Greenhouse Gas and Ammonia Emissions from an Open-Freestall Dairy in Southern Idaho

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Concentrated dairy operations emit trace gases such as ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O) to the atmosphere. The implementation of air quality regulations in livestock-producing states increases the need for accurate on-farm determination of emission rates. Our objective was to determine the emission rates of NH_3, CH_4, and N_2O from the open-freestall and wastewater pond source areas on a commercial dairy in southern Idaho using a flush system with anaerobic digestion. Gas concentrations and wind statistics were measured and used with an inverse dispersion model to calculate emission rates. Average emissions per cow per day from the open-freestall source area were 0.08 kg NH_3, 0.41 kg CH_4, and 0.02 kg N_2O. Average emissions from the wastewater ponds (g m^{-2} d^{-1}) were 6.8 NH_3, 22 CH_4, and 0.2 N_2O. The combined emissions on a per cow per day basis from the open-freestall and wastewater pond areas averaged 0.20 kg NH_3 and 0.75 kg CH_4. Combined N_2O emissions were not calculated due to limited available data. The wastewater ponds were the greatest source of total farm NH_3 emissions (67%) in spring and summer. The emissions of CH_4 were approximately equal from the two source areas in spring and summer. During the late fall and winter months, the open-freestall area constituted the greatest source area of NH_3 and CH_4 emissions. Data from this study can be used to develop trace gas emissions factors from open-freestall dairies in southern Idaho and other open-freestall production systems in similar climatic regions.

The environmental impact of large-scale animal production has garnered much interest in the past few decades. Concerns over concentrated animal production and its impact on water quality, air quality, and potential pathogen drift have generated lawsuits, reporting requirements, mandatory management plans, and regulations. For example, under the Emergency Planning and Community Right to Know Act, large production facilities are required to report air emissions if the estimated daily ammonia (NH_3) emission rate exceeds 45 kg d^{-1} (USEPA, 2009b). Under the Clean Air Act (CAA), a rule has been filed requiring reporting of greenhouse gas (GHG) emissions from manure management systems that produce >25,000 metric tons of carbon dioxide equivalents (CO_2e) per year (USEPA, 2009a). However, implementation of this rule has not taken effect because funding has not been provided by congress.

One area that has gained attention in the past several years is the link between GHG emissions and climate change. The gases of greatest concern, relative to animal production, are methane (CH_4) and nitrous oxide (N_2O), whereas NH_3 is considered a secondary source of GHG because its redeposition in the landscape can lead to emissions of N_2O (IPCC, 2006). Additionally, in the atmosphere, NH_3 primarily reacts to form ammonium sulfate and ammonium nitrate aerosols, which contribute to $PM_{2.5}$ (particulates with an aerodynamic diameter of 2.5 μm) formation. The emissions of $PM_{2.5}$ are regulated as part of the USEPA National Ambient Air Quality Standards because they are considered to be a human health concern. Because NH_3 is highly correlated with $PM_{2.5}$ formation, it is anticipated that NH_3 emissions from confined animal feeding operations in the United States may be regulated in the near future. It is estimated that >70% of the total NH_3 emissions in the United States are from the livestock sector (USEPA, 2004), whereas 3.3% of total CO_2e is from enteric CH_4 production and manure management (combined CH_4 and N_2O emissions) (USEPA, 2011). Enteric CH_4 production and manure management account for 32% of the total agricultural sources of GHG emissions (USDA, 2008), making cattle production a target for emissions reductions. The implementation of air quality regulations in livestock-producing states increases the need for accurate on-farm determination

J. Environ. Qual. 42:10–20 (2013)
doi:10.2134/jeq2012.0106
Received 9 Mar. 2012.
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USDA–ARS, Northwest Irrigation and Soils Research Lab., 3793N 3600 E, Kimberly, ID 83341. Assigned to Associate Editor Jan Willem van Groenigen.

Abbreviations: CAA, Clean Air Act; CO_2e, carbon dioxide equivalent; DMI, dry matter intake; FGM, photoacoustic field gas monitor; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; MOST, Monin-Obukhov similarity theory; OP/FT-IR, open-path Fourier transform infrared spectrometry.

of emission rates that reflect the range of animal production facilities and climatic conditions that exist in the United States.

In 2010, Idaho was the third-largest milk and cheese producer in the United States. Milk production is the number one agricultural sector for farm gate receipts (33% of total) in Idaho (USDA NASS, 2012; Eborn et al., 2011). In 2009, there were 529,366 milking cows in Idaho, with 71% of these being located in the Magic Valley region of southern Idaho (UDI, 2011). Dairy production in the state is dominated by concentrated feeding operations, with 55% of the milk cows on the 7% of dairy farms that milk more than 2500 cows (USDA NASS, 2012). Because this region is semiarid, cattle housing differs from many other regions of the country and, in Idaho, is split between (i) open-lot, (ii) freestall, and (iii) open-freestall systems. An open-freestall system is a combination of large, naturally ventilated freestall barns with adjacent open lots that the cattle have free access to for the majority of the year. This housing system is also common in other semiarid to arid western dairy producing states.

There is limited on-farm emissions data from dairy production facilities that cover the range of trace gases that are important from a regulatory and environmental standpoint. In particular, there is a lack of information from dairy cattle production systems typical of the semiarid western region that captures the diurnal and seasonal variation in emissions. One reason for this paucity of data is the methodological complexity of measuring emissions from open source area and naturally ventilated barns and the expense of the equipment associated with these measurements. Two studies examined the seasonal emissions of NH_3, CH_4, and N_2O from open-lot dairies (housing and manure storage) in southern Idaho using inverse dispersion modeling (Bjorneberg et al., 2009; Leytem et al., 2011). One study examined emissions for 5 d in the winter and summer from an open-lot dairy in Texas (housing, lagoons, and solid separators) using a chamber method (Mukhtar et al., 2008). Cassel et al. (2005) measured emissions using an integrated horizontal flux method for 1 wk in February from two open-freestall dairies in California, and Rumburg et al. (2008) measured emissions from a freestall dairy in Washington during the summer. One additional study reported CH_4 emissions from a dairy wastewater lagoon at an open-lot dairy in New Mexico for 8 d in August (Todd et al., 2011).

Other related work has been the measurement of GHGs from dairy cattle in chambers in California (Sun et al., 2008; Hamilton et al., 2010); NH_3 emissions from Wisconsin dairy farms (Flesch et al., 2009) and overseas (Pereira et al., 2010; Schrade et al., 2012); and NH_3 and CH_4 emissions from dairy barns in the eastern United States (Li et al., 2009; Adviento-Borbe et al., 2010), Canada (Kinsman et al., 1995; Bluteau et al., 2009), and overseas (Ngwabie et al., 2009; Ngwabie et al., 2011; Samer et al., 2011). Although some of these studies have reported seasonal variations in emissions, there is a lack of comprehensive datasets that determine the emissions of NH_3, CH_4, and N_2O over time to determine how management practices may affect the ratios of the gases produced in the housing and manure management sectors of the production facility. Therefore, the objective of this study was to determine the emission rates of NH_3, CH_4, and N_2O over time from two source areas (i.e., open-freestalls and wastewater ponds) on a large, open-freestall dairy in southern Idaho.

Materials and Methods

Study Farm

The dairy used in this study was a commercial dairy in a rural location in southern Idaho with 10,000 milking cows and a stocking density of approximately 26 m^2 cow^{-1} (Fig. 1). The milking cows consisted primarily of mature Holsteins with an average bodyweight of 635 kg. This dairy was similar in configuration to most open-freestall production facilities in southern Idaho. The operation consisted of six barns (four barns measuring 672 m in length and two barns measuring 336 m in length), exercise lots adjacent to each barn that the cows moved freely in and out of, four open lots to the south that housed dry cows, two milking parlors, a manure solid separator, an anaerobic digester, and three (2009) to five (2010–2011) wastewater storage ponds. In 2009, there were three wastewater ponds to the north of the open-freestall area, and in 2010, two additional wastewater ponds were added to the north of the three original ponds. The upper half of the barn walls were curtains that opened and closed depending on air temperature in the barn. The peak of the barn was open to allow for natural air exchange and was approximately 10 m above the feed alley. The barns were equipped with a loose housing system and had one main feed alley down the center of the barn with feed bunks down the length of the alley. There was a set of stalls behind the feed bunks on each side that the cows had free access to. The stalls were bedded with separated solids (a combination of sand and organic matter recovered from the solid separator that treated the wastewater before digestion). The concrete alleys behind the stalls were flushed with recycled water two or three times a day.

There were 10,000 (±5%) cows within the main barns and exercise areas at any given time. An additional 2000 (±5%) dry cows were housed to the south of the main barn area in open-lot pens. The open-lot pens and exercise lots adjacent to the barns were harrowed daily when dry. Wash water from the milking parlor and flush water from the barns went through a series of concrete settling basins, after which some water went directly to the wastewater ponds and the remainder went through further separation with a belt press with the separated liquid flowing into a plug flow anaerobic digester. Effluent from the digester was retained in the wastewater ponds along with undigested effluent; there was gravity flow between the ponds. At any given time, it was estimated that 50 to 70% of the liquid on farm went through the anaerobic digester. Effluent from the ponds was mixed with irrigation water and applied to the surrounding fields during the growing season. The separated solids were dried on a concrete pad and reused as bedding. Solid manure from the pens was land applied in the spring and fall to nearby fields. The facility was isolated on the landscape and was surrounded by irrigated crop land on four sides with a prevailing wind from the west. The nearest dairy to the west of the study location was 3 km due west, and the nearest dairy to the east of the study location was 6 km southeast.

The milking cows were fed a total mixed ration based on alfalfa (concentrates added to meet dietary requirements of energy, protein, and minerals), with a protein content of 17.6% and a target dry matter intake (DMI) of 24 kg cow^{-1} d^{-1}. Based on DMI and the protein content of the ration, this equates to a dietary nitrogen (N) intake of 0.7 kg N cow^{-1} d^{-1}. The average milk production for the herd was 34 kg milk cow^{-1} d^{-1}.

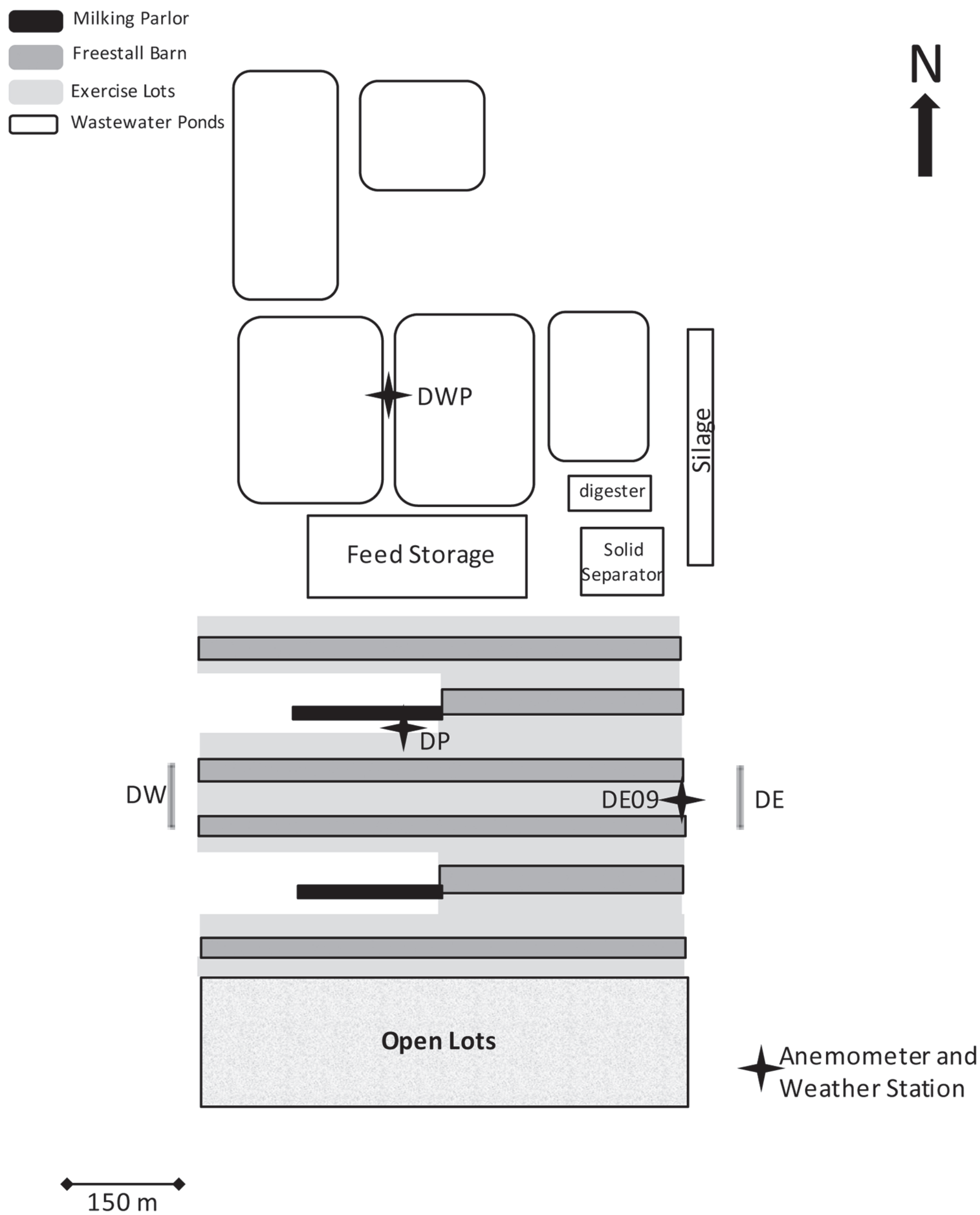

Fig. 1. A schematic of the open-freestall dairy including the locations of monitoring equipment and buildings. The gas concentration sampling points are denoted as follows: DE, dairy east location for 2010–2011; DE09, dairy east location for 2009; DP, dairy parlor; DW, dairy west location for 2010–2011; DWP, dairy wastewater ponds. Feed storage, silage storage, manure solid separator, and the anaerobic digester are also indicated.

Field Measurements

Our primary objective was to estimate the emissions of NH_3, CH_4, and N_2O from the open-freestall area and wastewater ponds. Figure 1 illustrates the farm layout with sensor placement and farm structures. The six barns as well as the adjacent exercise areas and two milking parlors were included in the "open-freestall" source area. The three (2009) to five (2010–2011) wastewater ponds were included in the "wastewater pond" source area. Measurements took place at the open-freestall source area from June to July of 2009 and from May 2010 to April 2011 (data were not acquired in February 2011). Measurements at the wastewater ponds occurred from August to October 2009 and from May 2010 to January 2011 (data were not acquired in July 2010).

Concentration Measurements

The concentrations of NH_3, CH_4, and N_2O were measured using four INNOVA 1412 photoacoustic field gas monitors (FGMs) (LumaSense Technologies) from June 2009 through September 2010 (open-freestall area) or November 2010 (wastewater pond area). Concentrations were measured continuously using a 5-s integration time and automatic flushing, providing a concentration measurement every 1 min. Because the operating temperature range of the FGM is 5 to 40°C, this equipment was not used from December 2010 to April 2011. Monitors were calibrated and then checked using standard gasses according to the manufacturer's instructions (LumaSense Technologies, 2007) each month before field deployment, and the detection limits of the gases were as follows: NH_3, 0.1 ppm; CH_4, 0.4 ppm; and N_2O, 0.03 ppm. The measured gas concentrations were normalized to 20°C and 101 kPa and were compensated for water and cross interferences. In June 2010, a problem developed with the N_2O calibration that was not resolved until October 2010; consequently, N_2O measurements are not reported from June to October. Measurements were made with the FGMs in 2009 at the eastern edge of the exercise lots located between the two central barns (DE09, 6 m height) and at a central location between the two westernmost wastewater ponds (DWP, 3 m height). In 2010 to 2011, FGMs were located 75 m east of the barns at the edge of the irrigated field and between the two long central barns (DE, 2 m height), at the edge of the exercise lot to the south of the north-most milking parlor (DP, 6 m height), and at the same location at the wastewater ponds (DWP) that was used in 2009. From 2009 to 2011, one FGM was located 800 m due south of the dairy to measure background concentrations (2 m height).

From October 2010 to April 2011, gas concentrations were measured using open-path Fourier transform infrared spectroscopy (OP/FT-IR). This equipment had previously been used to measure NH_3 and GHG concentrations on an open-lot dairy (Bjorneberg et al., 2009). One OP/FT-IR (Air Sentry, Cerex Monitoring Solutions) was located 75 m east of the barns between the two longest barns at the edge of the irrigated field (DE), and an additional OP/FT-IR unit (ABB-Bomem MB-100, MDA) was located 40 m west of the barns between the two longest barns (DW); the sensor height was at 2 m for both instruments. At the wastewater ponds, one of the OP/FT-IR units (Air Sentry) was placed between the two southwest ponds with a sensor height of 2 m. Spectra were collected over a 150-m pathlength (75 m between the telescope and retroreflector) at the open freestall area and a 110.5-m pathlength (55.25 m between the telescope and retroreflector) at the wastewater ponds with spectra acquired continuously and averaged at intervals of 5 min.

Background concentrations of NH_3, CH_4, and N_2O were measured at a location approximately 26 km south of the facility where there were no known sources of the these gasses. These concentrations were checked against the OP/FT-IR measurements made at the DE and DW locations when the wind was from the east or west, respectively, to ensure there was no variation between gas concentrations in the vicinity of the dairy and the background measurement location. There were no other source areas near the dairy that could have affected measured on-farm concentrations. Quantitative determinations of NH_3, CH_4, and N_2O concentrations were performed by partial least squares regression of the OP/FT-IR spectra (Shao et al., 2010; Griffiths et al., 2009), and the detection limits of the gases were as follows: NH_3, 0.001 ppm; CH_4, 0.002 ppm; and N_2O, 0.001 ppm at the open freestall area (150 m pathlength) and NH_3, 0.002 ppm; CH_4, 0.003 ppm; and N_2O, 0.002 ppm at the wastewater ponds (110.5 m pathlength).

Concentration data for the FGM and OP/FT-IRs were processed to produce 15-min average mixing-ratio concentrations (ppm_v) at the source areas (C) and background (C_b) location for the FGM measurements. The wind environment at the dairy was described by simple Monin-Obukhov similarity theory (MOST) relationships defined by u^*, L, z_0, and β, as provided by three-dimensional sonic anemometers (RM Young ultrasonic anemometer), where u^* is the friction velocity, L is the Obukhov stability length, z_0 is the surface roughness length, and β is wind direction.

Wind and Weather Measurements

One sonic anemometer was located at the southeast corner of the dairy at 3 m, where there were minimal flow disturbances from structures upwind, to capture a more idealized wind flow of the area, as suggested by Flesch et al. (2005a). The data from this anemometer were used for the open-freestall emissions calculations for DW and DE. Two additional anemometers were located at the DP and DE09 (in 2009) site at a height of 12 m to describe the wind characteristics at these locations. A fourth anemometer was located at the DWP location (3 m height), adjacent to the concentration sensor, for determining emissions from the wastewater ponds. There were no wind disturbance structures for over 100 m before the west-most wastewater pond, and farther upwind there was an irrigated field with silage corn during the growing season and corn stubble after harvest. Wind parameters were calculated for each 15-min period (corresponding to C observations). See Flesch et al. (2004) for details of how these parameters were calculated from a sonic anemometer. A meteorological station was located on the southeastern edge of the dairy that recorded air temperature, wind direction, wind speed, and barometric pressure (all at 2 m) during the experimental period.

Emissions Calculations

We used WindTrax software (Thunder Beach Scientific), which combines the backward Lagrangian stochastic inverse-dispersion technique described by Flesch et al. (2004) with an interface allowing sources and sensors to be conveniently mapped. This technique has been used in several controlled release studies to determine emissions from barn and lagoon source areas and was shown to provide estimates of emissions within 15% of actual emissions (McGinn et al., 2006; Gao et al., 2010; Ro et al., 2012). For a detailed description of the backward Lagrangian stochastic technique, see Flesch et al. (2004, 2005a, 2005b, 2007). The farm was mapped using available satellite imagery and on-farm GPS data. Emission estimates (kg d^{-1}) were calculated using N = 50,000 trajectories and measured background concentrations for the FGM data or fixed background concentrations for the OP/FT-IR data (determined from offsite measurements).

Because good emissions estimates are dependent on using data that do not violate the MOST assumptions (i.e., low winds, extreme stabilities, and wind profile errors), data were filtered using the criteria set forth by Flesch et al. (2005b) as follows: (i) removed periods where $u^* \leq 0.15$ m s^{-1} (low wind conditions), (ii) removed periods where $|L| \leq 10$ m (strongly stable/unstable atmosphere), and (iii) removed periods where $z_0 \geq 1$ m (associated with errors in wind profile).

Due to the location of the concentration sensors and other source areas on the site, for some wind directions, measurements of the downwind concentrations may not sample enough of the farm plume, which can lead to uncertainty in emission estimates (Flesch et al., 2005b). Additionally, there could be cross contamination due to emissions from other source areas on the farm. Therefore, we filtered out data at the DE09, DE, and DWP monitoring locations having a wind direction <240° and >305° and at the DP and DW locations having a wind direction of <60° and >120° to ensure that the concentration sensors were measuring gases from the source areas of interest.

Our goal was to calculate the average daily emissions from each source area during each month of measurement. We assumed that appropriate average rates could be calculated from ensemble-average daily (24 h) emission curves because one needs to capture the diurnal trend in emissions (Leytem et al., 2011). For each month, available data were averaged into 1-h blocks, after which multiples of 24 1-h average values were averaged to determine the daily emissions. This allowed a representative weighting of emissions estimates over a 24-h period.

In May 2010, we had noncontinuous observations at the open-freestall source area due to data filtering and used a "gap-filling" technique to fill in missing data. The emissions data were extrapolated to estimate emissions during missing times of a 24-h period using a regression model based on the ambient u^* and time of day as predictors as done by Flesch et al. (2009). The time of day was represented in the model in 15-min increments starting with time 0 and ending at 24 h. The regression models for NH_3 and CH_4 emissions were significant (α = 0.05), with r^2 values ranging from 0.55 to 0.65; four points were interpolated. Because there was no identifiable diurnal trend in the N_2O data for that month, we used a 12-h average because the data-filling technique was not reliable. In addition, there were three other months (August– October) when only one point was missing. In these instances we filled in the missing point by averaging the two surrounding points. At the wastewater ponds, there was one data point missing for the months of August, September, and January, which was filled in by averaging the two surrounding points. In instances where the background concentration was equal to the measured concentrations, we assigned an emission rate of 0.

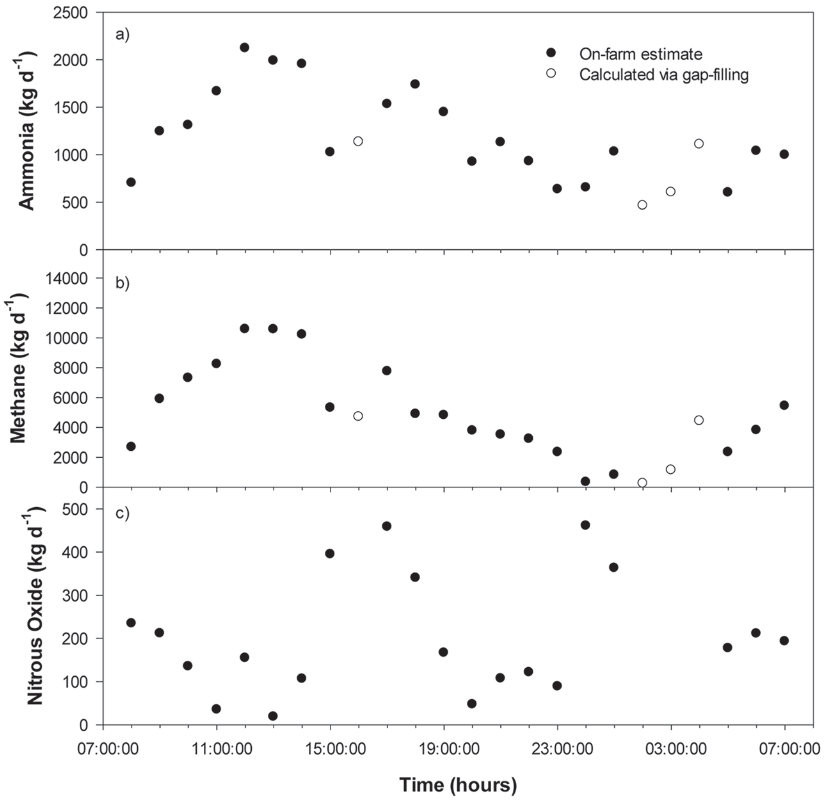

Fig. 2. Hourly averages of on-farm emission rates and calculated emission rates (gap-filling technique) of (a) NH_3, (b) CH_4, and (c) N_2O measured over time from the open-freestall area during May 2010.

Results and Discussion

Emissions from the Open-Freestall Source Area

Diurnal Patterns of Emissions

The on-farm emission estimates and calculated emissions (using the gap-filling technique described above) of NH_3 and CH_4 as well as the on-farm emission estimate of N_2O for May 2010 from the open-freestall source area are presented in Fig. 2. There was a strong diurnal trend in emissions of NH_3 and CH_4, with emissions being lower during late evening and early morning and then increasing throughout the day with maximum rates around 13:00 h. This strong diurnal trend can be associated with wind speed and temperature because winds tend to be light in the late evening and early morning and then, in most instances, steadily increase throughout the day to reach a peak at approximately 15:00 to 16:00 h (data not shown). Temperature also increases from early morning to late afternoon and then decreases again. Additionally, cattle activity tends to increase from morning to late afternoon as animals wake and begin to eat, drink, ruminate, and urinate. As these activities increase, one would also expect an increase in NH_3 and CH_4 emissions to occur.

Leytem et al. (2011) noted the same diurnal patterns in NH_3 and CH_4 emissions from a 10,000 milking cow open-lot dairy in southern Idaho. Ngwabie et al. (2011) also noted diurnal trends in NH_3 and CH_4 from a naturally ventilated dairy barn. They reported that NH_3 emissions had a positive correlation with indoor air temperature and that CH_4 emissions were strongly correlated with the daily relative activity of the cows, which was defined as movement of the cows. Flesch et al. (2009) and Cassel et al. (2005) saw this same diurnal trend in NH_3 emissions from dairy barns. Sun et al. (2008) noted a diurnal trend in CH_4 emissions from dairy cattle with higher rates during the day than during late evening and early morning. Kinsman et al. (1995) reported a sharp increase in CH_4 emissions immediately after the morning feeding that decreased slowly throughout the day and night. Gao et al. (2011) noted this same pattern with peaks in emissions following the feeding schedule. No diurnal trends in N_2O emissions were observed. Because animal activity (e.g., eating or urinating) should not contribute to N_2O emissions and because emissions rates tended to be very low, it is not entirely unexpected to find little trend over time. Ngwabie et al. (2009) also noted near background level concentrations of N_2O with no diurnal variation in a naturally ventilated dairy barn.

Data Completeness

The average emission rates of NH_3, CH_4, and N_2O from the open-freestall area for each monitoring period along with weather data and concentration sensor location used to estimate emissions are presented in Table 1. Although we attempted to obtain data for 13 mo, there were problems with data collection in some months. In November 2010, the space between the barns and the monitoring equipment on the east side of the dairy was used for straw storage. Because we were not sure how the straw may have affected gas concentrations, we decided not to include these data, although emissions estimates were similar to those reported in March 2011, which had a similar temperature (8.2°C in March and 8.8°C in November). In April 2011, the wind direction was predominantly from the south (180°); thus, the majority of the data were filtered out for this time period.

Ammonia Emissions from Housing

Average NH_3 emission rates ranged from 111 to 1389 kg NH_3 d^{-1}, with similar rates during May to October (Table 1). The emissions for June and July in 2009 were within 10% of the emissions for these same months in 2010. In January 2011, when the temperature was colder, the average NH_3 emission rate was smallest at 111 kg NH_3 d^{-1}. Flesch et al. (2009) reported that NH_3 emissions from dairy barns in Wisconsin were similar in summer and fall and decreased to 50% during the winter months, which they attributed to colder temperatures and reduced ventilation rates because the barn curtains were closed to retain heat. Adviento-Borbe et al. (2010) reported that NH_3 emissions from a freestall barn in Pennsylvania decreased by approximately 40% with a 13°C decrease in temperature. The winter emission rates in the current study are lower than expected (10% of summer emissions), which may be a function of the monitoring system. As ambient temperatures decrease, the curtain sides of the barns are raised, which effectively reduces the ventilation rate, thereby increasing the emissions from the roof ridge vents. This reduced ventilation combined with the majority of losses occurring from the roof vent make it more difficult to obtain accurate concentration measurements, and therefore it is likely that during these periods the emissions were underestimated to a certain degree.

On a per-animal basis, NH_3 emission rates in the present study ranged from 0.01 to 0.14 kg NH_3 cow^{-1} d^{-1}. When averaged over the 9 mo in 2010 to 2011, the NH_3 emission rates were 815 kg NH_3 d^{-1} or 0.08 kg NH_3 cow^{-1} d^{-1}. Using a mechanistic model based on on-farm measurements, Rumburg et al. (2008) calculated an average annual emission rate of 0.10 kg NH_3 cow^{-1} d^{-1} from a freestall barn in Washington. Samer et al. (2011) reported an average emission rate of 0.08 kg NH_3 cow^{-1} d^{-1} from a naturally ventilated dairy barn in Germany in the winter. Several studies have reported average NH_3 emissions estimates of 0.007 to 0.09 kg NH_3 cow^{-1} d^{-1} from naturally ventilated freestall barns (Bluteau et al., 2009; Flesch et al., 2009; Ngwabie et al., 2009; Pereira et al., 2010; Ngwabie et al., 2011, Schrade et al., 2012).

It has been shown that dietary N contents have a large influence on NH_3 emissions from dairy cattle (Monteny et al., 2002); therefore, we converted the emission rates into g N lost as NH_3 per kg N intake. In the present study, there was an average of 94 g NH_3–N lost per kg N intake, which compares well with the average of 112 reported by Rumburg et al. (2008) but is greater than the range of 30 to 40 reported by Ngwabie et al. (2009, 2011). Based on this calculation, approximately 9.4% of ingested N was lost as NH_3–N in the present study. Seasonal losses of NH_3–N ranging from 1.5 to 13.7% of feed intake, with an annual average for three farms of 7.6%, were reported by Harper et al. (2009) for naturally ventilated freestall dairy barns in Wisconsin. Pereira et al. (2010) reported average NH_3–N losses of 5.3 to 9.2% of N fed for dairy cattle in naturally ventilated barns with outdoor concrete yards in Portugal.

One factor that could have a large impact on the NH_3 emission rates from the open-freestall source area is the impact of the urine deposition in the exercise areas. Although urine deposited in the barn would be flushed from the barn on a regular basis, urine that is deposited on the soil of the exercise area would be available for NH_3 losses over several days. Because of this, we could expect to see higher emission rates from the exercise areas than from the barns, particularly during seasons when the cattle spend a great deal of time outside (spring, summer, and fall). Emissions of NH_3 from open-lot dairies in southern Idaho have been reported to range from 0.13 to 0.15 kg NH_3 cow^{-1} d^{-1}

Table 1. Average emission rates of ammonia, methane, and nitrous oxide measured from the open-freestall area of a 10,000 milking cow open-freestall dairy along with monitoring location and weather conditions during the monitoring period.

Date	Emissions			Instrument	Location†	Weather conditions		
	NH_3	CH_4	N_2O			Wind speed	Wind direction	Temperature
	kg d^{-1}							
24 June–1 July 2009	920 (607)‡	NA§	NA	Innova 1412	DE09	3.62	234	23.4
13–14 July 2009	1389 (541)	NA	NA	Innova 1412	DE09	3.58	271	18.76
25–27 May 2010	1165 (471)	4758 (3073)	223 (150)¶	Innova 1412	DE	3.38	239	11.9
24–27 June 2010	959 (558)	5870 (3550)	NA	Innova 1412	DE	3.71	275	21.6
2–4 July 2010	1242 (300)	4914 (2693)	NA	Innova 1412	DE	5.38	274	16.1
2–6 Aug. 2010	1035 (524)	2913 (1207)	NA	Innova 1412	DP	3.05	88	23.8
8–10 Sept. 2010	1093 (499)	5305 (3595)	NA	Innova 1412	DE	4.97	253	10.4
5–15 Oct. 2010	1013 (768)	4910 (3698)	253 (395)	OP/FT-IR#	DW	2.00	138	10.8
16–17 Dec. 2010	149 (55)	2455 (710)	373 (76)	OP/FT-IR	DW	3.29	96	−4.90
11–12 Jan. 2011	111 (70)	1831 (1377)	53 (34)	OP/FT-IR	DW	2.78	83	−8.3
28–31 Mar. 2011	570 (262)	3939 (1374)	204 (150)	OP/FT-IR	DE	2.51	260	8.2

† DE, dairy east location for 2010–2011; DE09, dairy east location for 2009; DP, dairy parlor; DW, dairy west location for 2010–2011.

‡ Values in parentheses are SD.

§ NA, no data available.

¶ Twelve-hour average.

Open-path Fourier transform infrared spectrometry.

(Bjorneberg et al., 2009; Leytem et al., 2011), whereas emissions from freestall barns have been reported to range between 0.01 to 0.10 (Rumburg et al., 2008; Bluteau et al., 2009; Flesch et al., 2009; Ngwabie et al., 2011). It is likely that NH_3 emissions at an open-freestall dairy would fall somewhere between the two systems, as did the emissions estimates in the present study.

Methane Emissions from Housing

Average CH_4 emission rates from the open-freestall area ranged from 1831 to 5870 kg CH_4 d^{-1}, with no discernible trends from spring to fall; winter rates were the smallest (Table 1). As with the NH_3 emissions estimates, this decrease in winter emissions may be a result of the raised curtains and underestimate the true CH_4 emissions from the open-freestall source area. The emission rates on a per animal basis ranged from 0.18 to 0.59 kg CH_4 cow^{-1} d^{-1}. When the CH_4 emissions were averaged, rates were 4099 kg CH_4 d^{-1} or 0.41 kg CH_4 cow^{-1} d^{-1}. Average CH_4 emission rates estimated from dairy cattle on open lot dairies in southern Idaho ranged from 0.30 to 0.49 (Bjorneberg et al., 2009; Leytem et al., 2011), with emissions being greater in spring/winter compared with summer/fall. Sun et al. (2008) reported an average of 0.44 kg CH_4 cow^{-1} d^{-1}, whereas Hamilton et al. (2010) reported an average of 0.27 kg CH_4 cow^{-1} d^{-1} for lactating dairy cattle in a chamber. Kinsman et al. (1995) reported an average emissions rate of 0.39 kg CH_4 cow^{-1} d^{-1} for lactating dairy cattle in a tie stall barn, with average emissions decreasing approximately 20% from June to November. Ngwabie et al. (2009, 2011) reported emission rates of 0.31 to 0.33 kg CH_4 cow^{-1} d^{-1} over a 70-d period for dairy cattle in a naturally ventilated freestall barn, with a decrease in the emission rate of approximately 17% from February to May.

In some instances the reported literature values are similar to those found in the present study, and in some instances literature values are lower. Variations in reported emission rates may be due to dietary differences such as forage type, forage quality, and DMI because these factors can influence production of CH_4 in the rumen. Flush water and accumulated manure in the barns may also contribute to greater CH_4 emission rates, although Sun et al. (2008) found that fresh manure contributed <2% to total CH_4 emissions from dairy cattle in chambers. On a DMI basis, the average CH_4 emissions rate in the present study was 17 g CH_4 kg DMI^{-1}, which is similar to ranges reported in the literature for lactating dairy cattle of 16 to 23 g CH_4 kg DMI^{-1} (Kinsman et al., 1995; Sun et al., 2008; Ngwabie et al., 2011, 2009). This highlights the importance of taking DMI into account when comparing on-farm enteric CH_4 emissions.

Nitrous Oxide Emissions from Housing

The N_2O emission rates from the open-freestall over the measurement period ranged from 53 to 373 kg N_2O d^{-1} or 5 g to 37 g N_2O cow^{-1} d^{-1}. There were only 5 mo with reliable N_2O emission estimates due to monitoring equipment problems. However, unlike the NH_3 and CH_4 emission estimates measured in the winter, the N_2O emissions measured in December and January averaged 213 kg N_2O d^{-1}, which was very similar to the range found in other months, suggesting that emissions of N_2O originate largely from the exercise areas and not from the barns. The average N_2O emissions measured over the study period were 221 kg N_2O d^{-1} or 22 g N_2O cow^{-1} d^{-1}. There are little published data reporting emissions of N_2O from cattle or cattle production facilities. Leytem et al. (2011) measured N_2O concentrations on an open-lot dairy and reported an average of 10 g N_2O cow^{-1} d^{-1}. Samer et al. (2011) reported an average emission rate of 45 g N_2O cow^{-1} d^{-1} from a naturally ventilated dairy barn in Germany. Ngwabie et al. (2009) reported near background concentrations of N_2O in a naturally ventilated freestall barn, suggesting that barns with liquid manure systems and frequent manure removal do not constitute a major source of N_2O. The majority of N_2O emissions from production facilities are associated with manure management systems, and, for this reason, there has been little emphasis placed on determining rates from cattle housing. In the present study, we found relatively limited emissions of N_2O from the open-freestall area, further supporting the contention that there may be little concern for N_2O losses from cattle housing.

Emissions from the Wastewater Ponds

Diurnal Patterns of Emissions

The emissions of NH_3, CH_4, and N_2O for May 2010 from the wastewater ponds are shown in Fig. 3. There was a diurnal trend in emissions of NH_3 and CH_4 from the wastewater ponds, with

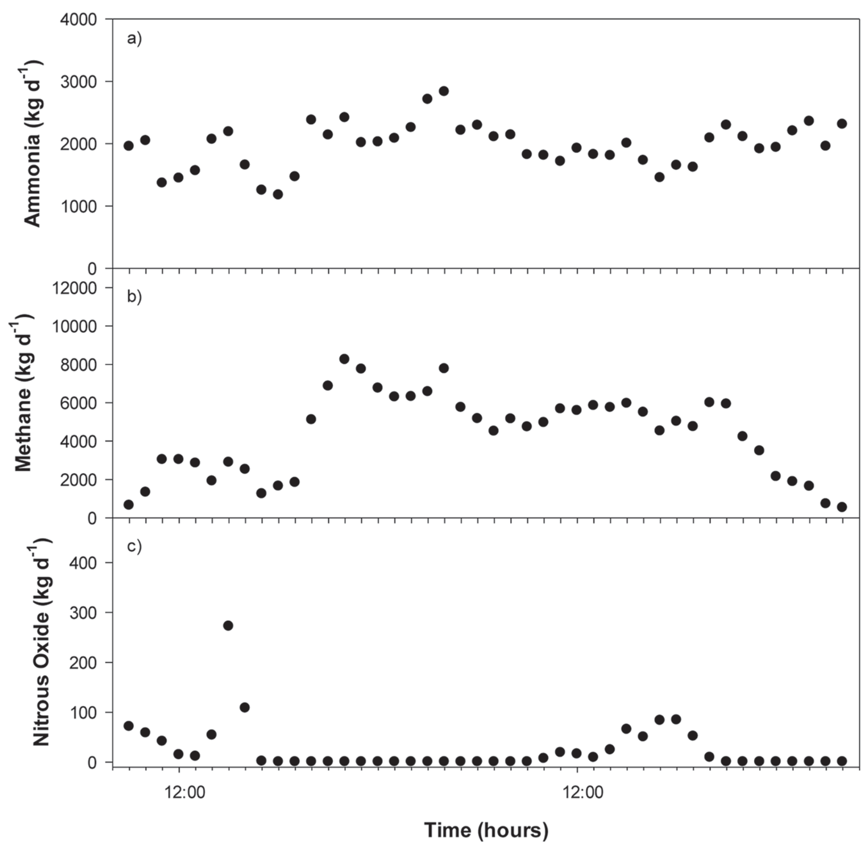

Fig. 3. Hourly averages of on-farm emission rates of (a) NH_3, (b) CH_4, and (c) N_2O measured over time from the wastewater ponds during May 2010.

concentrations being lower in the late evening and early morning and rising throughout the day. Nitrous oxide emissions tended to be low and showed peaks early in the day. Flesch et al. (2009) reported a similar diurnal trend in NH_3 emissions from dairy wastewater ponds. Because emissions are strongly related to temperature and wind speed, the diurnal fluctuations in both of these factors would explain the changes in emission rates because wind speed and temperature increase from early morning to late afternoon. The average emission rates of NH_3, CH_4, and N_2O from the wastewater pond for each monitoring period along with weather conditions are presented in Table 2.

Ammonia Emissions from Wastewater

Ammonia emissions ranged from 96 to 2464 kg NH_3 d^{-1}, with an average of 1292 kg NH_3 d^{-1} over the 2010 to 2011 study period. On an area basis, the emission rates ranged from 0.6 to 13.7 g NH_3 m^{-2} d^{-1}, with an average of 6.8 g NH_3 m^{-2} d^{-1} over the 2010 to 2011 study period. There was a linear increase in average monthly NH_3 emissions with increasing temperature ($r^2 = 0.92$). Bjorneberg et al. (2009) reported wastewater pond emission rates ranging from 0.25 to 2.0 g NH_3 m^{-2} d^{-1} on an open-lot dairy in Idaho, with an average of 0.91 g NH_3 m^{-2} d^{-1} over four seasons. The Bjorneberg et al. (2009) data also show a positive linear increase in NH_3 emissions with increasing seasonal temperatures ($r^2 = 0.96$). Leytem et al. (2011) reported NH_3 emissions ranging from 1.6 to 2.2 g NH_3 m^{-2} d^{-1} with an average of 2.0 g NH_3 m^{-2} d^{-1} over the course of a year from wastewater ponds on an open-lot dairy in Idaho, whereas Flesch et al. (2009) reported emissions of 2.3 and 3.5 g NH_3 m^{-2} d^{-1} from dairy lagoons in Wisconsin receiving parlor-wash water.

The average NH_3 emissions reported in the present study were 3.5 to 9 times greater than the averages found at the two open-lot dairies in the same region (Bjorneberg et al., 2009; Leytem et al., 2011). The increase in NH_3 emissions at this facility is likely a combination of two factors. First, a large percentage of the urine deposited in the housing area is transferred to the wastewater system via flushing, which leaves a greater source in the wastewater available for NH_3 losses compared with the open-lot system where urine is deposited on the lots and remains there. Second, the anaerobic digester affects NH_3 emissions as the digestion process converts organic N compounds to total ammoniacal N, which can then be lost as NH_3 in the storage ponds (Rotz and Hafner, 2011). Harper et al. (2010) reported that swine farms with biofuel production via manure digestion had 46% greater NH_3 emissions than farms where no biofuel production occurred. Although anaerobic digestion is potentially useful for reducing CH_4 emissions from wastewater ponds, the process can enhance NH_3 emissions unless additional measures are taken to remove N from the waste stream.

Methane Emissions from Wastewater

Methane emission rates from the wastewater ponds ranged from 471 to 8281 kg CH_4 d^{-1} or 3.6 to 54.1 g CH_4 m^{-2} d^{-1} (Table 2). As temperatures increased, emissions increased, reaching a peak in August. In fact, there was a linear increase in average monthly CH_4 emissions with increasing temperature ($r^2 = 0.87$, omitting June 2010 emission estimate). In the present study, the June CH_4 emissions were only 8.13 g CH_4 m^{-2} d^{-1}, which did not follow the trend seen in the other months. We were unable to ascertain why the emission rates were so low during this period. This same seasonal trend in CH_4 emissions was seen at the wastewater ponds of two open-lot dairies in the same region, with CH_4 emission rates reaching peaks in summer or fall (Bjorneberg et al., 2009; Leytem et al., 2011). Khan et al. (1997) reported a 25-fold increase in emissions from a dairy slurry pond from May (0.37 g CH_4 m^{-2} d^{-1}) to August (9.4 g CH_4 m^{-2} d^{-1}), which was associated with increasing temperatures. The average CH_4 emission rates over the 2010 to 2011 study period were 3609 kg CH_4 d^{-1} or 22 g CH_4 m^{-2} d^{-1}.

The emissions of CH_4 from a wastewater pond system vary and are dependent on the wastewater pond liquid characteristics and weather conditions. It has been shown that CH_4 emissions are related to the volatile solids content of the wastewater pond liquid and that emission rates increase with increasing temperature. Consequently, CH_4 conversion factors are calculated based on these two factors in combination with a value representing the maximum CH_4–producing capacity for that manure (IPCC, 2006). As a result, it is difficult to

Table 2. Average emission rates of ammonia, methane, and nitrous oxide measured from the wastewater ponds of a 10,000 milking cow open-freestall dairy along with instrumentation used, weather conditions, and pond area.

Date	Emissions			Instrument	Weather conditions			Area
	NH_3	CH_4	N_2O		Wind speed	Wind direction	Temperature	
	kg d^{-1}				m s^{-1}	degrees	°C	ha
27–28 Aug. 2009	1389 (736)†	4364 (2341)	103 (68)	Innova 1412	3.57	91	23.42	11.1
29 Sept.–1 Oct. 2009	746 (191)	2969 (2025)	108 (45)	Innova 1412	8.27	244	10.0	10.8
26–27 Oct. 2009	376 (78)	471 (784)	64 (39)	Innova 1412	12.24	266	2.64	10.6
17–21 May 2010	1788 (389)	4744 (2666)	61 (134)	Innova 1412	4.37	267	13.2	18.0
18–22 June 2010	2464 (434)	1467 (1224)	NA‡	Innova 1412	4.61	273	16.1	18.0
10–12 Aug. 2010	2013 (587)	8281 (1616)	NA	Innova 1412	4.17	251	19.7	15.3
8–10 Sept. 2010	1202 (1147)	5018 (4895)	NA	Innova 1412	4.97	244	10.4	16.4
9–10 Nov. 2010	311 (71)§	603 (122)§	4.9 (7)§	Innova 1412	2.5	267	1.8	16.4
13–16 Dec. 2010	190 (110)	1546 (986)	40 (35)	OP/FT-IR¶	2.39	252	−5.2	16.4
18–20 Jan. 2011	96 (61)	598 (506)	11 (11)	OP/FT-IR	8.67	257	−1.4	16.4

† Values in parentheses are SD.

‡ No data available.

§ Twelve-hour average.

¶ Open-path Fourier transform infrared spectrometry.

compare wastewater pond emission rates because systems vary in solids content and temperature, which can greatly influence CH_4 generation. Average CH_4 emission rates from wastewater ponds of open-lot dairies in southern Idaho ranged from 2.4 to 103 g CH_4 m^{-2} d^{-1} (Bjorneberg et al., 2009; Leytem et al., 2011). Todd et al. (2011) reported an emission rate of 40 g CH_4 m^{-2} d^{-1} for a wastewater pond receiving flush water from an open-lot dairy in New Mexico during August, which is similar to the emission rate found for the same month in the present study (54 g CH_4 m^{-2} d^{-1}).

Nitrous Oxide Emissions from Wastewater

Nitrous oxide emission rates from the wastewater pond tended to be low, ranging from 5 to 108 kg N_2O d^{-1} or 0.03 to 0.92 g N_2O m^{-2} d^{-1}. The N_2O emission rates were positively correlated with temperature ($r^2 = 0.49$), although not as strongly as emissions of NH_3 and CH_4. The N_2O emission rate was 37 kg N_2O d^{-1} or 0.22 g N_2O m^{-2} d^{-1} when averaged over the 2010 to 2011 study period. Sommer et al. (2000) reported N_2O emission rates from covered (fermented and nonfermented) cattle slurry ranging from 0 to 0.94 g N_2O m^{-2} d^{-1}. Leytem et al. (2011) reported N_2O emissions from a wastewater pond on an open-lot dairy in southern Idaho ranging from 0.12 to 0.85 g N_2O m^{-2} d^{-1}, similar to the rates in the present study.

Total Estimated Farm Emissions

The combined emission rates of NH_3 and CH_4 from the open-freestall and wastewater pond source areas for the four seasons are shown in Table 3. We did not calculate seasonal N_2O emissions due to the limited available data at the open-freestall source area. When the seasonal data were averaged, the emission rates of NH_3 and CH_4 were 2014 and 7519 kg d^{-1}, respectively. This translates to a rate of 0.20 and 0.75 kg cow^{-1} d^{-1} or 0.006 and 0.022 kg milk^{-1} d^{-1} for emissions of NH_3 and CH_4, respectively, assuming 34 kg milk cow^{-1} d^{-1}. The wastewater ponds made the greatest contribution to NH_3 emissions (67% of the total farm emissions) during the spring and summer seasons (Fig. 4). This decreased to 42% in the fall and 52% during the winter. We would have expected the open-freestall source area to have the largest emissions of NH_3 in late fall and winter due to cold temperatures and freezing of the wastewater pond surfaces during some time periods. Flesch et al. (2009) reported that NH_3 emissions from lagoons on naturally ventilated freestall dairies were between 37 and 63% of total farm emissions in the summer and fall.

Our findings in this report are in contrast to the work performed on open-lot dairies in southern Idaho (Bjorneberg et al., 2009; Leytem et al., 2011). At the open-lot dairies, the greatest source area of NH_3 was the lot area, where the majority of urine was deposited and available for volatilization. In the case of the open-freestall dairy, however, a large percentage of urine would be deposited in the barns and flushed to the wastewater pond system. In addition, the anaerobic digestion of the slurry would result in higher NH_4^+ concentrations in the digester effluent, leading to higher NH_3 losses from the wastewater ponds, particularly in hotter months.

There was an equivalent amount of CH_4 emissions from the open-freestall area (49% of total) and wastewater ponds (51% of total) during the spring and summer seasons (Fig. 4). The CH_4 emissions from the wastewater ponds dropped to 35% during the fall and 33% during the winter. As with the NH_3 emissions, we would expect that the open-freestall area would be the greatest source of CH_4 emissions during the late fall and winter due to cold temperatures and freezing of the pond surfaces. The average total farm CH_4 emissions on the open-freestall dairy (0.75 kg CH_4 cow^{-1} d^{-1}) was less than that reported from a similar-sized open-lot dairy (1.39 kg CH_4 cow^{-1} d^{-1}) (Leytem et al., 2011). Because the CH_4 emissions from the housing area on a per-head basis were similar for the two dairies (0.41 vs. 0.49 kg cow^{-1} d^{-1} for the open-freestall and open-lot dairies, respectively), the difference was mainly due to the manure handling system.

The total farm CH_4 emissions at the open-freeestall dairy were greater than those reported at a 700-cow open-lot dairy (0.35 kg CH_4 cow^{-1} d^{-1}) in southern Idaho (Bjorneberg et al., 2009). In this instance, the CH_4 emissions from the housing area were lower at the smaller dairy (0.30 kg CH_4 cow^{-1} d^{-1}) compared with the open-freestall dairy, but again the driving factor is the low emissions from the wastewater pond at the smaller dairy (2.43 g CH_4 m^{-2} d^{-1}) vs. the open-freestall dairy (22 g CH_4 m^{-2} d^{-1}). Manure was removed daily from feed alleys at the smaller open-lot dairy and applied to compost windrows, which were not included in the total farm emission estimate, although data from the 10,000-cow open-lot dairy (Leytem et al., 2011) determined that the CH_4 emissions from the compost area contributed only 7% to the total on-farm CH_4 emissions.

Table 3. Average combined emission rates of ammonia and methane measured from the open-freestall and wastewater pond areas of a 10,000 milking cow open-freestall dairy over four seasons.

Month	Emission rates NH_3	CH_4
	kg d^{-1}	
Spring (Mar.–May)	2656	9502
Summer (June–Aug.)	3318	9443
Fall (Sept.–Nov.)	1809	7917
Winter (Dec.–Feb.)	273	3215
Average total emission, kg d^{-1}	2014	7519
Average emission, cow^{-1} d^{-1}†	0.20	0.75
Average emission, kg milk^{-1} d^{-1}‡	0.006	0.022

† Average based on the 10,000 milk cows.

‡ Average based on 34 kg of milk produced per cow per day.

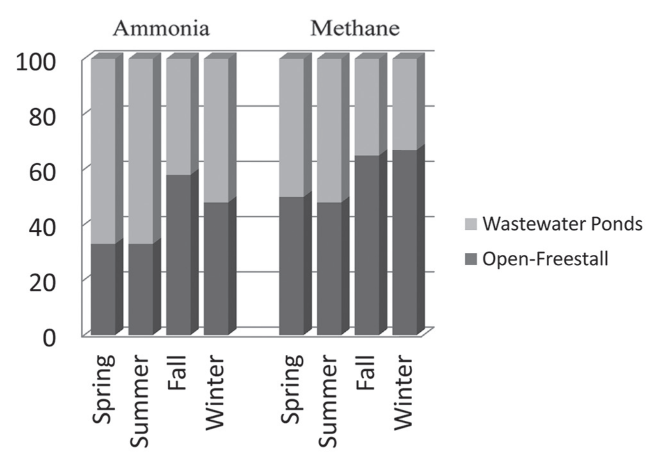

Fig. 4. Seasonal contribution of total on-farm emissions of NH_3 and CH_4 from each source area.

Implications for Regulations and Reporting Requirements

Because the data from this study represent only one open-freestall dairy with an anaerobic digester, it is unknown how much variability exists between farms with similar production systems. Therefore, the following discussion is illustrative in nature and may not apply to all open-freestall production facilities having anaerobic digesters. If the value of 0.20 kg NH_3 cow^{-1} d^{-1} is used to represent an open-freestall dairy with a digester in this region, then, according to the USEPA limit of 45.5 kg NH_3 d^{-1}, any farm with more than 228 cows would exceed the NH_3 emission threshold under the Emergency Planning and Community Right-to-Know Act (USEPA, 2009b). However, under the current regulation, farms containing fewer than 700 mature dairy cows are exempt from reporting. The state of Idaho developed a "permit by rule" that requires any farm emitting more than 90,909 kg NH_3 yr^{-1} to adopt a certain number of best management practices to reduce on-farm NH_3 emissions. Based on the data from the current study, an open-freestall dairy with a digester using a flushing system with more than 1245 cows would exceed the state threshold. The threshold number used in Idaho for flush dairies is 1638 mature cows.

The CO_2e from CH_4 at the open-freestall area, which should represent mainly enteric fermentation (with a small contribution from the manure and flushwater), was approximately 9.4 kg CO_2e cow^{-1} d^{-1}. Comparatively, the USDA GHG inventory reports an estimate of 5.9 kg CO_2e cow^{-1} d^{-1} , whereas the Intergovernmental Panel on Climate Change (IPCC) Tier 1 estimate is 8.1 kg CO_2e cow^{-1} d^{-1} for enteric emissions, both of which are lower than the value determined in the present study. However, when evaluated on a DMI basis, the value of 17 g CH_4 kg DMI^{-1} at this farm is similar to ranges reported in the literature for enteric CH_4 emissions from lactating dairy cattle of (16–23 g CH_4 kg DMI^{-1}) (Kinsman et al., 1995; Sun et al., 2008; Ngwabie et al., 2009, 2011) in both chamber and on-farm studies. This suggests that the methods used in the USDA GHG inventory report and IPCC Tier 1 estimates may underestimate on-farm enteric CH_4 production.

Enteric CH_4 production from the cattle would not fall under the USEPA CAA rule for mandatory reporting of GHGs; however, the CH_4 and N_2O generated from the manure handling system would fall under the CAA reporting rule. Because it is difficult to isolate the CH_4 emissions from the manure and flush water in the barns and manure in the exercise areas (due to the presence of the cattle) and because previous studies have shown little CH_4 generation from fresh manure, we did not consider this as a separate source in our subsequent calculation and only considered CH_4 and N_2O generation from the wastewater ponds. Because we had months with missing data, we used the regression equations generated from the relationship between temperature and CH_4 and N_2O emissions, along with average monthly temperatures measured on farm, to fill in missing data.

Based on the CH_4 and N_2O produced in the manure management system (wastewater ponds), CO_2e generation for the year at this facility would be approximately 36,800 metric tons of CO_2e or 3.7 metric tons of CO_2e per cow per year. Even though N_2O is considered a more potent GHG and has a CO_2e value of 296, compared with only 23 for CH_4, the estimated contribution from N_2O was only 22% of the CO_2e generated on farm. The USEPA reporting threshold value is 25,000 metric tons of CO_2e per year (USEPA, 2009a), which would equate to 6757 cows based on the information from this dairy. This threshold value is greater than the 4808 value we estimated for a similar sized open-lot dairy in the same region (Leytem et al., 2011). The final USEPA rule has determined that the average annual animal population (head) under which facilities are not required to report emissions is 3200 for dairy (mature dairy cows), which is less than either of our estimated threshold numbers.

Although more on-farm data need to be collected, it appears from examining the emissions from the three dairy farms in southern Idaho that changes in the manure handling system may be the best opportunity for mitigating emissions. The use of an anaerobic digester at the open-freestall dairy potentially mitigated the CH_4 emissions from the wastewater ponds; we would have expected high CH_4 production potential due to higher solids loading into the waste stream from a flush dairy. The resulting CH_4 emissions from the wastewater ponds of the freestall dairy were lower than from one open-lot dairy in the region but higher than the other. Therefore, it is not clear whether having a flush dairy with an anaerobic digester produces less CH_4 than an open-lot dairy where the majority of the manure is handled as a solid. We also need to take into account the possible secondary N_2O emissions resulting from deposition of NH_3 generated on farm and the potential health hazard associated with enhanced NH_3 emissions from the open-freestall dairy, which were 46% greater on a per cow basis than those measured at an open-lot dairy in the region. This highlights the importance of assessing all of the emissions from on-farm source areas to evaluate how management practices alter the system as a whole when promoting management practices or technologies aimed at reducing on-farm emissions.

Acknowledgments

The authors thank Dr. Michael Wojcik at the Energy Dynamic Laboratory, Utah State University, North Logan, Utah for lending one of the OP/FT-IR instruments used in the study and the reviewers for their input, which has greatly improved the quality of the manuscript.

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