Emissions of Ammonia, Methane, Carbon Dioxide, and Nitrous Oxide from Dairy Cattle Housing and Manure Management Systems

April B. Leytem,* Robert S. Dungan, David L. Bjorneberg, and Anita C. Koehn USDA–ARS

Concentrated animal feeding operations emit trace gases such as ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). The implementation of air quality regulations in livestock-producing states increases the need for accurate on-farm determination of emission rates. The objective of this study was to determine the emission rates of NH_3, CH_4, CO_2, and N_2O from three source areas (open lots, wastewater pond, compost) on a commercial dairy located in southern Idaho. Gas concentrations and wind statistics were measured each month and used with an inverse dispersion model to calculate emission rates. Average emissions per cow per day from the open lots were 0.13 kg NH_3, 0.49 kg CH_4, 28.1 kg CO_2, and 0.01 kg N_2O. Average emissions from the wastewater pond (g m^{-2} d^{-1}) were 2.0 g NH_3, 103 g CH_4, 637 g CO_2, and 0.49 g N_2O. Average emissions from the compost facility (g m^{-2} d^{-1}) were 1.6 g NH_3, 13.5 g CH_4, 516 g CO_2, and 0.90 g N_2O. The combined emissions of NH_3, CH_4, CO_2, and N_2O from the lots, wastewater pond and compost averaged 0.15, 1.4, 30.0, and 0.02 kg cow^{-1} d^{-1}, respectively. The open lot areas generated the greatest emissions of NH_3, CO_2, and N_2O, contributing 78, 80, and 57%, respectively, to total farm emissions. Methane emissions were greatest from the lots in the spring (74% of total), after which the wastewater pond became the largest source of emissions (55% of total) for the remainder of the year. Data from this study can be used to develop trace gas emissions factors from open-lot dairies in southern Idaho and potentially other open-lot production systems in similar climatic regions.

J. Environ. Qual.
doi:10.2134/jeq2009.0515
Published online 15 June 2010.
Received 23 Dec. 2009.
*Corresponding author (april.leytem@ars.usda.gov).
© ASA, CSSA, SSSA
5585 Guilford Rd., Madison, WI 53711 USA

The state of Idaho has experienced rapid growth of the dairy industry in the past decade, with the number of milk cows increasing approximately 88% and milk production increasing 114% (USDA National Agricultural Statistics Service, 2007). In 2006, there were 477,193 milking cows in Idaho, with 71% of these being located in the Magic Valley region of southern Idaho (UDI, 2007). Although 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 (NH_3), methane (CH_4), and nitrous oxide (N_2O).

In the atmosphere, NH_3 primarily reacts to form ammonium sulfate and ammonium nitrate aerosols, which contribute to particulate matter with an aerodynamic diameter <2.5 μm ($PM_{2.5}$) 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. Under the Emergency Planning and Community Right-to-Know Act, confined animal feeding operations are required to report NH_3 emissions if they emit more than 45 kg NH_3 d^{-1} (USEPA, 2009b). The USEPA Climate Change Division of the Office of Atmospheric Programs has recently adopted a rule for mandatory reporting of greenhouse gases (USEPA, 2009a). This rule requires that livestock facilities with manure management systems that emit 25,000 metric tons of carbon dioxide equivalents (CO_2e) report the annual aggregate CH_4 and N_2O emissions from their manure management system. The implementation of air quality regulations in livestock-producing states increases the need for accurate on-farm determination of emission rates that reflect the range of animal production facilities and climatic conditions that exist in the United States.

There are limited on-farm emissions data from dairy production facilities covering the range of trace gases that are important from a regulatory and environmental standpoint. One reason for this is the difficulty and expense of doing this type of research. There have been two studies that have looked at NH_3 emissions using chamber methods from the pens and lagoon areas of an open-lot dairy

USDA–ARS, Northwest Irrigation and Soils Research Lab., 3793 N. 3600 E., Kimberly, ID 83341. Assigned to Associate Editor Jan Willem van Groenigen.

Abbreviations: CO_2e, carbon dioxide equivalents; DMI, dry matter intake; FGM, photoacoustic field gas monitor; LU, livestock unit; $PM_{2.5}$, particulate matter with an aerodynamic diameter <2.5 μm; UV-DOAS, ultraviolet-differential optical absorption spectrometer.

in Texas (Mukhtar et al., 2008) or from concrete yards in the United Kingdom (Misselbrook et al., 2006). In both of these studies, measurements were taken for up to 5 d during one or two seasons. Other studies have determined NH_3 emissions from dairy cattle housing (Cassel et al., 2005; Rumburg et al., 2008) or dairy cattle housing and manure handling systems (Flesch et al., 2009) using downwind measurements and modeling to estimate emissions. These studies measured NH_3 emissions from 3 to 31 d, with some studies measuring emissions during different seasons (winter, summer, and fall).

Methane emissions from dairy cattle have been estimated using sulfur hexafluoride tracers with grazing cattle (Lassey et al., 1997; Ulyatt et al., 2002), emissions from cattle in barns (Kinsman et al., 1995; Sun et al., 2008), emissions from grazing cattle (Laubach and Kelliher, 2005a; Laubach and Kelliher, 2005b), or the whole farm (McGinn et al., 2006) using downwind measurements and modeling techniques. There have been two studies that estimated emissions of NH_3, N_2O, and CH_4 from a barn (Amon et al., 2001) or concrete yards (Misselbrook et al., 2001); one study that estimated emissions of N_2O, CH_4, and carbon dioxide (CO_2) emissions from dairy cattle in a chamber (Hamilton et al., 2010); and one study that estimated CO_2 emissions from a dairy barn (Kinsman et al., 1995). As with the NH_3 emissions estimates, data from these other studies were collected for limited time periods, and most studies did not look at seasonal variation in emissions. Ngwabie et al. (2009) estimated emissions of NH_3, N_2O, and CH_4 from a dairy cattle building during multiple seasons (winter, spring, and summer).

There is also limited on-farm evaluation of emissions from manure storage areas. Khan et al. (1997) estimated CH_4 emissions from stored cattle slurry, and Su et al. (2003) measured emissions of CH_4, CO_2, and N_2O from covered anaerobic wastewater treatment systems on several dairies. Mukhtar et al. (2008) and Flesch et al. (2009) estimated NH_3 emissions from dairy manure storage areas. A few studies have looked at some combination of NH_3, CH_4, CO_2, or N_2O emissions from dairy cattle slurry using laboratory or pilot scale techniques (Sommer et al., 2000; Amon et al., 2006; Guarino et al., 2006). Two studies evaluated a combination of NH_3, CH_4, CO_2, or N_2O emissions from composting dairy manure (Hellebrand and Kalk, 2001; Hao et al., 2004).

The development of accurate on-farm emissions factors have to take into account diurnal and seasonal variations in emissions under different production scenarios and climatic regions. Additionally, comprehensive datasets that determine the emissions of all trace gases are valuable particularly when we begin to change management practices that may positively affect the emissions of one gas but may negatively affect another. Therefore, the objective of this study was to determine the emission rates of NH_3, CH_4, CO_2, and N_2O over the course of 1 yr from three source areas (open-lots, wastewater pond, compost) on a large open-lot dairy located in southern Idaho.

Materials and Methods

Study Farm

The dairy used in this study was a commercial dairy in southern Idaho, in a rural location, with 10,000 milking cows and a stocking density of approximately 55 m^2 per cow (Fig. 1). The milking cows consisted primarily of mature Holsteins with an average bodyweight of 635 kg. This dairy is similar in configuration to most open-lot production facilities in southern Idaho. The operation consists of 20 open-lot pens (60 ha), two milking parlors, a hospital barn, a maternity barn, a manure solid separator, a wastewater storage pond (10 ha), and a compost yard (10 ha). The feed lanes run east and west with a concrete pad directly behind the stanchions and three automatic waterers per lot located approximately 10 m behind the concrete pad at the east, center, and west ends of the loafing sheds.

There were approximately 10,800 cows within the main lot area (including milking, maternity, and sick cows). Approximately 2200 dry cows and replacement heifers were located in pens to the north of the main lot area and contributed manure to the compost and wastewater pond (lot runoff in wet seasons). Within each lot there were a loafing shed and two wind breaks. Manure was scraped and piled in the pens or vacuumed from feed alleys daily and placed into cells near the solid separator. The open-lot pens were harrowed daily when dry. Wash water from the milking parlor and runoff from the open lots was retained in the wastewater pond to the east of the pens, and solid manure from the pens was composted in an area northwest of the facility. The facility was surrounded by irrigated crop land on three sides and open range to the north.

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 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 cow^{-1} d^{-1}.

Field Measurements

Our primary objective was to estimate the emissions of NH_3, CH_4, CO_2, and N_2O from the three main sources located on the farm, which included the open lots, wastewater pond, and composting areas. Figure 1 illustrates the farm layout with sensor placement and farm structures. The 20 main open-lot pens as well as the maternity and hospital barn areas were included in the "open-lot" source area. The milking parlors area, areas without pens, and feed alleys that run from west to east were excluded. Alleys running north to south were included because these tend to accumulate urine and feces as cows are moved to and from the milking parlors. Gas concentrations at the open lots were measured at a location that was central to the housing area at 3 m above the surface. At the compost yard, the gas concentrations were measured at a location near the center of the windrows (at 2 m above the windrows). At the wastewater pond, concentrations were measured on a floating raft that was located in the northwest corner of the pond (at 1 m above the surface). Ambient background concentrations were measured at a location 0.6 km due south of the dairy at 2 m above the surface.

Measurements at the open-lot took place for 2 to 3 d out of each month over the course of 1 yr starting in March of 2008. Only NH_3 data were collected in January and February of 2009 due to equipment limitations. Measurements at the compost yard were made for 2 to 3 d each month starting in March 2008

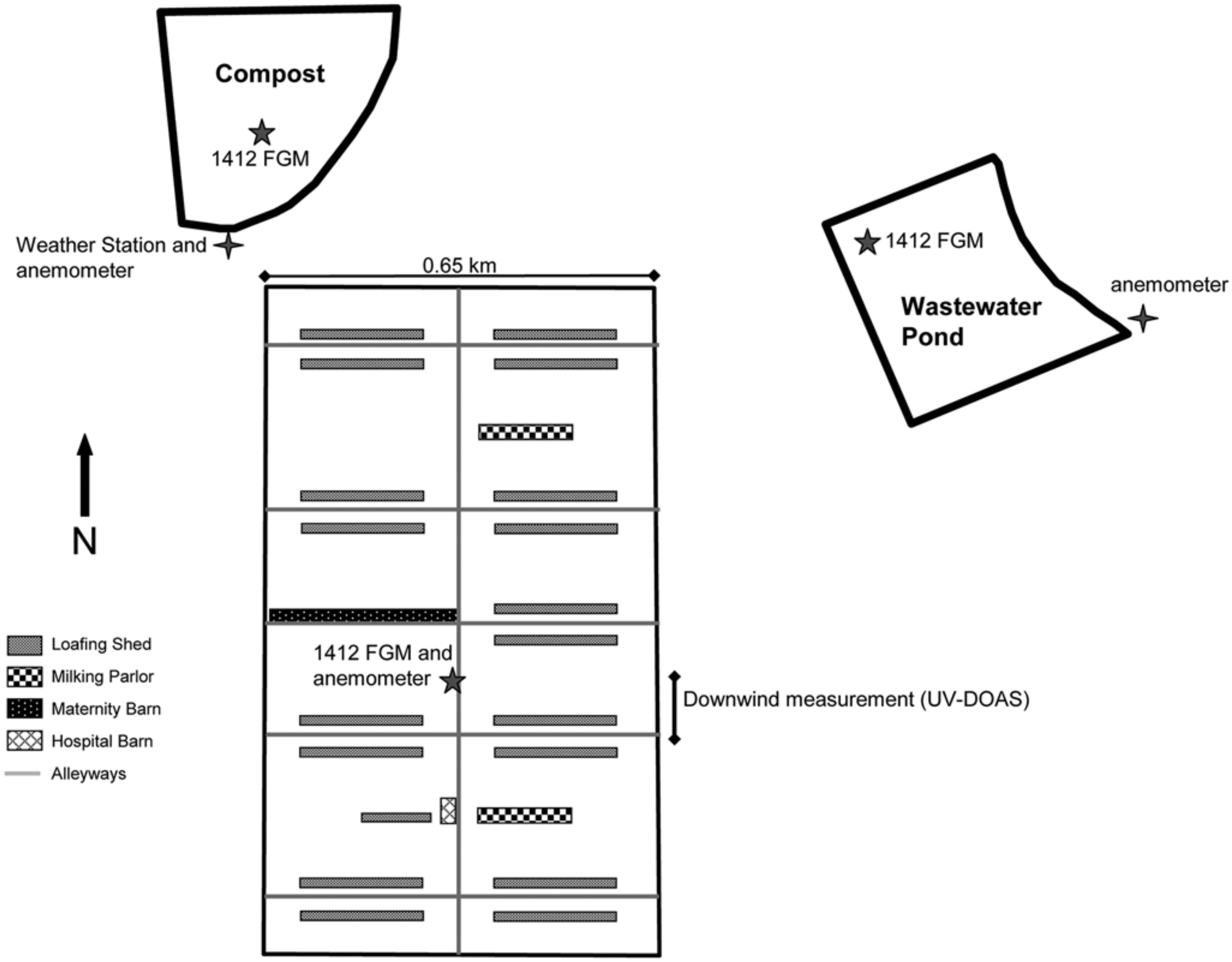

Fig. 1. Schematic of the open-lot dairy including the locations of monitoring equipment and buildings.

until September 2008, when the compost was removed from the facility. Measurements at the wastewater pond were made for 2 to 3 d each month from April 2008 to October 2008, after which the wastewater pond was emptied. Measurements were not made in July 2008 because the equipment was being recalibrated and in December 2008 due to ambient air temperatures below the minimum operating conditions for the instrument.

The concentrations of NH_3, CH_4, CO_2, and N_2O were measured continuously using a photoacoustic field gas monitor (FGM) (INNOVA 1412; LumaSense Technologies, Santa Clara, CA). The detection limits of the gases were as follows: 0.1 mg L^{-1} NH_3, 0.4 mg L^{-1} CH_4, 1.5 mg L^{-1} CO_2, and 0.03 mg L^{-1} N_2O. The initial FGM was factory calibrated before the start of the study and in July 2008. Additional FGMs that had been factory calibrated before use were purchased in October 2008. Due to limited equipment availability from March through September 2008, the FGM was rotated between the four locations. During October and November of 2008, there were enough FGMs to have one at each of the locations monitored. Because the operating temperature range of the FGM is 5 to 40°C, this equipment could not be used from December 2008 to February 2009, and in March 2008 measurements were only taken when the temperature was above 5°C.

In January and February of 2009, NH_3 concentrations were measured 120 m downwind of the eastern edge of the open-lot pens using an open-path, ultraviolet-differential optical absorption spectrometer (UV-DOAS) (UV Sentry; Cerex Monitoring Solutions, LLC, Atlanta, GA). This equipment cannot measure CH_4, CO_2, and N_2O concentrations. For the downwind measurements, gas concentrations were determined at a height of 2 m and at distances of approximately 10 times the height (or greater) of the nearest fence and loafing shed. The UV-DOAS unit provided a line-average concentration between the source and detector, which were separated by 75 m. Concentration data for the FGM and UV-DOAS were processed to produce 15-min average mixing-ratio concentrations (ppm_v) at the source areas (C) and background (C_b) locations. The emissions estimates for NH_3 made using the UV-DOAS were compared with estimates made using the FGM at the center lot for several days in February and May of 2009. There was a <5% difference in average emissions estimates using these two different techniques at these two time periods.

The wind environment at each location 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 (CSAT-3; Campbell Sci., Logan, UT, and RM Young ultrasonic anemometer; Traverse City, MI), where u^* is the friction velocity, L is the Obukhov stability length, z_0 is the surface roughness length, and β is wind direction. There were sonic anemometers located in three places on the farm: (i) on the south edge of the compost area (RM Young ultrasonic anemometer), (ii) at the center of the lots (CSAT-3), and (iii) at the eastern edge of the wastewater pond (CSAT-3). Wind parameters were calculated for each 15-min period (corresponding to C and C_b 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 southern edge of the compost area and recorded air temperature, barometric pressure, wind direction, and wind speed (all at 2 m) during the experimental period.

Emissions Calculations

We used WindTrax software (Thunder Beach Scientific, Nanaimo, Canada), 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. 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. Emission rates (Q kg d^{-1}) were calculated using N = 50,000 trajectories and measured background concentrations.

Because good emissions estimates are dependent on data that do not violate the MOST assumptions, 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).

For gas concentrations determined with the FGM, the measurement site was within the source area, and therefore wind direction did not affect transport of trace gases from the source to the sampling location. However, during January and February, the location of the UV-DOAS system was downwind of the lot area. Due to the location, for some wind directions, there would be minimal transport of trace gases from the source to the sampling location, which can lead to uncertainty in Q estimates. Therefore, we filtered out data at the downwind measuring location having a wind direction <200° and >340° to ensure that the detection equipment was downwind of the source area.

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, as one needs to capture the diurnal trend in emissions. During a few months there were limited data, and during this time 12-h averages were used to capture the diurnal fluctuations in emissions. For each month, data were averaged into 1-h blocks, after which 24 (or 12) 1-h average values were averaged to determine the daily emissions. This allowed a representative weighting of emissions estimates over a 24-h (or 12-h) period.

Because there were times when we had noncontinuous observations due to data filtering, we used a "gap-filling" technique to fill in missing data. We extrapolated the emissions data to estimate Q during missing periods using a regression model based on the ambient u^* and time of day as predictors as done by Flesch et al. (2009). There were 5 mo where we used the gap-filling technique for the lot estimates (May–September and October). All open-lot regression models were significant (α = 0.05), with r^2 values ranging from 0.25 to 0.65 and the number of interpolated points ranging from 1 to 6. There was 1 mo where we used the gap-filling technique for the wastewater pond estimates (May, r^2 = 0.47–0.63; 4 pts), and the compost estimates (August, r^2 = 0.30–0.65; 4 pts). During June and September, the wind speeds at the wastewater pond were very low, resulting in low u^* values; therefore, a large amount of data was filtered out. Because we did not want to overextrapolate the available data, we did not calculate average emissions for these months.

We calculated seasonal (spring, summer, fall, and winter) total farm estimates by averaging the available emission estimates at each location for each season and then summing the averages of the three locations to obtain emissions (kg d^{-1}) for the whole farm for that time period. The seasons were considered to be spring (March–May), summer (June–August), fall (September–November), and winter (December–February). Because the wastewater pond was frozen over from December to February and there was no compost in the compost area, the winter NH_3 emissions value is an average of only the lot data. Due to equipment limitations, we were unable to collect CH_4, CO_2, and N_2O data from December through February. Therefore, we substituted CH_4, CO_2, and N_2O emissions estimates from the lot during March to represent winter emissions rates so that the yearly emissions rate would not be inflated due to inclusion of seasons when there were emissions from all three areas. In previous work on an open lot dairy, we determined that March (spring) was more representative of winter emissions than summer or fall values (Bjorneberg et al., 2009).

Results and Discussion

Emissions from the Open Lot

The emissions of NH_3, CH_4, CO_2, and N_2O for April 2008 from the open lots are presented in Fig. 2. There was a strong diurnal trend in emissions of NH_3, CH_4, and CO_2 from the open-lot area with emissions being lower during late evening and early morning and then increasing throughout the day, with maximum rates late in the day. 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 1500 to 1600 (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 expect an increase in NH_3 and CH_4 emissions.

Flesch et al. (2007) also noted a strong diurnal trend in NH_3 emissions from a beef feedlot, with lower emissions during early morning and rising emissions throughout the day, which they attributed to wind speed and animal activity. Flesch et al. (2009) and Cassel et al. (2005) saw the same diurnal trend in NH_3 emissions from dairy barns. Sun et al. (2008) noted a

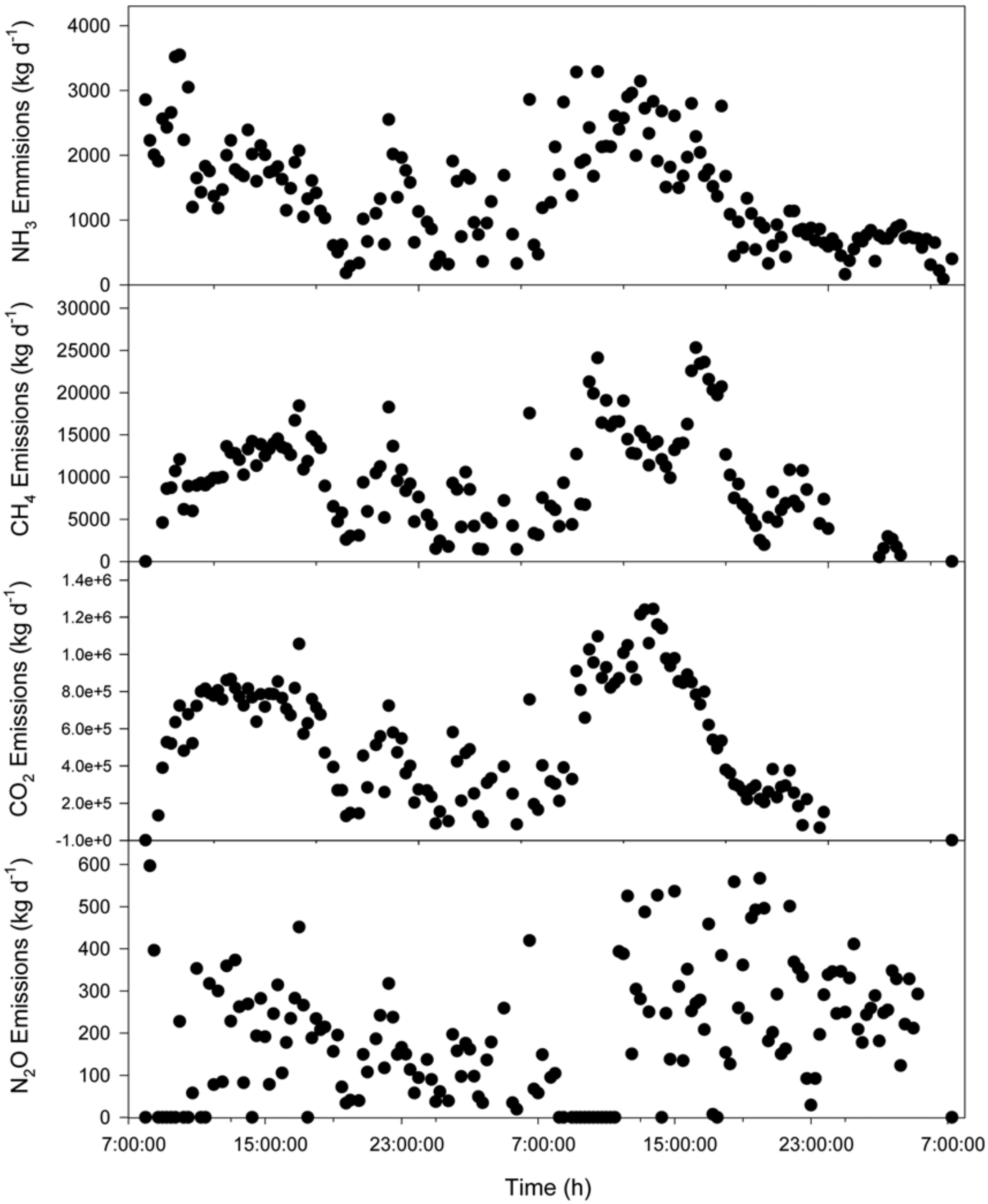

Fig. 2. Daily emission rates of (a) NH_3, (b) CH_4, (c) CO_2, and (d) N_2O measured over time from the open lots during April 2008.

strong diurnal trend in CH_4 emissions from dairy cattle with higher rates during the day than late evening and early morning. There did not seem to be a diurnal trend in N_2O emissions. Because animal activity should not contribute to N_2O emissions and emissions rates tended to be very low, it is not unexpected to find little trend over time.

The average emission rates of NH_3, CH_4, CO_2, and N_2O from the open-lot area for each monitoring period along with weather data and lot conditions are presented in Table 1. Average NH_3 emission rates ranged from 747 to 2129 kg NH_3 d^{-1}. In early 2008 when lots were wet and manure was present, emission rates were over 1200 kg NH_3 d^{-1}; as lots dried and manure was removed, the rates decreased and then increased in the late fall when the lots became wet and manure began to accumulate. During January when the lots were frozen, emission rates were lower than in spring and late fall. Although in February, the emission rates were the highest, which could have been due to warming weather and wet conditions on the lots. Leytem et al. (2009) described the spatial variability of NH_3 concentrations on this facility and determined that when the lots were wet NH_3 concentrations were the highest and tended to decrease as the lots dried out or were frozen. Hutchinson et al. (1982) reported the highest NH_3 emission rates when beef feedlots had been wet and were drying rapidly, which is similar to the trends found in the present study.

On a per-animal basis, NH_3 emission rates in the present study ranged from 0.08 to 0.20 kg NH_3 cow^{-1} d^{-1}. When averaged over the year, the NH_3 emission rates were 1365 kg NH_3

Table 1. Average emission rates of ammonia, methane, carbon dioxide, and nitrous oxide measured from the open-lot area of a 10,000-milking-cow open-lot dairy along with weather and lot conditions.

Monitoring dates	Emissions				Weather conditions			Lot conditions
	NH_3	CH_4	CO_2	N_2O	Wind speed	Wind direction	Temp.	
	kg d^{-1}				m s^{-1}	degrees	°C	
24 Mar. (1015 h) to 25 Mar. (2045 h)	1272 (490)†	5760 (2321)	97,038 (31,018)	50 (57)	2.18 (1.27)	279 (26)	8.35 (1.67)	lots partially frozen, some wet areas, manure piles present
28 Apr. (0800 h) to 30 Apr. (1600 h)	1669 (485)	9996 (2774)	540,976 (194,160)	185 (111)	3.80 (2.52)	244 (79)	13.68 (6.75)	lots very wet with standing water in some pens, manure piles present
19 May (1000 h) to 20 May (1815 h)	1237 (726)	6760 (6314)	544,676 (426,839)	359 (157)	3.06 (1.94)	237 (82)	20.60 (6.48)	all manure piles removed from pens; pens were dry
25 June (1045 h) to 26 June (1500 h)	1235 (1277)	3800† (1690)	161,004‡ (94,823)	140 (66)	2.05 (1.66)	244 (39)	22.24 (4.78)	lots dry; some buildup of manure piles
18 Aug. (1100 h) to 20 Aug. (1055 h)	987 (478)	5077 (3905)	204,523 (111,140)	65 (44)	1.82 (1.10)	205 (94)	23.49 (6.43)	lots dry; some buildup of manure piles
22 Sept. (1200 h) to 24 Sept. (1130 h)	747 (219)	1097 (1320)	90,112 (59,505)	62 (27)	1.68 (1.20)	155 (95)	11.68 (4.65)	lots dry; some buildup of manure piles
27 Oct. (1115 h) to 31 Oct. (0900 h)	1854 (609)	5413 (2779)	600,415 (179,408)	2§	2.34 (1.50)	98 (45)	12.43 (5.98)	lots wet and muddy in some areas; manure piles present
18 Nov. (0930 h) to 21 Nov. (0915 h)	1697 (1250)	4019 (4101)	193,963 (109,869)	21 (52)	2.49 (1.55)	116 (62)	8.43 (4.94)	lots wet and muddy in some areas; manure piles present
28 Jan. (1830 h) to 29 Jan. (0900 h)	819‡ (297)	NA¶	NA	NA	3.69 (1.62)	269 (24)	–4.01 (0.65)	lots frozen over
24 Feb. (0630 h) to 27 Feb. (0800 h)	2129 (1016)	NA	NA	NA	3.65 (1.79)	237 (6)	4.76 (2.66)	lots mostly frozen over starting to thaw; standing water in some places

† Values in parentheses are SD.

‡ 12-h average.

§ Mostly below background.

¶ NA, no data available.

d^{-1} or 0.13 kg NH_3 cow^{-1} d^{-1}. Bjorneberg et al. (2009) reported a range of NH_3 emission rates of 0.03 to 0.25 kg NH_3 cow^{-1} d^{-1} on a 700-cow open-lot dairy (average of 0.15 kg NH_3 cow^{-1} d^{-1} over four seasons), with higher emissions in the spring when the lots were wet and the lowest emissions in January when lots were frozen. Flesch et al. (2007) reported an emission rate of 0.15 kg NH_3 cow^{-1} d^{-1} on a beef feedlot in Texas, and Cassel et al. (2005) reported an emission rate of 0.12 kg NH_3 cow^{-1} d^{-1} from a dairy in California with a combination of open-freestall and open-lot housing, which is similar to the rate found in the present study.

Average CH_4 emission rates from the open lots ranged from 1097 to 9996 kg CH_4 d^{-1}, with no discernable effect of season. The low emission rate measured in September (1097 kg CH_4 d^{-1}) was due to unusually high background CH_4 concentrations during this month, which may have skewed this emissions estimate. The emissions rates on a per-animal basis ranged from 0.10 to 0.93 kg CH_4 cow^{-1} d^{-1}. When the CH_4 emissions were averaged over the year, rates were 5240 kg CH_4 d^{-1} or 0.49 kg CH_4 cow^{-1} d^{-1}. Bjorneberg et al. (2009) measured CH_4 emissions during four seasons on an open-lot dairy and reported rates ranging from 0.17 to 0.53 kg CH_4 cow^{-1} d^{-1} (average of 0.30 kg CH_4 cow^{-1} d^{-1} over four seasons), with higher emissions occurring in the winter and spring compared with summer and 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. Laubach and Kelliher (2005b) reported an average emission rate of 0.40 kg CH_4 cow^{-1} d^{-1} for lactating dairy cattle on pasture. Kinsman et al. (1995) reported an emissions rate of 0.39 kg CH_4 cow^{-1} d^{-1} for lactating dairy cattle. Ngwabie et al. (2009) reported emission rates of 0.22 to 0.31 kg CH_4 LU^{-1} d^{-1} for dairy cattle in a barn (LU is the livestock unit based on LU = 500 kg).

The values reported in the literature are similar to those found in the present study. Differences in reported values 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. Accumulated manure in the lots may also contribute to greater CH_4 emission rates, although Sun et al. (2008) found that fresh manure contributed less than 2% to total CH_4 emissions from dairy cattle in chambers. On a DMI basis, the CH_4 emissions rate was approximately 20 g CH_4 kg DMI^{-1}, which is similar to that found by Sun et al. (2008) with a calculated rate of 23 g CH_4 kg DMI^{-1} from dairy cattle and McGinn et al. (2009), who reported a rate of 20 g CH_4 kg DMI^{-1} from beef cattle.

Average CO_2 emission rates from the open lots ranged from 90,112 to 600,415 kg CO_2 d^{-1}. Because it is impossible to separate the CO_2 emissions of the cattle and lot surfaces from the combustion engines operating on the dairy, these values cannot be strictly linked to cow activity or lot conditions. The changes in CO_2 emissions over the year do not seem to follow a discernable pattern and may be more related to farm equipment usage than changes in weather or lot conditions. If one were to calculate emissions on an animal basis, the rates would range from 8.3 to 55.6 kg CO_2 cow^{-1} d^{-1}. The average emissions rate calculated over the study period was 304,088 kg CO_2 d^{-1}. There have been no published data of CO_2 emission rates from open-lot dairy production facilities. One study that measured CO_2 emissions from dairy cattle (tie-stall barn) reported a rate of 11 kg CO_2 cow^{-1} d^{-1} (Kinsman et al., 1995), whereas Hamilton et al. (2010) reported a rate of 13 kg CO_2 cow^{-1} d^{-1} from dairy cattle in a chamber. These values are similar to the rates reported in March, August, and September in the present study. However, there is a large variation from this value in other months. Because we cannot attribute the CO_2 emissions rates measured on the farm strictly to cattle activity, it is difficult to make comparisons.

The N_2O emission rates from the open lots over the course of the year ranged from 2 to 359 kg N_2O d^{-1} or 0.19 g to 33 g N_2O cow^{-1} d^{-1}. In October and November, the majority of lot N_2O concentrations were at background levels, leading to very little net emissions during these times. There did not seem to be a discernable trend in N_2O emissions from the lot area. The average N_2O emissions measured over the study period were 110 kg N_2O d^{-1} or 10 g N_2O cow^{-1} d^{-1}. There are little published data reporting emissions of N_2O from cattle or cattle production facilities. Bjorneberg et al. (2009) measured N_2O concentrations on an open-lot dairy and found that there was no difference between lot and background N_2O concentrations and therefore no net N_2O emissions from the lots. Hamilton et al. (2010) reported an average N_2O emission rate of 0.48 g N_2O cow^{-1} d^{-1} from dairy cattle in a chamber. Amon et al. (2001) reported N_2O emission rates from dairy barns ranging from 0.14 to 1.19 g LU^{-1} d^{-1}. Sneath et al. (1997) reported a rate of 0.8 g LU^{-1} d^{-1} for dairy cattle in a loose housing system. The majority of N_2O emissions from production facilities are associated with manure management systems; therefore, 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 lots, further supporting the contention that there may be little concern for N_2O losses from cattle housing.

Emissions from the Wastewater Pond

The emissions of NH_3, CH_4, CO_2, and N_2O for April 2008 from the wastewater pond are shown in Fig. 3. As with the lots, there was a strong diurnal trend in emissions of NH_3, CH_4, and CO_2 from the wastewater pond; concentrations were lower in the late evening and early morning and rose throughout the day. Flesch et al. (2009) reported a similar diurnal trend in NH_3 emissions from dairy wastewater ponds. Because NH_3 emissions are strongly related to temperature and wind speed, the diurnal fluxes 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, CO_2, and N_2O for each monitoring period along with weather conditions are presented in Table 2.

The average NH_3 emission rate was 203 kg NH_3 d^{-1} over the study period. On an areal basis, the average emission rates ranged 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 study period. There did not appear to be a trend in NH_3 emissions over the time period of the study, although emissions were only measured during months when the pond contained wastewater and was not frozen. Bjorneberg et al. (2009) reported wastewater pond emission rates ranging from 0.25 to 2.01 g NH_3 m^{-2} d^{-1} on an open-lot dairy, with an average of 0.91 g NH_3 m^{-2} d^{-1} over four seasons. Flesch et al. (2007) measured an NH_3 emissions rate of 0.9 g NH_3 m^{-2} d^{-1} from the retention pond at a beef feedlot, and Flesch et al. (2009) reported emissions of 3.5 and 2.3 g NH_3 m^{-2} d^{-1} from dairy lagoons receiving parlor-wash water, which are similar to the rate determined in the present study.

Methane emission rates from the wastewater pond ranged from 1944 to 23,067 kg CH_4 d^{-1} or 19.4 to 231 g CH_4 m^{-2} d^{-1}. In April, when the temperature was cooler, emissions appear to be the lowest. As temperatures increased, emissions also increased, reaching a high of 23,067 g CH_4 m^{-2} d^{-1} in October. 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}). The average CH_4 emission rates over the study period were 10,287 kg CH_4 d^{-1} or 103 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. Therefore, 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). It is therefore difficult to compare wastewater pond emission rates because systems vary in solids content and temperature, which can greatly influence CH_4 generation. Bjorneberg et al. (2009) reported a range of CH_4 emission rates from 1.51 to 4.03 g CH_4 m^{-2} d^{-1} from a lagoon located on an open-lot dairy. Kaharabata et al. (1998) reported an average emission rate of 203 g CH_4 m^{-2} d^{-1} from an aboveground open manure slurry tank during summer and fall. Guarino et al. (2006) reported CH_4 emission rates from cattle slurry ranging from 432 to 1461 g CH_4 m^{-2} d^{-1}, which are much higher than the rates reported in the present study. In the study by Guarino et al. (2006), slurry was placed into batch reactors, which may account for these differences in emissions rates.

Average CO_2 emission rates from the wastewater pond ranged from 28,917 to 85,477 kg CO_2 d^{-1} or 289 to 855 g CO_2 m^{-2} d^{-1}, with no discernable pattern over the year. The average CO_2 emission rate over the study period was 63,744 kg d^{-1} or 637 g CO_2 m^{-2} d^{-1}. There are limited data published reporting CO_2 emissions from wastewater ponds. Guarino et al. (2006) reported emission rates ranging from 3386 to 7966 g CO_2 m^{-2} d^{-1} from cattle slurry in batch reactors, which is much higher than the values reported in the present study. This may be due to the use of a batch reactor vs. an uncovered wastewater pond.

Nitrous oxide emission rates from the wastewater pond tended to be low, ranging from 12 to 85 kg N_2O d^{-1} or 0.12 to 0.85 g N_2O m^{-2} d^{-1}. Emissions were at least 2-fold greater in the spring compared with the summer and fall. The N_2O emission rate was 49 kg N_2O d^{-1} or 0.49 g N_2O m^{-2} d^{-1} when averaged over the study period. Sommer et al. (2000) reported

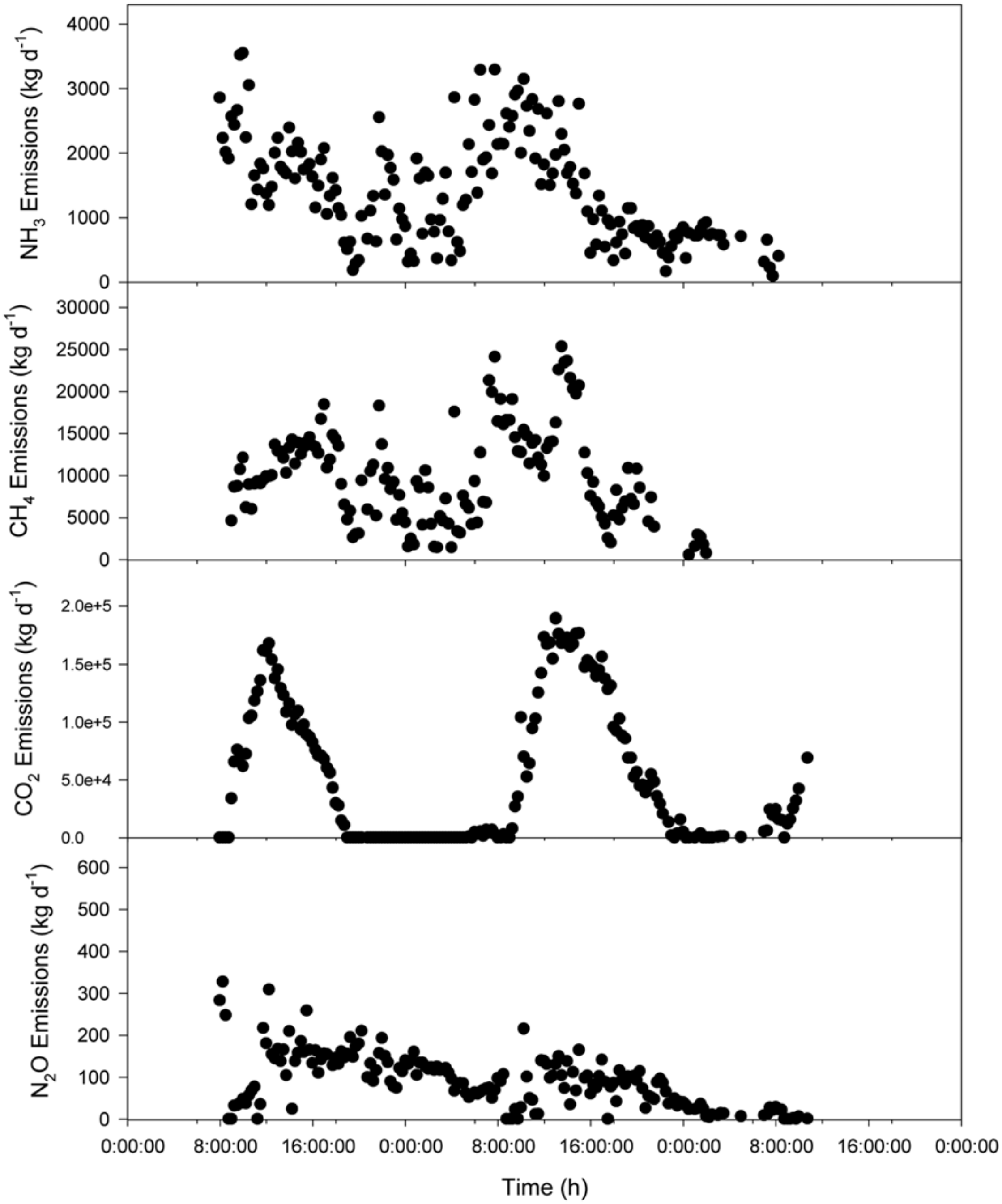

Fig. 3. Daily emission rates of (a) NH_3, (b) CH_4, (c) CO_2, and (d) N_2O measured over time from the wastewater pond during April 2008.

N_2O emission rates from covered (fermented and nonfermented) cattle slurry ranging from 0 to 0.94 g N_2O m^{-2} d^{-1}. Bjorneberg et al. (2009) measured N_2O concentrations from a wastewater pond on an open-lot dairy and found that there was no difference between wastewater pond and background N_2O concentrations, and therefore there were no net N_2O emissions from the wastewater pond.

Emissions from the Compost

The emissions of NH_3, CH_4, CO_2, and N_2O for April 2008 from the compost area are shown in Fig. 4. As with the other source areas, there was a diurnal trend in NH_3, CH_4, and CO_2 emissions from the compost area, with higher concentrations later in the afternoon and lower concentrations in the late evening and early morning. These trends can be attributed to changes in wind speed and temperature because both tend to increase from early morning to late afternoon and then decrease again. There was little trend in N_2O emissions, which tended to be low, and in some cases there were no net emissions of N_2O. The average emission rates of NH_3, CH_4, CO_2, and N_2O for each monitoring period along with weather conditions are presented in Table 3.

The average NH_3 emission rates ranged from 34 to 345 kg NH_3 d^{-1} or 0.34 to 3.45 g NH_3 m^{-2} d^{-1}, with the highest emissions rates in June and August. The compost piles were being turned frequently in June and August, which would explain the elevated emissions measured during these time periods. In particular, in June the piles were turned and moved, and new manure

Table 2. Average emission rates of ammonia, methane, carbon dioxide, and nitrous oxide measured from the wastewater pond of a 10,000-milking-cow open-lot dairy along with weather conditions.

Monitoring dates	Emission rates				Weather conditions		
	NH_3	CH_4	CO_2	N_2O	Wind speed	Wind direction	Temp.
	kg d^{-1}				m s^{-1}	degrees	°C
30 Apr. (0800 h) to 2 May (1045 h)	211 (83)†	1,944 (929)	61,365 (66,068)	85 (31)	5.2 (2.8)	244 (79)	5.0 (6.3)
28 May (1345 h) to 30 May (1415 h)	217 (109)	9,608 (3,256)	79,219 (63,366)	70 (53)	1.98 (1.06)	230 (55)	15.4 (7.1)
20 Aug. (1600 h) to 21 Aug. (1030 h)	164‡ (84)	6,526‡ (4,286)	28,917‡ (10,760)	12‡ (87)	1.18 (0.65)	221 (39)	20.8 (6.7)
27 Oct. (1115 h) to 31 Oct. (0900 h)	220 (43)	23,067 (5,259)	85,477 (20,609)	29 (14)	2.34 (1.50)	98 (1.5)	15.3 (9.7)

† Values in parentheses are SD.

‡ 12-h averages.

was brought into the compost yard, which would explain the elevated emissions during this time period. The average NH_3 emission rate from the compost area was 164 kg NH_3 d^{-1} or 1.64 g NH_3 m^{-2} d^{-1} over the monitoring period. Hellebrand and Kalk (2001) reported initial emission rates ranging from 7.2 to 16.8 g NH_3 m^{-2} d^{-1} from composting mixed cattle and swine manure. These rates decreased to 10% of the initial value within 2 to 3 wk into the composting period. Because the compost windrows in the present study were somewhat mature, the NH_3 emission rates are similar to the latter emissions rates reported by Hellebrand and Kalk (2001).

Average CH_4 emission rates from the compost ranged from 258 to 3522 kg CH_4 d^{-1} or 2.6 to 35.2 g CH_4 m^{-2} d^{-1}, with the greatest emission rates occurring in June. The average CH_4 emission rate was 1354 kg CH_4 d^{-1} or 13.5 g CH_4 m^{-2} d^{-1} over the monitoring period. Hellebrand and Kalk (2001) reported initial emissions rates ranging from 96 to 288 g CH_4 m^{-2} d^{-1} from composting mixed cattle and swine manure. These rates dropped to 10% of the initial values within a few weeks of composting. Hao et al. (2004) reported emissions rates of 21.9 and 2.4 g CH_4 m^{-2} d^{-1} for early and late stages of composting cattle manure. Average CO_2 emission rates ranged from 20,350 to 126,308 kg CO_2 d^{-1} or 204 to 1263 g CO_2 m^{-2} d^{-1} over the study period. As with the other gases, the greatest CO_2 emissions were in June when there was more activity in the compost area. This increase in CO_2 emissions could be caused by a combination of the microbial activity in the compost windrows and machinery operating in the area. The average CO_2 emission rate was 51,608 kg CO_2 d^{-1} or 516 g CO_2 m^{-2} d^{-1} over the study period. Hao et al. (2004) reported CO_2 emissions of 293 to 184 g CO_2 m^{-2} d^{-1} for early and late composting of cattle manure. The average N_2O emission rates ranged from 12 to 267 kg N_2O d^{-1} or 0.12 to 2.67 g N_2O m^{-2} d^{-1}, with the greatest emission rates occurring in June. The average N_2O emission rate was 90 kg N_2O d^{-1} or 0.90 g N_2O m^{-2} d^{-1} over the monitoring period. Hellebrand and Kalk (2001) reported emissions rates of N_2O ranging from 0 to a maximum of 2.4 g N_2O m^{-2} d^{-1} from composting mixed cattle and swine manure. Hao et al. (2004) reported N_2O emissions 0.03 to 0.22 g N_2O m^{-2} d^{-1} from composting cattle manure.

Total Estimated Farm Emissions

The combined emission rates of NH_3, CH_4, CO_2, and N_2O from the lots, wastewater pond, and compost are shown in Table 4. When averaged over the study period, the emission rates of NH_3, CH_4, CO_2, and N_2O were 1625, 15,042, 323,880 and 186 kg d^{-1}, respectively. This translates to a rate of 0.15, 1.39, 30.0, and 0.02 kg cow^{-1} d^{-1} or 0.005, 0.044, 0.94, and <0.001 kg kg $milk^{-1}$ d^{-1} for emissions of NH_3, CH_4, CO_2, and N_2O, respectively. To obtain an improved estimate of yearly emissions from the farm, we used all the available monthly data and substituted data from missing months with comparative data from other months. For example, June data were used for July, and the missing CH_4, CO_2, and N_2O data in January were replaced with data from March. Using these assumptions, the rates on an animal basis were similar with 0.14, 1.18, 29.5, and 0.02 kg cow^{-1} d^{-1} for NH_3, CH_4, CO_2, and N_2O, respectively. These values are used in the following discussion.

The open-lot areas had the greatest contribution to emissions of NH_3, CO_2, and N_2O, with averages of 78, 80, and 57% of the total farm emissions, respectively (calculated for months when there were values for all three sources). The wastewater pond contributed 12, 11, and 15% of the total farm emissions for NH_3, CO_2, and N_2O, respectively. The compost area contributed 10, 9, and 27% of the total farm emissions for NH_3, CO_2, and N_2O, respectively. Because the lot is approximately 6-fold greater in area than the wastewater pond and compost areas, these numbers are not surprising. In addition, because much of the ammonia loss occurs from evaporating urine patches, the majority of NH_3 would be expected to be released from the area with the greatest urine deposition, which in this management system is the lot area. The CH_4 emissions, however, had the greatest contribution from the lots in April (74% of total emissions), but, once temperatures began to increase, the wastewater pond became the largest source of CH_4 emissions, averaging 55% of total emissions for the remainder of the year. The compost area contributed an average of 7% of total CH_4 emissions over the season.

Implications for Regulations and Reporting Requirements

If the value of 0.14 kg NH_3 cow^{-1} d^{-1} is used to represent an open-lot dairy in this region, then according to the USEPA limit of 45.5 kg NH_3 d^{-1}, any farm over 325 cows would have

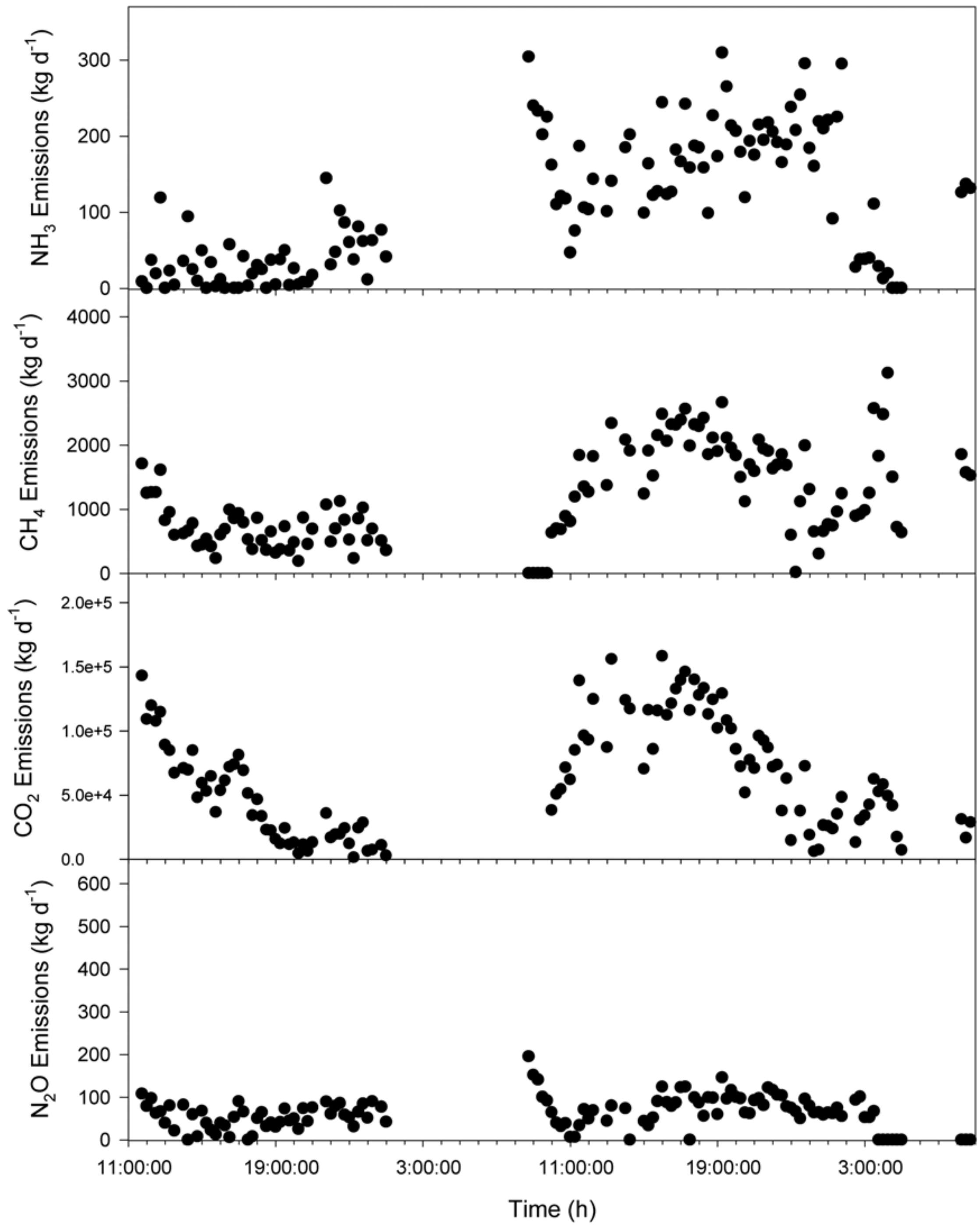

Fig. 4. Daily emission rates of (a) NH_3, (b) CH_4, (c) CO_2, and (d) N_2O measured over time from the compost area during April 2008.

to report NH_3 emissions under the Emergency Planning and Community Right-to-Know Act (USEPA, 2009b). The state of Idaho has a requirement that any farm emitting more than 90,909 kg NH_3 yr^{-1} adopt a certain number of best management practices to reduce NH_3 emissions. This would mean that any farm over 1779 cows would be over the state threshold and be required to reduce NH_3 emissions.

Emissions of greenhouse gases are expressed in equivalent terms, normalized to CO_2 using global warming potentials, and are referred to as CO_2 equivalents (CO_2e). The generation of CO_2e from CH_4 production at the open lots, which should represent mainly enteric fermentation (with some additional contribution from the manure stockpiles), was approximately 10.8 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 IPCC Tier 1 estimate is 8.1 kg CO_2e cow^{-1} d^{-1}, both of which are lower than the value determined in the present study. Because the USEPA does not consider CO_2 production from manure storage systems to be anthropogenic, it would not fall under the proposed rule for mandatory reporting of greenhouse gasses. However, both the CH_4 and N_2O generated from the lots (excluding enteric fermentation), wastewater pond, and compost would fall under the proposed reporting rule.

Table 3. Average emission rates of ammonia, methane, carbon dioxide, and nitrous oxide measured from the compost area of a 10,000-milking-cow open-lot dairy along with weather conditions.

Monitoring dates	Emissions rates				Weather conditions		
	NH_3	CH_4	CO_2	N_2O	Wind speed	Wind direction	Temp.
	kg d^{-1}				m s^{-1}	degrees	°C
18 Mar. (1045 h) to 18 Mar. (2015 h)	59† (43)‡	1506† (991)	30,295† (28,037)	12† (14)	2.7 (1.5)	265 (32)	13.0 (4.2)
21 Apr. (1145 h) to 23 Apr. (0845 h)	183† (40)	1660† (546)	81,299† (41,283)	79† (18)	2.4 (1.2)	244 (79)	8.1 (8.0)
21 May (1000 h) to 23 May (0715 h)	34 (72)	476 (578)	26,550 (26,727)	121 (44)	4.2 (3.2)	236 (56)	9.8 (3.9)
16 June (1000 h) to 17 June (0900 h)	345 (232)	3522 (2594)	126,308 (84,309)	267 (103)	1.7 (0.8)	205 (99)	23.6 (10.3)
13 Aug. (1030 h) to 15 Aug. (0815 h)	267 (120)	703 (708)	24,846 (19,489)	43 (32)	1.6 (0.7)	180 (78)	24.4 (9.7)
24 Sept. (1400 h) to 26 Sept. (0930 h)	95 (64)	258 (247)	20,350 (9095)	19 (8)	1.3 (0.6)	106 (82)	15.0 (10.3)

† 12-h averages.

‡ Values in parentheses are SD.

Table 4. Average combined emission rates of ammonia, methane, carbon dioxide, and nitrous oxide measured from the open-lot, wastewater pond, and compost areas of a 10,000-milking-cow open-lot dairy over four seasons.

Month	Emission rates			
	NH_3	CH_4	CO_2	N_2O
	kg d^{-1}			
Spring (Mar.–May)	1699	14,495	510,570	231
Summer (June–Aug.)	1581	13,080	287,258	270
Fall (Sept.–Nov.)	1748	26,834	400,657	76
Winter (Dec.–Feb.)	1474	5,760†	97,038†	50†
Average total emission, kg d^{-1}	1625	15,042	323,880	186
Average emission cow^{-1} d^{-1}‡	0.15	1.39	30.0	0.02
Average emission kg milk^{-1} d^{-1}§	0.005	0.044	0.94	<0.001

† Values substituted from March 2008.

‡ Average based on the 10,800 cows in the lot area,

§ Average based on the milk produced from the 10,000 milking cows in the lot area.

Because it is difficult to discern the CH_4 emissions from the manure stockpiles in the lots (due to the presence of the cattle) and previous studies have shown little CH_4 generation from fresh manure, we did not consider this as a separate source in our subsequent calculation. The combined manure management (wastewater pond and compost) CO_2e generation for the year at this facility would be approximately 67,690 metric tons of CO_2e. Even though N_2O is considered a more potent greenhouse gas and has a CO_2e value of 310, compared with a CO_2e value of 21 for CH_4, the contribution from N_2O was only 14% of the CO_2e generated from the manure management system. If all cows on the facility are included (13,000 cows, including dry cows and replacement heifers because they all contribute to the manure volume), this would be approximately 5.2 metric tons of CO_2e per cow per year. The USEPA reporting threshold value is 25,000 metric tons of CO_2e per year (USEPA, 2009a), which would equate to 4808 cows based on the information from this dairy. 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 our estimated threshold numbers.

When making decisions regarding regulation of dairy facilities, it is important to consider the productivity of these facilities. Although the kg CO_2e cow^{-1} d^{-1} from enteric fermentation on this open-lot dairy is 10.8, the average milk cow at this facility generates 34 kg milk d^{-1}, which translates to a value of 0.31 CO_2e per kg of milk produced. Other production systems, particularly pasture-based systems, not only generate less milk per cow but also generate higher CH_4 due to the high intake of lower quality forage. In these systems, the CO_2e kg milk can be as high as 0.74 CO_2e per kg of milk (Ulyatt et al., 2002). Therefore, it is imperative for emissions regulations to be based on unit of production instead of on an animal basis, as is typically used by USEPA. Related to this is the issue of scale. Because air quality is a regional issue, large producers are being penalized by reporting requirements or adoption of best management practices to control ammonia emissions when on an air-shed basis the total number of cows is likely more important. This is an issue that needs to be discussed by regulators to more fairly assess the burden of emissions reductions throughout an air-shed.

References

Amon, B., V. Kryvoruchko, T. Amon, and S. Zechmeister-Boltenstern. 2006. Methane, nitrous oxide, and ammonia during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112:153–162.

Amon, B., T. Amon, J. Boxberger, and C. Alt. 2001. Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutr. Cycling Agroecosyst. 60:103–113.

Bjorneberg, D.L., A.B. Leytem, D.T. Westermann, P.R. Griffiths, L. Shao, and M.J. Pollard. 2009. Measurement of atmospheric ammonia, methane, and nitrous oxide at a concentrated dairy production facility in southern Idaho using open-path FT-IR spectrometry. Trans. ASABE 52:1749–1756.

Cassel, T., L. Ashbaugh, R. Flocchini, and D. Meyer. 2005. Ammonia emission factors for open-lot dairies: Direct measurements and estimation by nitrogen intake. J. Air Waste Manage. Assoc. 55:826–833.

Flesch, T.K., L.A. Harper, J.M. Powell, and J.D. Wilson. 2009. Inverse-dispersion calculation of ammonia emissions from Wisconsin dairy farms. Trans. ASAE 52:253–265.

Flesch, T.K., J.D. Wilson, and L.A. Harper. 2005a. Deducing ground-to-air emissions from observed trace gas concentrations: A field trial with wind disturbances. J. Appl. Meteorol. 44:475–484.

Flesch, T.K., J.D. Wilson, L.A. Harper, and B.P. Crenna. 2005b. Estimating gas emissions from a farm with an inverse-dispersion technique. Atmos. Environ. 39:4863–4874.

Flesch, T.K., J.D. Wilson, L.A. Harper, B.P. Crenna, and R.R. Sharpe. 2004. Deducing ground-to-air emissions from observed trace gas concentrations: A field trial. J. Appl. Meteorol. 43:487–502.

Flesch, T.K., J.D. Wilson, L.A. Harper, R.W. Todd, and N.A. Cole. 2007. Determining ammonia emissions from a cattle feedlot with an inversion dispersion technique. Agric. For. Meteorol. 144:139–155.

Guarino, M., C. Fabbri, M. Brambilla, L. Valli, and P. Navarotto. 2006. Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. Trans. ASAE 49:737–747.

Hamilton, S.W., E.J. DePeters, J.A. McGarvey, J. Lathrop, and F.M. Mitloehner. 2010. Greenhouse gas, animal performance, and bacterial population structure responses to dietary monensin fed to dairy cows. J. Environ. Qual. 39:106–114.

Hao, X., C. Chang, and F.J. Larney. 2004. Carbon, nitrogen balances and greenhouse gas emission during cattle feedlot manure composting. J. Environ. Qual. 33:37–44.

Hellebrand, H.J., and W.D. Kalk. 2001. Emission of methane, nitrous oxide, and ammonia from dung windrows. Nutr. Cycling Agroecosyst. 60:83–87.

Hutchinson, G.L., A.R. Mosier, and C.E. Andre. 1982. Ammonia and amine emissions from a large cattle feedlot. J. Environ. Qual. 11:288–293.

Intergovernmental Panel on Climate Change. 2006. Emissions from livestock and manure management. p. 10.1–10.87. *In* S. Eggelston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (ed.) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmetal Strateges (IGES) for the IPPCC, Geneva, Switzerland.

Kaharabata, S.K., P.H. Schuepp, and R.L. Desjardins. 1998. Methane emissions from above ground open manure slurry tanks. Global Biogeochem. Cycles 12:545–554.

Khan, R.Z., C. Müller, and S.G. Sommer. 1997. Micrometeorological mass balance technique for measuring CH_4 emission from stored cattle slurry. Biol. Fertil. Soils 24:442–444.

Kinsman, R., F.D. Sauer, H.A. Jackson, and M.S. Wolynetz. 1995. Methane and carbon dioxide emissions from dairy cows in full lactation monitored over a six-month period. J. Dairy Sci. 78:2760–2766.

Lassey, K.R., M.J. Ulyatt, R.J. Martin, C.F. Walker, and I.D. Shelton. 1997. Methane emissions measured directly from grazing livestock in New Zealand. Atmos. Environ. 31:2905–2914.

Laubach, J., and F.M. Kelliher. 2005a. Measuring methane emission rates of a dairy cow herd (II): Results from a backward-Lagrangian stochastic model. Agric. For. Meteorol. 129:137–150.

Laubach, J., and F.M. Kelliher. 2005b. Methane emissions from dairy cows: Comparing open-path laser measurements to profile-based techniques. Agric. For. Meteorol. 135:340–345.

Leytem, A.B., R.S. Dungan, and D.L. Bjorneberg. 2009. Case study: Seasonal and spatial distribution of ambient ammonia concentrations measured at a large open-lot dairy. Prof. Anim. Sci. 25:786–793.

McGinn, S.M., K.A. Beuchemin, and T.K. Flesch. 2009. Performance of a dispersion model to estimate methane loss from cattle in pens. J. Environ. Qual. 38:1796–1802.

McGinn, S.M., T.K. Flesch, L.A. Harper, and K.A. Beuchemin. 2006. An approach for measuring methane emissions from whole farms. J. Environ. Qual. 35:14–20.

Misselbrook, T.H., J. Webb, D.R. Chadwick, S. Ellis, and B.F. Pain. 2001. Gaseous emissions from outdoor concrete yards used by livestock. Atmos. Environ. 35:5331–5338.

Misselbrook, T.H., J. Webb, and S.L. Gilhespy. 2006. Ammonia emissions from outdoor concrete yards used by livestock-quantification and mitigation. Atmos. Environ. 40:6752–6763.

Mukhtar, S., A. Mutlu, S.C. Capareda, and C.B. Parnell. 2008. Seasonal and spatial variations of ammonia emissions from an open-lot dairy operation. J. Air Waste Manage. Assoc. 58:369–376.

Ngwabie, N.M., K.H. Jeppsson, S. Nimmermark, C. Swensson, and G. Gustafsson. 2009. Multi-location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally-ventilated barn for dairy cows. Biosystems Eng. 103:68–77.

Rumburg, B., G.H. Mount, J. Filipy, B. Lamb, H. Westberg, D. Yonge, R. Kincaid, and K. Johnson. 2008. Measurement and modeling of atmospheric flux of ammonia from dairy milking cow housing. Atmos. Environ. 42:3364–3379.

Sneath, R.W., V.R. Phillips, T.G.M. Demmers, L.R. Burgess, J.L. Short, and S.K. Welch. 1997. Long term measurements of greenhouse gas emissions from UK livestock buildings. p. 146–153. *In* Livestock Environment V. Proceedings of the Fifth Int. Symp., Bloomington, MN. ASABE, St. Joseph, MI.

Sommer, S.G., S.O. Petersen, and H.T. Søgaard. 2000. Greenhouse gas emission from stored livestock slurry. J. Environ. Qual. 29:744–751.

Su, J.J., B.Y. Liu, and Y.C. Chang. 2003. Emission of greenhouse gas from livestock waste and wastewater treatment in Taiwan. Agric. Ecosyst. Environ. 95:253–263.

Sun, H., S.L. Trabue, K. Scoggin, W.A. Jackson, Y. Pan, Y. Ahao, I.L. Malkina, J.A. Koziel, and F.M. Mitloehner. 2008. Alcohol, volatile fatty acid, phenol, and methane emissions from dairy cows and fresh manure. J. Environ. Qual. 37:615–622.

Ulyatt, M.J., K.R. Lassey, I.D. Shelton, and C.F. Walker. 2002. Methane emissions from dairy cows and wether sheep fed subtropical grass-dominated pastures in mid summer in New Zealand. N. Z. J. Agric. Res. 45:217–226.

United Dairymen of Idaho. 2007. Available at http://www.idahodairycouncil.com/generaldairyinfo.asp (verified 15 Apr. 2010).

USDA National Agricultural Statistical Service. 2007. Livestock and animals. http://www.nass.usda.gov/QuickStats/indexbysubject.jsp?Text1=&site=NASS_MAIN&select=Select+a+State&Pass_name=&Pass_group=Livestock+%26+Animals&Pass_subgroup=Dairy (verified 3 May 2010).

USEPA. 2009a. 40 Code of Federal Regulations: Mandatory reporting of greenhouse gases. Federal Register 74:56373–56519.

USEPA. 2009b. Rule change provides exemptions from reporting requirements for air releases of hazardous substances from farm animal waste. USEPA fact sheet, January 2009. Available at http://water.unl.edu/c/document_library/get_file?folderId=67759&name=DLFE-3634.pdf (verified 16 Apr. 2010).