Methane Emission Patterns from Stored Liquid Swine Manure*

Kyu-Hyun Park and Claudia Wagner-Riddle

Department of Land Resource Science, University of Guelph, ON., N1G2W1, Canada

ABSTRACT : With the increase of human activities since the Industrial Revolution, atmospheric greenhouse gas (GHG) concentration has increased, which is believed the cause of climate change. Methane (CH_4) fluxes were measured at two commercial swine barns (Jarvis and Guelph) with a four tower micrometeorological mass balance method. Two and three separate measurements were conducted at Jarvis and at Guelph, respectively. In the Jarvis experiments from May to July, mean CH_4 flux (490.4 $\mu g/m^2/s$) during daytime was lower than that during nighttime (678.0 $\mu g/m^2/s$) ($p < 0.05$), which would be caused by break of slurry temperature stratification. In the Guelph experiment from January to April, mean CH_4 flux (62.9 $\mu g/m^2/s$) during daytime was higher than that during nighttime (39.0 $\mu g/m^2/s$) ($p < 0.05$), which would be generated by high slurry temperature at 3 cm depth after April 6. Slurry temperature stratification in the Guelph experiment would happen from January to March. (**Key Words :** Climate Change, Greenhouse Gases, Manure, Stratification)

INTRODUCTION

Human activities such as population growth, fossil fuel burning and deforestation since the Industrial Revolution are suspected of causing climate change, and anthropogenic greenhouse gases (GHG) are suspected as the main reason. Since 1750, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentration in the atmosphere have increased by 30, 151, and 17%, respectively (IPCC, 2001). Global emissions of CH_4 and N_2O from livestock manure contributes 5 to 10% of the total emission of CH_4 (Hogan et al., 1991; Rotmans et al., 1992) and 7% of N_2O (Khalil and Rasmussen, 1992). Stored animal manure shares 12 and 33% of total agricultural emissions of CH_4 and N_2O, respectively (Mosier et al., 1998a,b).

GHG emissions are affected by several environmental and animal factors and GHG emission estimates from stored manure have large uncertainties (Kaharabata et al., 1998; Sharpe et al., 2002). Slurry temperature affected microbial activity in slurry, was not affected by air temperature (Khan et al., 1997) and its increase caused more CH_4 emissions from stored animal manure (Hashimoto et al., 1981; Huested, 1994; Safley and Westerman, 1994).

IPCC (2000) suggested to use non-invasive GHG emission measurement methods year round in actual livestock production systems, which would reduce the large uncertainties in emission factors. Micrometeorological methods are proper to apply as these do not interfere with gas exchange processes between the surface source and the atmosphere (Denmead et al., 1998). Many research groups (Denmead, 1977, 1995; Beauchamp et al., 1978; Khan et al., 1997; Denmead et al., 1998) have used the micrometeorological mass balance (MMB) method as it is suitable for heterogeneous emission sources such as fertilized fields, waste storage sites or gas emissions from confined animals.

A year-round study with micrometeorological four tower mass balance method, measuring CH_4 emissions from circular manure storage tanks at two commercial farms in Ontario, Canada, was conducted in attempt to diminish the uncertainty of CH_4 fluxes from stored liquid manure. This paper was focused on the effects of environmental conditions on CH_4 fluxes from stored liquid swine manure

in the circular concrete storage tanks with MMB method.

MATERIALS AND METHODS

Experimental sites

Measurements were conducted at circular manure storage tanks of two commercial swine barns. One experiment site, Jarvis (42°58' N, 80°4'W), was located approximately 70 km South of Guelph, ON, Canada. The storage tank received manure from 2000 weaners, 650 sows and 75 gilts. The diameter and the depth of the storage tank were 34.4 m and 2.4 m, respectively. Animals were fed a commercial ration with alfalfa added. Four air sampling towers were placed at 31.5, 87, 235, and 300°, and one wind tower was set up at 227° on storage tank wall. Nitrous oxide and CH_4 emissions were examined over two periods, May 21 to July 16 (Jarvis 1) and November 8 to November 28 (Jarvis 2) in 2001, were examined. The other experimental site, Guelph (43°33'N, 80°25'W), was located about 10 km North from the University of Guelph, Guelph, ON., Canada. The storage tank received manure from 460 growers and 30 gilts. The diameter and the depth of the storage tank were 16.9 m and 3.0 m, respectively. The ration was chopped whole corn with soybean. Four sampling towers were placed at 83, 185, 270, and 345° and one wind tower was placed at 263° on the storage tank wall. Methane and N_2O emissions were studied over three periods, July 27 to August 10 (Guelph 1), October 11 to 30 (Guelph 2) in 2001, and January 14 to April 18 (Guelph 3) in 2002. However, N_2O fluxes were not used in this paper as it was negligible as shown in Wagner-Riddle et al. (2006). More information is shown in Park et al. (2006).

Methane flux measurement

Micrometeorological mass balance (MMB) approach used in this study was well explained in Wagner-Riddle et al. (2006). Brief information of MMB approach follows. The flux of a gas is given by the integration of the horizontal flux with omission of turbulent diffusion flux term. Hence, wind speeds and gas concentrations on upwind and downwind directions of source area, and the length (R) of wind traveled over the source area should be measured for flux calculation (Eqn. 1).

$$\bar{F} = \frac{1}{\bar{R}} \sum_{i=1}^{4} [(\bar{u}_i \Delta \bar{c}_i) \cdot \Delta z_i]$$

Eqn. 1

First, the fetch (R) was calculated through the one minute mean wind direction data and then 30 minute averaged fetch ($\bar{R}$) was calculated with one minute fetches (R). The Δc was calculated from the subtraction of CH_4 concentrations measured on the upwind tower(s) from CH_4 concentrations measured on the downwind tower(s) on the same height. Subscript i represented heights for air sampling and windspeed measurement. The 30 minute mean wind directions were used to designate upwind and downwind towers. The height of 25, 100, 200, and 350 cm on the sampling tower were assumed to represent the layers of 0 to 50 (z_1), 50 to 150 (z_2), 150 to 250 (z_3), 250 to 450 (z_4) cm, respectively. Further information was well described in Wagner-Riddle et al. (2006).

Four air sampling towers and one wind data collecting tower were installed on the wall of the circular manure storage tanks. Air sampling intakes were located at height of 25, 100, 200 and 350 cm on each air sampling tower. The wind tower had four arms parallel to ground. Each arm had a cup anemometer (F460, Climatronics Corp., Newton, PA) at the same heights (25, 100, 200, and 350 cm) of the air sampling tower. A wind vane (R.M.Young, Model 05102, Traverse, MI) recording wind direction was mounted on the top of the wind tower (400 cm). Four thermocouples collecting slurry temperature were mounted on a floating PVC pipe frame to measure slurry temperatures at the depth of 3, 20, 60, and 100 cm. Electrical wires of the anemometers, wind vane, and thermocouples were connected to a datalogger (CR7, Campbell Scientific, Edmonton, AB) housed in the trailer. The datalogger saved the mean wind direction data every minute, and mean wind speed and mean temperature data every half hour.

Methane concentrations in samples were quantified by a Tunable Diode Laser Trace Gas Analyzers (TGA) (Campbell Scientific, Inc., Logan, UT). The TGA was programmed to collect 10 Hz concentration data (=10 data points per second) as follows. Switching every 12.5 sec between the 16 air sampling intakes (four towers×four intakes) was controlled by the TGA operation computer. Twenty data points were discarded in order to remove air samples of previous intakes, resulting in collection of 105 data points (= analyzed CH_4 and N_2O concentrations) during every 12.5 sec. Hence, averaged CH_4 and N_2O concentrations over the 30-minute were obtained from 945 observations (= 105 data points×9 cycle = 945 observations), which made overall 15,120 observations (= 945 observations×16 intakes) during 30 minutes. The 30 min average concentrations and standard deviation data were stored in the TGA operation computer every 30 minutes.

RESULTS AND DISCUSSION

Basic information of weather

The mean annual temperature and precipitation Normals (1971-2000) for Jarvis and Guelph are 8.4 and 6.5°C, and

Table 1. Manure compositions as determined from samples taken at 30 cm depth of each experimental period at Guelph and Jarvis farms. Bracket shows standard deviation.

Site (Period)	Jarvis 1 May 21-July 16, 2001	Guelph 1 July 27-Aug 10, 2001	Guelph 2 Oct. 11-Oct 30, 2001	Jarvis 2 Nov. 8-Nov 28, 2001	Guelph 3 Jan. 14-Apr 18, 2002
pH	7.7 (0.05)	6.8 (0.11)	7.5 (0.08)	7.9 (0.24)	7.4 (0.09)
Redox (mV)	-333.7 (14.4)	-318.3 (6.9)	-333.4 (17.7)	-259.7 (8.6)	-255.2 (31.8)
TS (mg/kg)	6,629 (2,135)	30,519 (12,343)	17,126 (3,441)	6,253 (937)	8,530 (3,695)
TSN (mg/kg)	797.5 (94.6)	2,299.3 (135.7)	1,873.8 (402.5)	1,074.5 (46.9)	1,778.3 (315.2)
NH_4^+ (mg/kg)	677.9 (68.6)	2,066.3 (123.4)	1,397.6 (247.0)	882.3 (81.5)	1,244.9 (175.3)
TOC (mg/kg)	376.6 (57.5)	6,281.5 (195.2)	2,636.9 (491.9)	439.8 (16.2)	2,999 (493.9)

842.4 and 923.3 mm, respectively. Monthly atmospheric temperatures during the experiments were similar during May to October, 2001, but warmer (-2.7 to 7.7°C) than Normals (-7.6 to 5.9°C) during November, 2001 to April, 2002. Monthly mean slurry temperature measured at 60 cm depth was always higher than air temperature except on April, 2002 when steep air temperature increase happened. Slurry temperature increase followed air temperature increase. The standard deviation of slurry temperature during June and July, 2001 and April, 2002 were higher than those during other months because of large air temperature variations.

Composition of manure and CH₄ fluxes on experimental sites

The slurry samples collected at each site had similar pH, redox potential, total soluble nitrogen (TSN), ammonium (NH_4^+), and total organic carbon (TOC) values regardless of sampling locations within the storage tank (data not shown), but TS concentrations were different among the locations. This was reasonable because soluble nutrients should have similar concentration regardless of sampling location due to mixing of the liquid phase. Harper et al. (2000) found soluble ions had little concentration changes between lagoons or between effluent and sludge. Samples collected on different dates had different nutrient values during each period (data not shown). This would be mostly caused by flushing manure from below slat floor in the barn into the outdoor storage tank, and variable rate of manure decomposition over the course of the experimental period. Mean values of measured variables were shown in Table 1.

Environmental effects on GHG emissions

Slurry temperature effect : Microbial activities in stored

manure during Jarvis 1, Guelph 1 and Guelph 2 would be higher than during Jarvis 2 and Guelph 3 because of higher slurry temperature (Table 1). More active microbes at higher temperature consumed more substrates, resulting in more reduced condition by consuming oxygen (Nozhevnikova et al., 1997). In Jarvis experiments, mean CH₄ flux (583.4 μg/m²/s) during Jarvis 1 was over three times higher than that during Jarvis 2 (174.1 μg/m²/s). In Guelph experiments, mean CH₄ flux (1,054.8 μg/m²/s) during Guelph 2 was over 46 times higher than that during Guelph 3 (22.7 μg/m²/s). Mean CH₄ flux in Guelph 1 was 247.6 μg/m²/s. This low flux was due to wet crust on manure surface as it acted as strong resistance to gas exchange between manure surface and atmosphere. Sommer et al. (2006) reported the surface cover reduced CH₄ fluxes from stored livestock slurry.

Diurnal and nocturnal effects : High CH₄ emissions during daytime were reported (Khan et al., 1997; Kaharabata et al., 1998). In Jarvis 1, however, average CH₄ flux during daytime was smaller than during nighttime with statistical significance (Table 2). Figure 1 shows slurry temperatures at 3, 20, and 60 cm deep during June 1 to 9, 2001 at Jarvis 1. Slurry temperatures at 60 and 100 cm deep were highly correlated (r = 0.999) so that slurry temperature at 60 cm would be sufficient to represent slurry temperature below 100 cm deep. Temperature increased, peaked, and then decreased during daytime with higher temperature at upper part of stored manure. The slurry temperatures among depths were, however, similar from 19:00 to 7:00 next morning. Jarvis 1 had the largest temperature differences between 3 and 60 cm deep and did not have surface cover which would suppress gas emissions from stored manure. The highest slurry temperature at 3 cm deep and the lowest temperature at 60 cm deep during daytime would cause

Table 2. Diurnal (8:00 to 20:00) and nocturnal (20:00 and 08:00 next day) CH_4 fluxes during each experimental period. Methane flux data after stirring event in Jarvis 2 and before ice-cover melting in Guelph 3 were not used. Standard error (SE) and number of observed data (n) are shown in bracket (SE, n)

| CH_4 flux ($\mu g/m^2/s$)	Jarvis 1*	Jarvis 2	Guelph 1	Guelph 2	Guelph 3*
Diurnal	490.4	180.6	229.4	1,068.0	62.9
	(21.7, n = 120)	(10.8, n = 185)	(79.0, n = 22)	(39.1, n = 123)	(5.9, n = 29)
Nocturnal	678.0	165.7	271.1	1,038.9	39.0
	(34.8, n = 118)	(12.7, n = 128)	(55.6, n = 17)	(39.2, n = 102)	(3.6, n = 23)

* Significant difference between diurnal and nocturnal CH_4 fluxes with 5% significance level.

stratification within slurry (Figure 2). Water has the thermal anomaly of being densest at 4°C so that water below or over 4°C does not sink but stay at the surface. This stratification breaks down in the spring (spring turnover), followed by development of the summer stratification (Atlas and Bartha, 1998). Slurry mixing would be active with no temperature difference within slurry as no stratification would exist. Produced gas during daytime would be stored within slurry and be released when there was no stratification. In Jarvis 1, hourly mean of CH_4 fluxes tended to increase after 18:00, peaked at 2:00, and decreased afterward (Figure 1B). This

would be explained by stratification broken. There was no significant difference between diurnal and nocturnal CH_4 fluxes during Jarvis 2, Guelph 1 and Guelph 2 periods. This would be reasonable as slurry had small temperature change within a day so that CH_4 productions during daytime and nighttime would not be different. Guelph 3 had significantly higher average diurnal CH_4 fluxes than nocturnal ones (Table 2). Slurry temperature at 60 cm deep was near 4°C and slurry temperature at 3 cm deep was near 0°C at 60 cm deep before April 6 (DOY 98 in Figure 2). After April 6, slurry temperature at 3 cm deep exceeded slurry
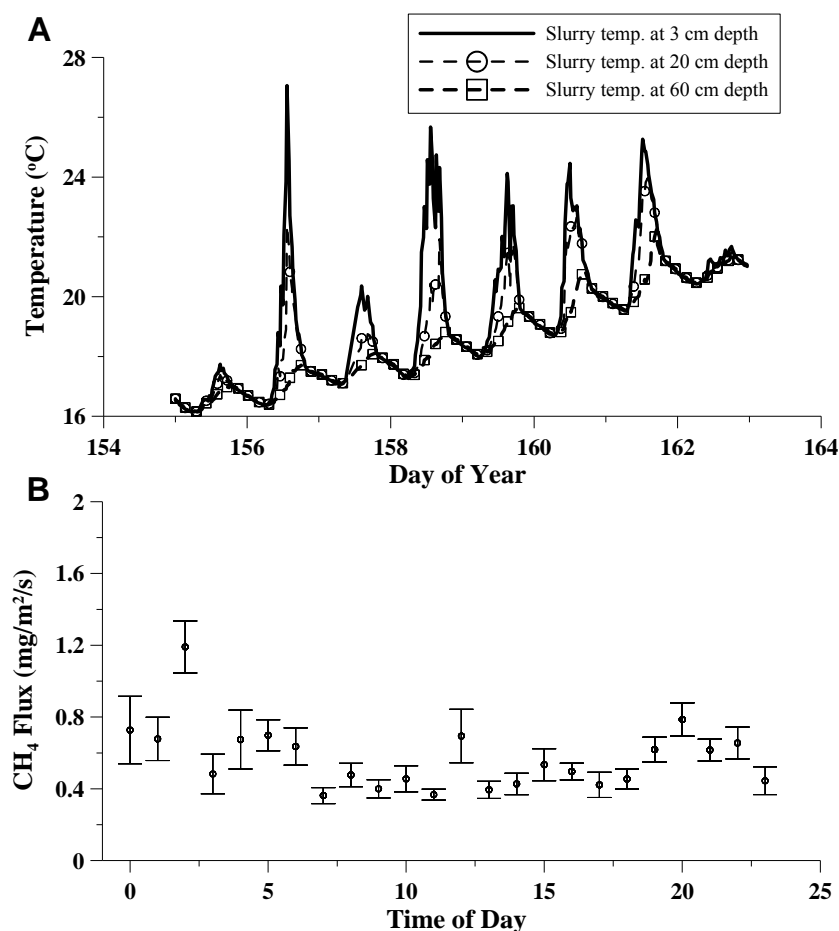
Figure 1. Slurry temperatures at 3, 20, and 60 cm depth during June 1 to 9 on Jarvis 1 (A) and CH_4 fluxes over time of day during Jarvis 1 period (B).
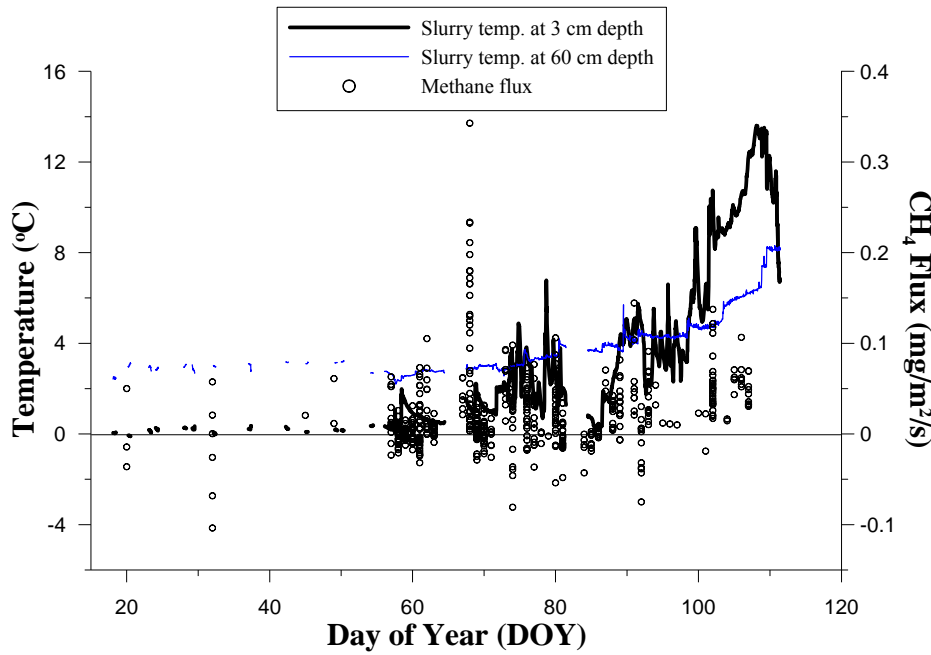
Figure 2. Half hourly CH$_4$ fluxes and slurry temperatures at 3 and 60 cm depth at Guelph 3 from January to April.

temperature at 60 cm deep. Winter stratification within slurry did not happen before April 6 and happened after April 10. Slurry temperature near surface was high to produce CH$_4$ after April 6 and this could explain high diurnal CH$_4$ flux on Guelph 3 because of methanogenesis during daytime. Methane produced in the sludge on the bottom of the storage tanks would be transported to the surface by ebullition and diffusion. Methane losses in the form of bubbles from lake sediments are a common and significant mechanism accounting for between 49 and 100% of total flux (Bartlett et al., 1988; Crill et al., 1988). Slurry temperature stratification would also play a role on

CH$_4$ loss patterns between daytime and nighttime.

The effect of stirring stored manure : Farmers stir their stored manure before they spread manure on crop fields. Much high gas emissions are usually detected with stirring or pumping (Husted, 1993; Sommer et al., 1993). In Guelph 2, the highest CH$_4$ fluxes were observed during stirring with large standard error of the mean. Sudden decrease of CH$_4$ fluxes after stirring were observed as stored CH$_4$ were emitted during stirring (Figure 3A). In Jarvis 2, daily average CH$_4$ fluxes were surged on DOY 326, the first stirring day, and then decreased on the next day (Figure 3B). Methane fluxes were the lowest on DOY 328 without
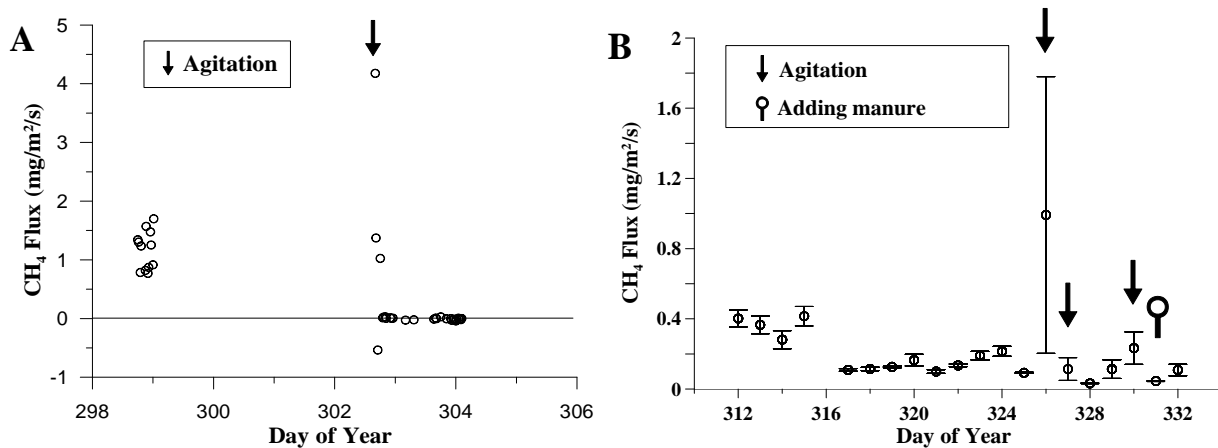
Figure 3. The effect of stirring event and flushing manure in the barn into a storage tank. Daily average CH$_4$ fluxes showing the effect of stirring event (DOY 302) and the effect of emptying stored manure at Guelph 2 (A) and the effect of stirring manure and flushing manure in a barn into a storage tank during Jarvis 2 (B) are shown. 'Bar' means standard error of CH$_4$ fluxes on each day. During Jarvis 2, farmer stirred and pumped stored manure out on November 22-23 (DOY 326-327) and on November 27 (DOY 330). Farmer flushed stored manure in the barn into the manure storage tank in the afternoon on November 28 (DOY 331).

stirring, even though the depth of slurry was 1.7 m. Methane fluxes were recovered to ordinary flux level the next day of stirring. Daily average CH_4 flux was increased on DOY 330 with short stirring event and low CH_4 flux on DOY 331 was observed. Farmer flushed barn manure into the storage tank in the afternoon on DOY 331 and CH_4 fluxes were increased on DOY 332. Kaharabata et al. (1998) reported CH_4 fluxes were peaked during stirring and decreased after stirring event.

CONCLUSIONS

Two and three separate measurements were conducted at Jarvis and at Guelph, respectively. In Jarvis 1, mean CH_4 flux (490.4 $\mu g/m^2/s$) during daytime were lower than that during nighttime (678.0 $\mu g/m^2/s$) ($p<0.05$), which would be caused by break of slurry temperature stratification. In Guelph 3, mean CH_4 fluxes (62.9 $\mu g/m^2/s$) during daytime was higher than that during nighttime (39.0 $\mu g/m^2/s$) ($p<0.05$), which would be generated by high slurry temperature at 3 cm deep after April 6. Slurry temperature stratification in Guelph 3 would happen as slurry temperature was near 0°C at 3 cm deep and was near 4°C at 60 cm deep.

REFERENCES

Atlas, R. M. and R. Bartha. 1998. Microbial ecology: fundamentals and applications, 4th ed., Benjamin/Cummings Publishing Company, Inc., Menlo Park, California.

Bartlett, K. B., P. M. Crill, D. I. Sebacher, R. C. Harriss, J. O. Wilson and J. H. Melack. 1988. Methane flux from the central Amazonian floodplain. J. Geophys. Res. 93:1571-1582.

Beauchamp, E. G., G. E. Kidd and G. Thurtell. 1978. Ammonia volatilization from sewage sludge applied in the field. J. Environ. Qual. 7:141-146.

Crill, P. M., K. B. Bartlett, J. O. Wilson, D. I. Sebacher, R. C. Harriss, J. M. Melack, S. MacIntyre, L. Lesack and S. Smith-Morrill. 1988. Tropospheric methane from an Amazonian floodplain lake. J. Geophys. Res. 93:1564-1570.

Denmead, O. T. 1977. A direct field measurement of ammonia emission after injection of anhydrous ammonia. Soil Sci. Soc. Am. J. 41:1001-1004.

Denmead, O. T. 1995. Novel meteorological methods for measuring trace gas fluxes. Philosophical Transactions of the Royal Society of London Series A: Math. Phys. Sci. 351:383-

396.

Denmead, O. T., L. A. Harper, J. R. Freney, D. W. T. Griffith, R. Leuning and R. R. Sharpe. 1998. A mass balance method for non-intrusive measurements of surface-air trace gas exchange. Atmos. Environ. 32:3679-3688.

Harper, L. A., R. R. Sharpe and T. B. Parkin. 2000. Gaseous nitrogen emissions from anaerobic swine lagoons: ammonia, nitrous oxide, and dinitrogen gas. J. Environ. Qual. 29:1356-1365.

Hashimoto, A. G., V. H. Varel and Y. R. Chen. 1981. Ultimate methane yield from beef cattle manure: effect of temperature, ration constituents, antibiotics and manure age. Agric. Wastes 3:241-256.

Hogan, K. B., J. S. Hoffman and A. M. Thompson. 1991. Methane on the greenhouse agenda. Nature 354:181-182.

Husted, S. 1993. An open chamber technique for determination of methane emission from stored livestock manure. Atmos. Environ. 27:1635-1642.

Husted, S. 1994. Seasonal variation in methane emission from stored slurry and solid manure. J. Environ. Qual. 23:585-592.

IPCC. 2000. Good practice guidance and uncertainty management in national greenhouse gas inventories (Ed. J. Penman, D. Kruger, I. Galbally, T. Hiraishi, B. Nyenzi, S. Emmanul, L. Buendia, R. Hoppaus, T. Martinsen, J. Meijer, K. Miwa and K. Tanabe). The Institute for Global Environmental Strategies, Japan.

IPCC, 2001, Climate change 2001: The scientific basis (Ed. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu). Cambridge University Press, UK.

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

Khalil, M. A. K. and R. A. Rasmussen. 1992. Forest hydrocarbon emissions: relationships between fluxes and ambient concentrations. J. Air Water Manag. Assoc. 42:810-813.

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

Mosier, A., J. M. Duxbury, J. R. Freney, O. Heinemeyer, K. Minami and D. E. Johnson. 1998a. Mitigating agricultural emissions of methane. Clim. Change 40:39-80.

Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger and O. van Cleemput. 1998b. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycl. Agroecosys. 52:225-248.

Nozhevnikova, A. N., C. Holliger, A. Ammann and A. J. B. Zehnder. 1997. Methanogenesis in sediments from deep lakes at different temperatures (2-70°C). Water Sci. Technol. 36:57-64.

Park, K-H., A. G. Thompson, M. Marinier, K. Clark and C. Wagner-Riddle. 2006. Greenhouse gas emissions from stored liquid swine manure in a cold climate. Atmos. Environ. 40:618-627.

Rotmans, J., M. G. J. Den Elzen, M. S. Krol, R. J. Swart and H. J. van der Woerd. 1992. Stabilizing atmospheric concentrations: Towards international methane contol. Ambio 21:404-413.

Safley, L. M. and P. W. Westerman. 1994. Low temperature

digestion of dairy and swine manure. Bioresour. Technol. 47:165-171.

Sharpe, R. R., L. A. Harper and F. M. Byers. 2002. Methane emissions from swine lagoons in southeastern US. Agric. Ecosyst. Environ. 90:17-24.

Sommer, S. G., B. T. Christensen, N. E. Nielsen and J. K. Schjørring. 1993. Ammonia volatilization during storage of cattle and pig slurry: effect of surface cover. J. Agric. Sci. 121:63-71.

Sommer, S. G., S. O. Petersen and H. T. Søgaard. 2006. Atmospheric pollutants and trace gases: greenhouse gas emission from stored livestock slurry. J. Environ. Qual. 29: 744-751.

Wagner-Riddle, C., K. H. Park and G. W. Thurtell. 2006. A micrometeorological mass balance approach for greenhouse gas flux measurements from stored animal manure. Agric. Forest Meteorol. 136:175-187.