	E	F
2-3	B	B	C	E	F
3-5	B	C	C	D	E
5-6	C	C	D	D	D
>6	C	D	D	D	D

centrations measured at the west property line or the offsite background location.

Pearson correlation coefficients were calculated using the CORR procedure of SAS (2004). Median NH_3 and CH_4 concentrations were compared between locations during a month and between months for a given location using the SAS GLM procedure on ranked concentration values. Mean ranks were separated using Tukey's test at $p < 0.05$. This method was similar to using the nonparametric Mann-Whitney test but compared multiple parameters with one test.

RESULTS

Monitoring initially occurred for 20 to 25 h at all locations on the dairy (table 2), with longer durations when monitoring continued over a weekend. After initial analysis of January data indicated greater variability in concentrations from the cattle pens compared to the storage pond or compost locations, monitoring was extended to two or three days at the pen location. Average temperatures measured during monitoring ranged from –8.3°C to 43.3°C, and relative humidity ranged from 13% to 100% (table 2). During January measurements, the average wind speed ranged from 1.41 to 1.64 m s^{-1} (table 2). Average wind speeds in March and June were greater and ranged from 1.55 to 4.64 m s^{-1} in March to 1.74 to 3.13 m s^{-1} in June. Average wind speeds measured in September ranged from 1.18 to 1.81 m s^{-1}, similar to January.

CONCENTRATIONS

Ammonia concentrations ranged from 0.01 to 4.30 ppmv and methane concentrations ranged from 1.54 to 6.20 ppmv at all sites during this study (data not shown). Nitrous oxide concentrations varied little among sites or months, ranging from 0.24 to 0.45 ppmv over all sites (data not shown) and are not discussed further. Maximum background NH_3, CH_4, and N_2O concentrations were 0.07, 2.20, and 0.34 ppmv, respectively. Median NH_3, CH_4, and N_2O concentrations are shown in table 3.

Ammonia concentrations were significantly different among locations on the dairy during each month of measurement and generally followed the trend of pens > compost > storage pond, with the exception of June when the storage pond NH_3 concentrations were greater than the compost (table 3). Ammonia concentrations from the pens were always greater than the background. Ammonia concentrations from the storage pond in January and March and from the compost in June were not different from the background.

The NH_3 concentrations were greatest during June and September for the pens and storage pond, and during March and September for the compost (table 3). Pen and storage pond NH_3 concentrations were lowest in January when temperatures were lowest. Compost NH_3 was lowest in January and June.

Methane concentrations were significantly different among locations during each month of measurement (table 3). Methane concentrations followed the trend of pens > storage pond > compost during January and March, and pens = storage pond > compost during June and September. Methane concentrations at the pens and storage pond were always greater than the background. Compost CH_4 concentrations were not different from the background during January and March.

Generally, there was less fluctuation in median CH_4 concentrations among months than among locations (table 3). The greatest CH_4 concentrations occurred during January at the pens, June at the storage pond, and September at the compost.

Pearson correlation coefficients were calculated between gas concentrations (NH_3 and CH_4) and environmental parameters (air temperature, soil temperature, wind speed, wind direction, solar radiation, barometric pressure, and relative humidity) to identify factors that had the greatest influence on gas concentrations. Ammonia concentrations were only significantly correlated to wind speed ($r = -0.07$, $P = 0.0005$), while CH_4 concentrations were significantly correlated to both wind speed ($r = -0.35$, $P < 0.0001$) and wind direction ($r = -0.09$, $P < 0.0001$). However, wind speed and wind direction were highly correlated ($r = 0.41$, $P < 0.0001$), with greater wind speeds tending to occur with the prevailing west

Table 2. Monitoring information for the different locations during the four monitoring periods.

Month and Location		Date/Time Start	Date/Time End	Path	Pathlength (m)	Air Temperature Range (°C)	Relative Humidity Range (%)	Average Wind Speed (m s^{-1})
January	Pens	1/24/05 15:40	1/25/05 10:50	2	244	-8.3 - 2.4	74-96	1.50
	Storage pond	1/27/05 14:20	1/28/05 12:00	3	153	0.3 - 7.8	6-97	1.41
	Compost	1/28/05 13:00	1/29/05 5:10	4	270	-0.1 - 9.3	58-100	1.64
	W. prop. line	1/25/05 17:00	1/26/05 11:40	1	186	NA[a]	NA	NA
March	Pens	3/15/05 10:00	3/18/05 8:40	2	243	-1.3 - 13.9	13-83	4.64
	Storage pond	3/18/05 16:00	3/19/05 9:00	3	129	-0.4 - 11.3	30-82	1.55
	Compost	3/19/05 9:30	3/21/05 14:00	4	271	1.0 - 15.5	27-93	4.16
	Off site	3/21/05 15:50	3/22/05 9:20	NA	168	0.1 - 9.2	55-91	3.13
June	Pens	6/23/05 10:40	6/25/05 9:30	2	241	8.0 - 43.3	NA	2.06
	Storage pond	6/25/05 11:00	6/27/05 9:00	3	153	7.7 - 35.7	NA	2.28
	Compost	6/27/05 10:10	6/28/05 8:50	4	265	11.4 - 24.2	NA	1.74
	W. prop. line	6/28/05 10:20	6/29/05 8:30	1	184	9.1 - 23.4	NA	3.13
September	Pens	9/26/05 10:50	9/28/05 15:30	2	240	4.9 - 23.2	24-95	1.81
	Storage pond	9/28/05 16:00	9/29/05 14:50	3	163	0.8 - 22.7	15-94	1.18
	Compost	9/29/05 15:50	9/30/05 14:40	4	180	4.5 - 25.9	14-80	1.58

[a] NA = data not available. Temperature, relative humidity, or wind speed were not available due to a power failure on the weather station in January and instrument error in June.

**Table 3. Median ammonia, methane,
and nitrous oxide concentrations.[a]**

Location	Median Concentration (ppmv)			
	January	March	June	September
Ammonia				
Pens	0.14 x,C	0.29 x,B	0.40 x,A	0.37 x,A
Storage pond	0.04 z,C	0.07 z,B	0.17 y,A	0.14 z,A
Compost	0.11 y,B	0.20 y,A	0.06 z,B	0.22 y,A
Background	0.01 z,B	0.02 z,A	<0.01 z,C	NA
Methane				
Pens	2.80 x,A	2.11 x,B	2.07 x,BC	2.07 x,C
Storage pond	1.94 y,B	1.87 y,C	2.15 x,A	1.96 x,B
Compost	1.73 z,AB	1.71 z,B	1.75 y,AB	1.76 y,A
Background	1.78 z,A	1.76 z,B	1.66 z,C	NA
Nitrous oxide				
Pens	0.33 y,A	0.31 z,C	0.32 y,B	0.31 y,B
Storage pond	0.34 x,A	0.32 y,C	0.32 x,B	0.33 x,B
Compost	0.32 z,A	0.31 z,B	0.31 y,A	0.32 xy,A
Background	0.33 y,A	0.33 x,B	0.31 z,C	NA

[a] For a given parameter, values followed by different letters in a column
(x, y, z) or row (A, B, C) are significantly different at $P < 0.05$.

winds. Methane concentrations tended to decrease to background concentrations at wind speeds >2 m s⁻¹ (data not shown). Ammonia concentrations also decreased as wind speed increased up to about 2 m s⁻¹. At wind speeds greater than 2 m s⁻¹, the NH_3 concentration decreased at a much lower rate, but remained at least an order of magnitude greater than background concentrations.

EMISSION RATES

Ammonia and methane emission rates were calculated by the WindTrax model for the pen area and wastewater storage pond. Emission rates were not calculated for N_2O because measured concentrations differed little from background concentrations. Emission rates also were not calculated for the compost area because the areal extent of the compost area was not accurately measured during each monitoring period and therefore we were unable to accurately assign a representative source area. Ammonia emissions from the pens ranged from nearly zero to approximately 400 kg d⁻¹ during the four monitoring periods, with rates being greatest in March and lowest in January (fig. 2). There were large diurnal effects, with NH_3 emission rates tending to be lower near midnight and then increasing until late afternoon.

The average NH_3 emission rates from the pens for January, March, June, and September were 24, 172, 120, and 97 kg NH_3 d⁻¹, respectively (table 4). Ammonia emissions from the storage pond did not vary much diurnally and were much lower than from the pens, partially because the pen area (4.5 ha) was much larger than the storage pond (0.8 ha). Average NH_3 emission rates from the storage pond for January, March, June, and September were 2, 4, 16, and 7 kg NH_3 d⁻¹, respectively. Average emission rates on an area basis still tended to be greater for the pens than the storage pond, with 5, 39, 27, and 22 kg ha⁻¹ d⁻¹ emitted from the pens and 3, 5, 20, and 9 kg ha⁻¹ d⁻¹ emitted from the storage pond for January, March, June, and September, respectively (data not shown). The combined NH_3 emissions from the pens and storage pond ranged from a low of 26 kg d⁻¹ in January to a high of 176 kg d⁻¹ in March, and translates to 0.04, 0.25, 0.19, and 0.15 kg NH_3 cow⁻¹ d⁻¹ for January, March, June, and September, respectively (table 4). Assuming this limited moni-
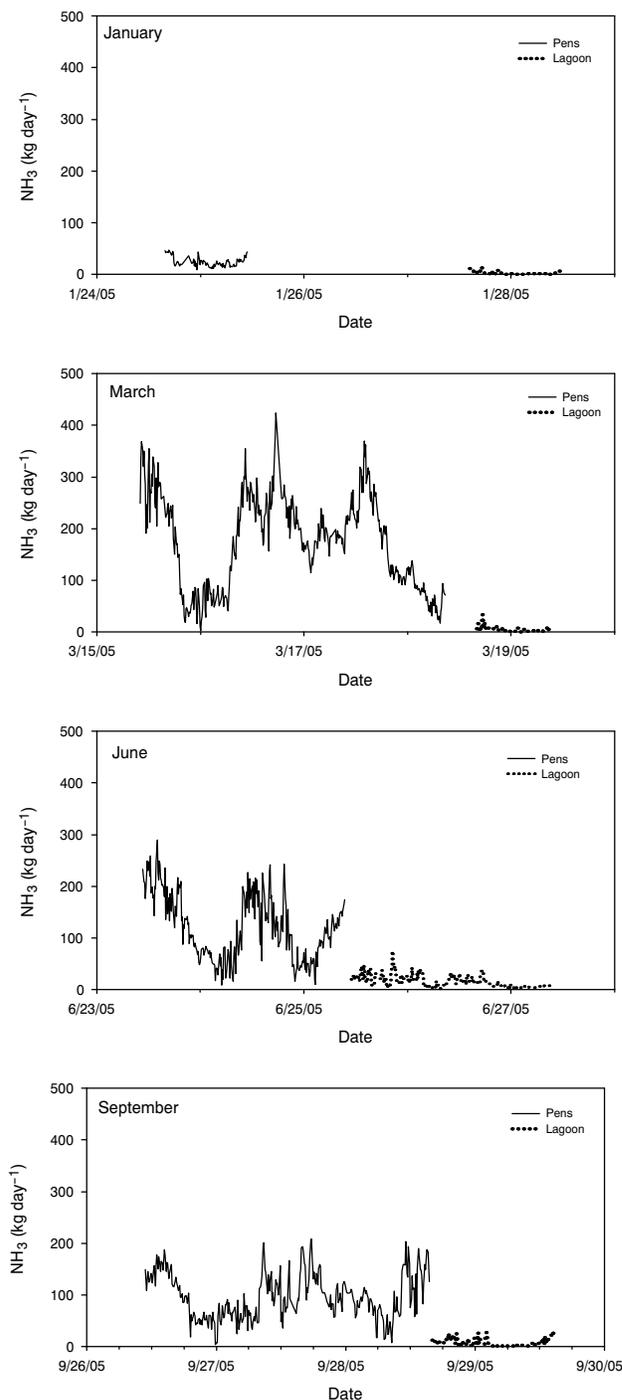

Figure 2. Average ammonia emission rates for the pens and wastewater storage pond for January, March, June, and September 2005.

toring was representative of the entire year, annual NH_3 emissions from the pens and storage pond were 57 kg cow⁻¹.

Methane emission rates from the pens were variable and ranged from nearly zero to approximately 650 kg CH_4 d⁻¹ (fig. 3). The average CH_4 emissions from the pens for January, March, June, and September were 227, 371, 116, and 117 kg CH_4 d⁻¹ (table 4). Methane emissions from the storage pond ranged from near zero to approximately 250 kg CH_4 d⁻¹. The average CH_4 emissions from the storage pond for January, March, June, and September were 13, 12, 32, and 20 kg CH_4 d⁻¹, which were less than for the pens because of the
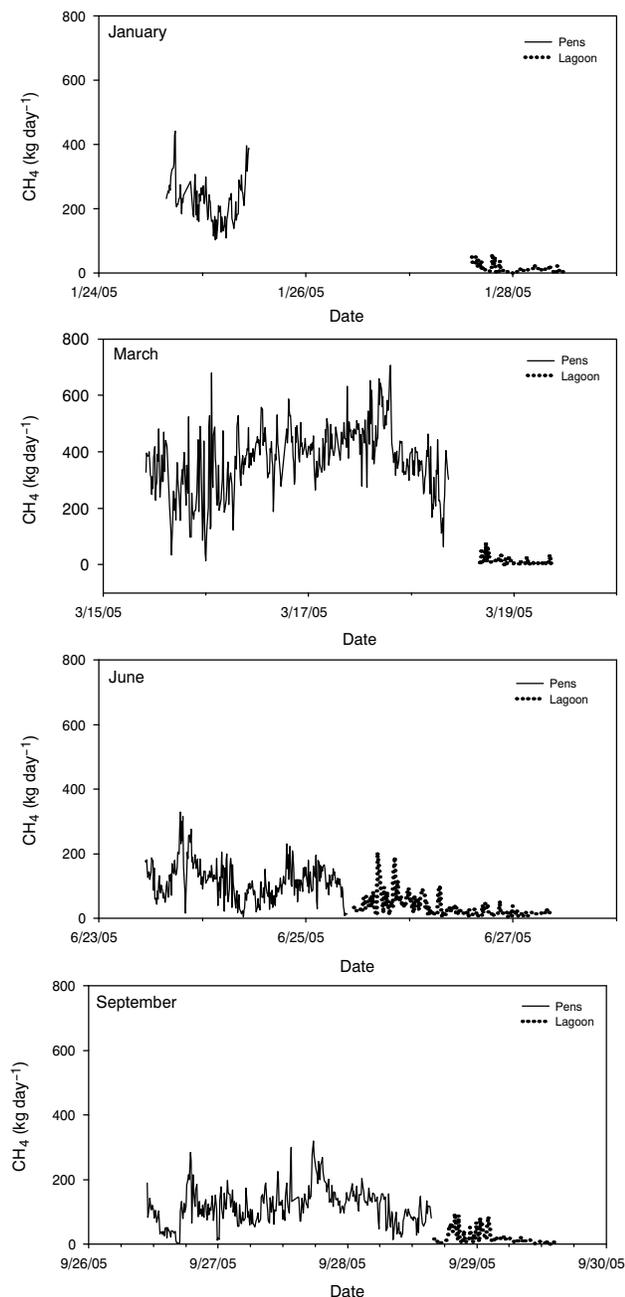
Figure 3. Average methane emission rates for the pens and wastewater storage pond for January, March, June, and September 2005.

Table 4. WindTrax calculated emission rates of methane and ammonia from the pen areas and wastewater storage pond.

Location	Average Emission Rate (kg d⁻¹)			
	January	March	June	September
Ammonia				
Pens	24	172	120	97
Storage pond	2	4	16	7
Total	26	176	136	104
Total per cow[a]	0.04	0.25	0.19	0.15
Methane				
Pens	227	371	116	117
Storage pond	13	12	32	20
Total	240	383	148	137
Total per cow	0.34	0.55	0.21	0.20

[a] Assumed 700 cows to calculate total emission rate per cow.

smaller area of the storage pond. On an area basis, however, methane emissions were 51, 83, 26, and 26 kg ha⁻¹ d⁻¹ for the pens and 16, 15, 41, and 25 kg ha⁻¹ d⁻¹ for the storage pond for January, March, June, and September, respectively. The combined CH_4 emissions from the pens and storage pond ranged from a low of 148 kg d⁻¹ in June to 383 kg d⁻¹ in March, which translates to 0.34, 0.55, 0.21, and 0.20 kg CH_4 cow⁻¹ d⁻¹ for January, March, June, and September, respectively. Estimated annual CH_4 emission from the pens and storage pond were 120 kg per cow.

DISCUSSION

CONCENTRATIONS

The greatest NH_3 concentrations occurred over the pens, followed by the compost area, with the wastewater storage pond having the lowest NH_3 concentrations. Pens likely had higher concentration from the nearly constant supply of NH_3 from urine. Median concentrations measured at all three locations on the farm were lowest during the winter (January) when temperatures were low and the ground was covered in some areas with snow and ice. The low NH_3 concentrations from the compost in June may have resulted from the compost windrows being very dry in the arid climate.

The inverse correlation between wind speed and NH_3 concentration was expected because more air moves over the source area with higher wind speeds, essentially diluting the concentration. The greatest NH_3 concentrations were found at night, when wind speed was low (reduced mechanical turbulence) and the atmosphere was stable (reduced thermal turbulence).

The NH_3 concentrations measured in the present study were similar to other published data. Mount et al. (2002) used differential optical absorption spectroscopy (DOAS) to measure NH_3 concentrations at various locations on a dairy at Washington State University (WSU) and reported NH_3 concentrations of 0.04 to 0.11 ppmv over a slurry lagoon (November). They also reported concentrations of 7 to 11 ppmv NH_3 (July) over a concrete pen that held milking cows, which are considerably greater than the concentrations measured over the pens in June in the present study (table 3). This difference in concentrations could be a combined effect of a greater concentration of cows in the pen at WSU as well as the impermeability of the concrete that kept urine and feces on the surface, preventing its infiltration into and reaction with the soil.

Flesch et al. (2007) measured NH_3 concentrations over a beef cattle feedlot in Texas, which were much closer to the conditions found in an open-lot dairy. They reported NH_3 concentrations in the feedlots of 0.02 to 5.0 ppmv in 2004 and 0.02 to 3.8 ppmv in 2005, which are close to the values measured over the pens in the present study. The maximum concentrations reported by Flesch et al. (2007) were greater than in the present study, probably because of the greater animal density (14 m² per steer vs. 60 m² per milk cow), which would increase the NH_3 source material (urine and feces) per unit area, thereby producing greater NH_3 concentrations.

Methane concentrations from the pens tended to be the greatest followed by the storage pond, with the compost area consistently having the lowest concentrations. Few studies have reported CH_4 concentrations over animal feeding operations using an open-path measurement. Childers et al.

(2001) used OP/FTIR to measure a variety of gases, including CH_4, at a swine production facility and reported a range of CH_4 concentrations from 1.92 to 11.0 ppmv, with most of the areas measured being in the range of 2 to 5 ppmv, which is similar to the results reported in the present study.

Global background N_2O concentrations have been reported to be approximately 0.31 to 0.32 ppmv (Childers et al., 2001). In the present study, the median concentrations of N_2O measured at all sites were very close to the global background concentration, only ranging from 0.31 to 0.34 ppmv, and therefore there was little effect of wind speed, source area, or time of year on N_2O concentrations. Childers et al. (2001) measured N_2O concentrations from a variety of locations on a swine production facility and reported concentrations that ranged from 0.30 to 0.33 ppmv, which are very close to the values found in the present study.

Emission Rates

Average emission rates of both NH_3 and CH_4 were greater from the cattle pens than the storage pond, as both animal activity and greater area of the pens provided a greater source for emissions. There did not appear to be a discernable diurnal patter of CH_4 emissions during the monitoring periods (fig. 3). The CH_4 emission rates ranged from 0.20 to 0.55 kg CH_4 cow^{-1} d^{-1} over the four seasons, with an average of 0.33 kg CH_4 cow^{-1} d^{-1}. Laubach and Kelliher (2005) reported a similar emission rate of 0.40 kg CH_4 cow^{-1} d^{-1} from dairy cows in a confined paddock during the months of January, March, and October.

Ammonia emissions from the pens varied throughout the four seasons, with a low of 24 kg d^{-1} in January and a high of 172 kg d^{-1} in March (table 4). The lower NH_3 emissions in January would be expected, as the temperatures were low and the ground was frozen. During March, the pen area was wet due to melting snow and rain, and wind speeds during pen measurements were more than twice that of the other months (table 2), all of which contributed to a greater mass of NH_3 emitted from the pens.

There was a distinctive diurnal pattern in NH_3 emissions, with emission rates being lowest near midnight and then increasing throughout the day (fig. 2). Flesch et al. (2007) reported the same diurnal pattern of NH_3 emissions from a beef feedlot. This diurnal effect on NH_3 emissions was most likely caused by a combination of animal activity and wind speed. Animal activity was lower during the night and early morning, and then increased near sunrise when animals were fed and there were more animals eating, drinking, and excreting nitrogen (urine and feces). Wind speeds tended to be lower in the morning and then increase over the course of the day, with a maximum typically between 18:00 and 20:00, which caused greater NH_3 losses over the course of the day.

Ammonia losses on a per cow basis ranged from 0.04 to 0.25 kg NH_3 cow^{-1} d^{-1} (table 4). Flesch et al. (2007) reported emission rates of 0.149 kg NH_3 cow^{-1} d^{-1} during the summer and 0.151 kg NH_3 cow^{-1} d^{-1} during the spring on a Texas beef feedlot, which are similar to our June value of 0.19 kg NH_3 cow^{-1} d^{-1} but less than our March value of 0.25 kg NH_3 cow^{-1} d^{-1} (table 4). Hutchinson et al. (1982) reported emission rates of 0.02 to 0.08 kg NH_3 cow^{-1} d^{-1} during the months of April to July. The lower emission rate occurred during a cold period where there was recent snowfall, similar to our value of 0.04 kg NH_3 cow^{-1} d^{-1} during January (table 4). The highest emission rate reported by Hutchinson et al. (1982) occurred when the lots had been wet and were drying rapidly. Although temperatures were not necessarily high in March (table 2), the lots had been wet and the high wind speed tended to dry the surface quickly, which would create an environment favorable for increased NH_3 volatilization.

Ammonia emissions calculated for two dairies in California were similar to the present study. Average emission rates at a free-stall dairy were estimated at 0.05 kg NH_3 cow^{-1} d^{-1} based on seven, 1 to 4 h measurement periods in February (Cassel et al., 2005a). Average emission rates at a combination open-lot/free-stall dairy were 0.10 kg NH_3 cow^{-1} d^{-1} based on five measurement periods on one day in March (Cassel et al., 2005b).

Mukhtar et al. (2008) measured NH_3 emission rates of 11.6 kg cow^{-1} year^{-1} in summer and 6.2 kg cow^{-1} year^{-1} in winter, with an estimated annual emission rate of 9.2 kg NH_3 cow^{-1} year^{-1} (0.25 kg NH_3 cow^{-1} d^{-1}), at a Texas open-lot dairy. Their estimated annual rate matches the highest rate calculated in this study (table 4). However, the emission rates measured by Mukhtar et al. (2008) represent conditions inside a 40 cm diameter flux chamber with spherical top, not the actual air flowing over a dairy.

Summary

Ammonia, methane, and nitrous oxide concentrations were measured with an open-path FTIR on a 700 cow, open-lot dairy in southern Idaho for one to two days during January, March, June, and September 2005. Measured nitrous oxide concentrations varied little among locations and seasons. Average NH_3 concentrations for each monitoring period were two to three times greater for the cattle pens than the storage pond. Ammonia emission rates calculated with the WindTrax model were also greater from the pens than the storage pond on an area basis. Combined NH_3 emissions from the pens and storage pond ranged from 26 kg d^{-1} in January to 176 kg d^{-1} in March, which translates to 0.04, 0.25, 0.19, and 0.15 kg NH_3 cow^{-1} d^{-1} for January, March, June, and September, respectively. Average methane concentrations and emission rates on an area basis were not consistently greater from the pens than from the storage pond. Combined CH_4 emissions from the pens and storage pond ranged from 148 kg d^{-1} in June to 383 kg d^{-1} in March, which translates to 0.34, 0.55, 0.21, and 0.20 kg CH_4 cow^{-1} d^{-1} for January, March, June, and September, respectively. This limited monitoring indicated that annual emissions from the pens and storage pond at this dairy operation were 57 kg NH_3 per cow and 120 kg CH_4 per cow. However, these annual emission rates were calculated from only 13 days of monitoring for the entire year. More extensive monitoring should be conducted to better quantify emissions throughout the year.

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