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Methane emissions from an anaerobic swine lagoon

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Abstract

Gaseous methane (CH_4) emissions from a swine waste holding lagoon were determined periodically during the year. Micrometeorological techniques were used in order that emission rates from the lagoon were measured under ambient conditions with little disturbance to the natural environment. During the cold winter measurement period, CH_4 fluxes were linearly related to lagoon water temperature below 22°C ($r = 0.87$). During warmer measurement periods, both water and air temperatures and windspeed affected emissions rates. In general, flux rates followed a diurnal pattern with greater fluxes during the day when both temperature and windspeed were greatest. Mathematical models using air and water temperature and windspeed factors could explain 47 to 75% of the variation in fluxes. Daily emission rates ranged from 1 to 500 kg CH_4 ha^{-1} d^{-1}. The average flux for the year was 52.3 kg CH_4 ha^{-1} d^{-1} which corresponded to about 5.6 kg CH_4 animal^{-1} yr^{-1} from the primary lagoon.

Keywords: Anaerobic lagoon; Micrometeorological; Hogs; Pigs; Greenhouse gases

1. Introduction

Reported CH_4 emissions from the decomposition of animal manure in North America are about 2 300 000 mt yr^{-1} with about 40% of the total from swine (Adler, 1994). There are about 55 800 000 swine in the United States (USDA/NASS, 1998) and anaerobic lagoons are used in about 25% of the swine facilities (Safley et al., 1992). Anaerobic lagoons which produce significantly more CH_4 than solid systems account for about 61% of the total North American CH_4 emissions from animal waste (Adler, 1994). The EPA estimates that 788 000 mt of CH_4 are produced each year from anaerobic swine lagoons (Safley et al., 1992).

Current estimates of CH_4 emissions are based on biogas production from anaerobic digesters and covered lagoons or on the CH_4 production potential of animal waste. Most anaerobic digesters are operated at constant mesophilic or thermophilic temperatures (Hill, 1984) and CH_4 production rates of about 1.1 m^3 gas m^{-3} digester volume have been reported for swine waste (Hashimoto, 1983; Pos et al., 1985). Ambient temperatures influence both the short- and long-term production of CH_4. Cullimore et al. (1985) reported CH_4 emissions of about 0.03 m^3 gas m^{-3} digester volume at 8–10°C and 0.3 m^3 gas m^{-3} digester volume at 22–26°C. In studies with covered lagoons, biogas production rates are reduced at lagoon temperatures below 13–15°C (Safley and Westerman, 1989). Methane emissions from covered lagoons are influenced by organic acid concentrations and position of collection covers as well as lagoon temperatures (Safley and Westerman, 1988). Most agricultural lagoons are loaded at one or two points resulting in higher loading rates in these areas. Consequently, CH_4 emission rates may vary depending on the areas of lagoon covered (Safley and Westerman, 1988). Reported CH_4 emissions from covered lagoons have ranged from 0.04 to 0.2 m^3 CH_4 m^{-2} lagoon surface area (Safley and Westerman, 1988; Humenick and Overcash, 1976).

Carbon dioxide (CO_2), CH_4, and nitrous oxide (N_2O) have grown about 13%, 145%, and 15%, respectively,

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since 1750 (IPCC, 1996). Methane is the most rapidly increasing greenhouse gas and accounts for about 27% of all climate forcing (IPCC, 1996). Since anaerobic lagoons are widely used in the United States for the treatment of swine waste and lagoons are a significant source of CH_4, accurate emission measurements and emission factors are needed in order to evaluate the effects of concentrated animal production on the atmospheric environment. The objectives of this research were to determine CH_4 emissions from an anaerobic swine waste holding lagoon under natural conditions, to compare these emissions to those determined under covered lagoons and to evaluate climate influences on CH_4 emissions.

2. Experimental techniques

The swine production unit was a farrow to finish farm with 12 000 animals located in the Coastal Plains of Georgia. The waste disposal system was a series of four lagoons with the animal house waste being emptied into the first lagoon (Fig. 1). The lagoon surface areas were 3.5, 1.3, 3.5 and 1.3 ha for lagoons 1–4, respectively. The effluent was pumped from all the houses into lagoon 1 and then gravity fed in succession to the other lagoons. All micrometeorlogical measurements were from the first lagoon. Annually, about 300 000 m^3 water (82% recycled from lagoon # 4 and 18% fresh water) was used to remove waste from the houses.

Micrometeorological instrumentation was located on a platform "barge" in lagoon 1 with wires and tubing connected to a trailer on the north shore. Instruments for wind speed, temperature and gas concentration profiles were affixed to the barge with attached flotation tanks. The barge with micrometeorological equipment was floated into the lagoon to obtain a minimum fetch of at least 50 : 1 (upwind lagoon distance : measurement height), secured into place with adjustable legs extending to the bottom and guylines attached to the shore. The barge was then sunk to about 50 mm below the water surface to minimize structural interference of wind flow patterns by the platform itself. The barge was located about 80 m from the north shore, 112 m from the south shore and 93 m from the east and west shores. Windspeed (sensitive cup anemometers, model 106-LED-DC, Thornthwaite Asso.) and air temperatures (aspirated thermocouples, model ASPTC, Campbell Scientific) profiles were measured at six heights (0.2, 0.4, 0.6, 1.6, and 2.7 m) above the lagoon. Water temperature was measured with thermocouples at three vertical depths, near the surface (about 0.05 m), in the sludge layer (about 3 m), and at a mid-point between the two layers.

Methane concentration profiles were measured at the 0.6 and 1.6 m heights using tunable diode laser spectroscopy (TDL). The TDL (model TGA100, Campbell Scientific) technique is based on infrared spectroscopy (Dias et al., 1996; Edwards et al., 1994). The diode laser is mounted in a liquid nitrogen-cooled dewar and a heater in the dewar gives precise control of the laser in the 78–110 K region. The laser was operated in the IR spectral region between 3000 and 3025 cm^{-1}. The sample and reference cells are 1.54 and 0.05 m long, respectively. Both sample and reference detectors were Peltier-cooled mercury–cadmium–tellurium IR detectors (EG & G, Judson). The instrument had a total noise of about 10 ppbv. The TDL was located in a trailer beside the primary lagoon (Fig. 1) and was connected to the barge with a 90 m copper inlet tube. The TDL's electronics

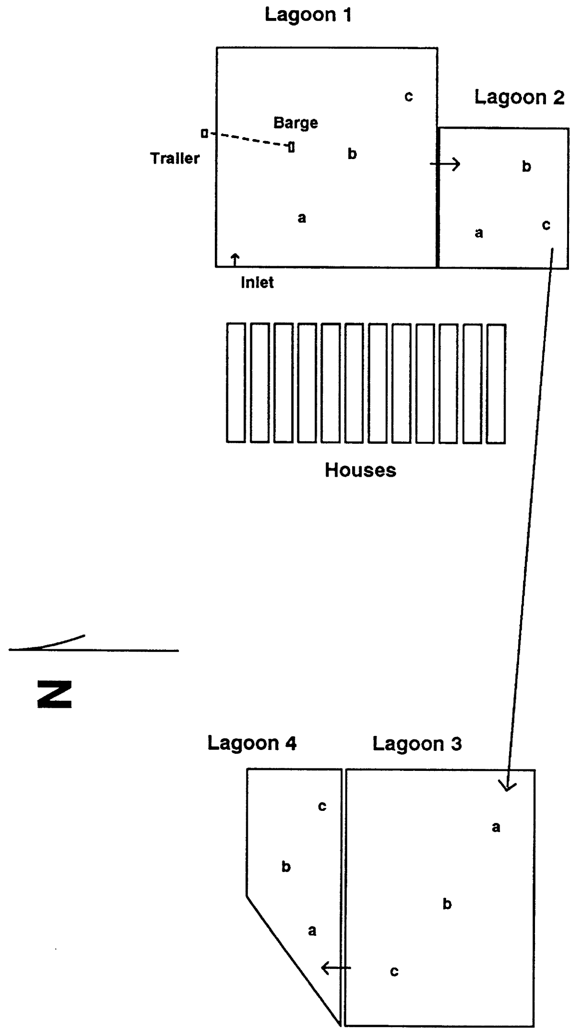

Fig. 1. Schematic diagram of swine production facility. Lagoons 1 and 3 are 3.5 ha and lagoons 2 and 4 are 1.3 ha. Approximate location of temperature sensors and gas collection carboys are indicated by the letters a, b, and c in each lagoon.

were integrated with a PC for software control of the digital signal processing, laser function, real-time display of laser-operating functions and for data storage. Methane concentrations were measured 10 times s^{-1} and delta CH_4 concentrations (concentration differences between the two sample heights) were calculated every minute. Delta concentrations were averaged over 30-min periods for use in the flux gradient technique. Mylar balloons were used to transport references gases to the barge to calibrate the laser spectrometer.

Seventeen data collection periods (24 h period) were made during three measurement seasons, in 1996. Methane flux densities were determined during the measurement seasons above the lagoon surface using CH_4 profile concentrations and the momentum balance transport coefficient. The relationship for CH_4 flux density is

$$C = K_{mb}\frac{\Delta n}{\Delta z}, \quad (1)$$

where C is the CH_4 flux densities (kg CH_4 ha^{-1} d^{-1}), n the atmospheric CH_4 concentration (μg CH_4 m^{-3}), z the gradient measurement height (cm), and K_{mb} the momentum balance transport coefficient. K_{mb} is determined from the relationship

$$K_{mb} = \frac{-k^2(\mu_2 - \mu_1)}{\{\ln[(z_2 - z_d)/(z_1 - z_d)]\}^2\Psi^2}, \quad (2)$$

where k is the von Karmon constant, μ the windspeed (cm s^{-1}), $z_d \cong 0$ (cm) for a water surface, and Ψ the stability correction factor (Dyer and Hicks, 1970). Errors associated with the flux gradient micrometeorlogical technique have been discussed by Harper (1988) and Denmead and Raupach (1993). Data were analyzed using the stepwise regression procedures of SAS (SAS Inst., 1991).

In addition to the primary measurements made in lagoon 1, gas bubbles emitted from each of the lagoons were trapped at the surface of the sludge layer (about 3 m deep) and at the 0.5 m depth in the spring of 1998. Open bottom carboys with tubing extending to the surface were used for trapping and sampling gases [locations a, b and c (Fig. 1)]. When the carboys were about full, collected gas was transferred to an evacuated summa canister (model 6L, BRC/Rasmusson) and transported to the laboratory for analysis with a gas chromatograph (Tracor model 540) with a porpak Q column and flame ionization detector. Calibration gases for the mass spectrometer were Scott Specialty Gases, Certified Standards. Instrumentation calibration was from a two to four calibration procedure and all samples were run in duplicate. Checks for atmospheric contamination in the sampling procedure was done my immersing a carboy into the lagoon bubbling helium (He) beneath the carboy until full. Collected He was then analyzed for dinitrogen (N_2) contamination. Mass flux of gas bubbles emitted were estimated by measuring the volume of the collected gas with time in the four lagoons.

3. Results and discussion

The average flux rates and lagoon pH are shown in Table 1. Flux rates ranged from 44.7 in the winter to 60.3 kg CH_4 ha^{-1} d^{-1} in the summer. The decrease in pH in both the liquid effluent and the bottom sludge during the winter (Table 1) was probably caused by an accumulation of organic acids indicating less productivity of methanogenic bacteria and thus reduced CH_4 emission rates. During the winter, CH_4 fluxes were closely related to water temperature (Fig. 2). As water temperatures decreased CH_4 fluxes decreased, but even below 5°C average fluxes were about 12 kg CH_4 ha^{-1} d^{-1}. As water temperature increased there was a linear increase in CH_4 flux ($r = 0.87$) up to about 22°C. A logarithmic transformation of the CH_4 flux data was used to normalize the errors about the line before calculation correlation coefficients. These results agree with laboratory studies which indicated that CH_4 production was linear below 26°C (Cullimore et al., 1985).

Both the average fluxes and the day to day variations in fluxes were larger during the spring and summer measurement periods than during the winter (Figs. 3 and 4). During the warmer seasons, windspeed and air temperature as well as lagoon temperature effected CH_4 emissions. In general, flux rates followed a diurnal pattern with greater fluxes during the day when both temperature and windspeed were the greatest. Mathematical

Table 1
Dates, average CH_4 flux rates (kg ha^{-1} d^{-1}) and pH of liquid effluent and bottom sludge for a swine lagoon

Season	Date	Average CH_4 flux	pH	
			Effluent	Bottom
Winter	Feb. 11–Feb. 16	44.7	7.44 ± 0.02	6.90 ± 0.38
Spring	May 16–May 23	52.0	7.51 ± 0.10	7.28 ± 0.24
Summer	Aug. 12–Aug. 17	60.3	7.70 ± 0.06	7.20 ± 0.22

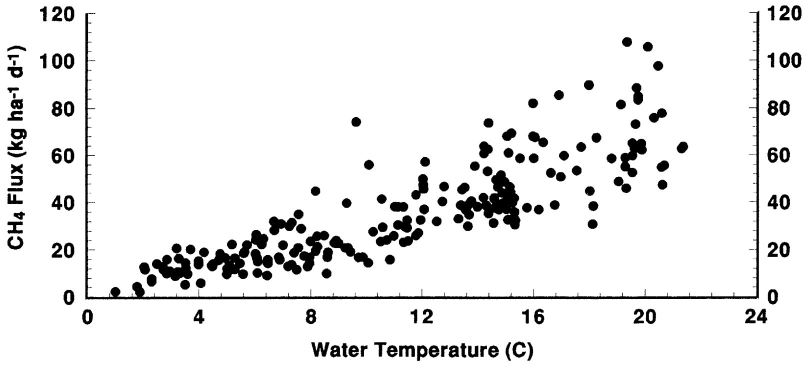

Fig. 2. Relationship between liquid effluent temperature and CH_4 flux during winter measurement period (11 February–16 February).

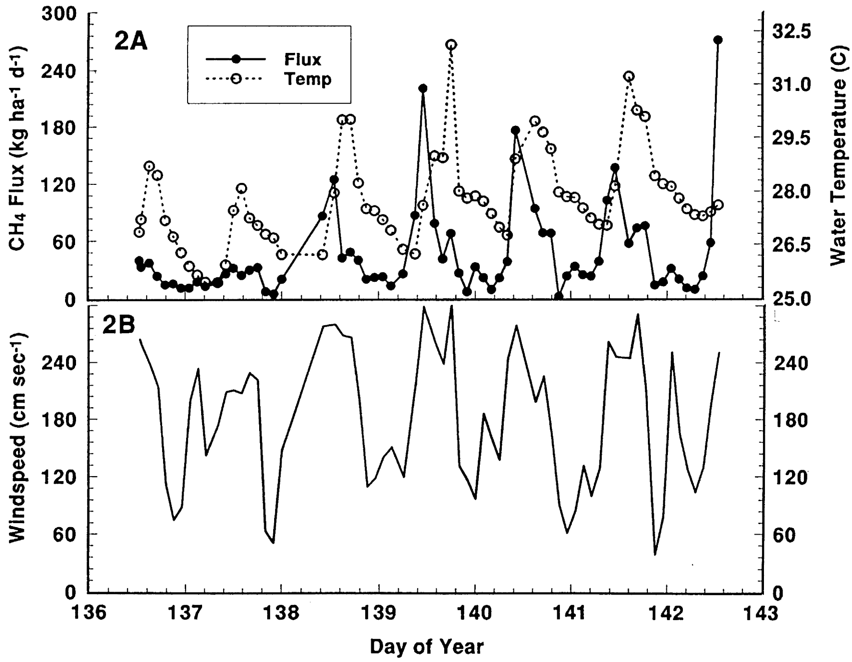

Fig. 3. Relationship between liquid effluent temperature, windspeed (cm/s) and CH_4 flux (kg ha^{-1} d^{-1}) during spring measurement period, 16 May–22 May (DOY 136–143).

models based on environmental factors such as air temperature, windspeed, and lagoon temperature were developed to try to predict CH_4 flux rates. Depending on the measurement period, these factors explained 47–75% of the variation in fluxes. During the spring and summer measurement periods, CH_4 flux was related to air and effluent temperature and windspeed ($R^2 = 0.47$ and 0.52, respectively) (Figs. 3 and 4). Increasing windspeed and temperatures resulted in higher flux densities. However, there was no single environmental factor or group of factors which consistently explained day to day variations in CH_4 flux in all the measurement periods. It appears that some other factor such as total C, soluble C, volatile solids, or daily input were major factors in controlling CH_4 emissions from lagoons. Samples were not analyzed for C daily, but soluble C averaged 193 ± 8 and 405 ± 273 mg l^{-1} in the effluent and sludge, respectively. Soluble C in the input was 373 ± 56 mg l^{-1}.

When data for the entire year were combined (Fig. 5) the correlation between environmental factors and CH_4 flux was low ($R^2 = 0.36$). The discrepancy between predicted and measured fluxes may have been due to

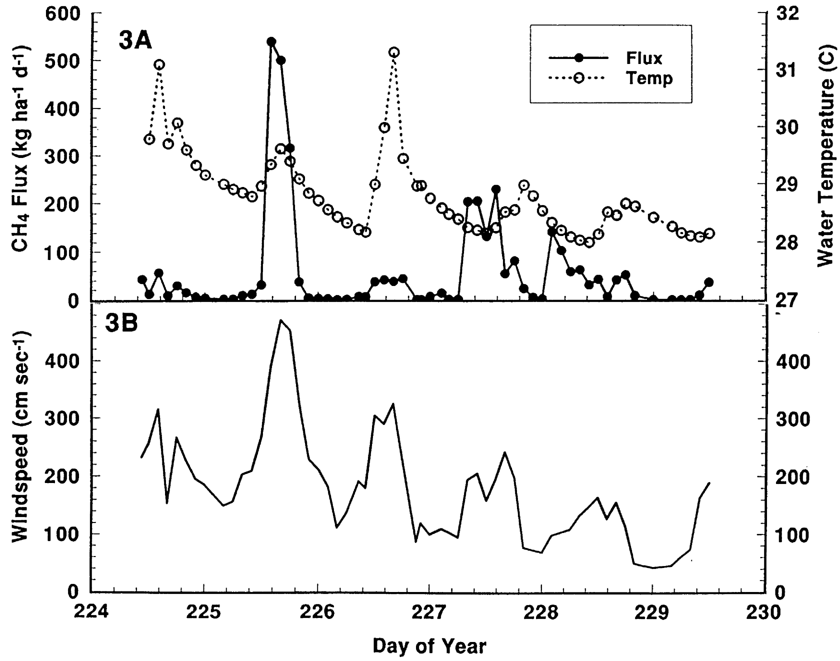

Fig. 4. Relationship between liquid effluent temperature, windspeed (cm/s) and CH_4 flux (kg ha^{-1} d^{-1}) during summer measurement period, 12 August–17 August (DOY 224–229).

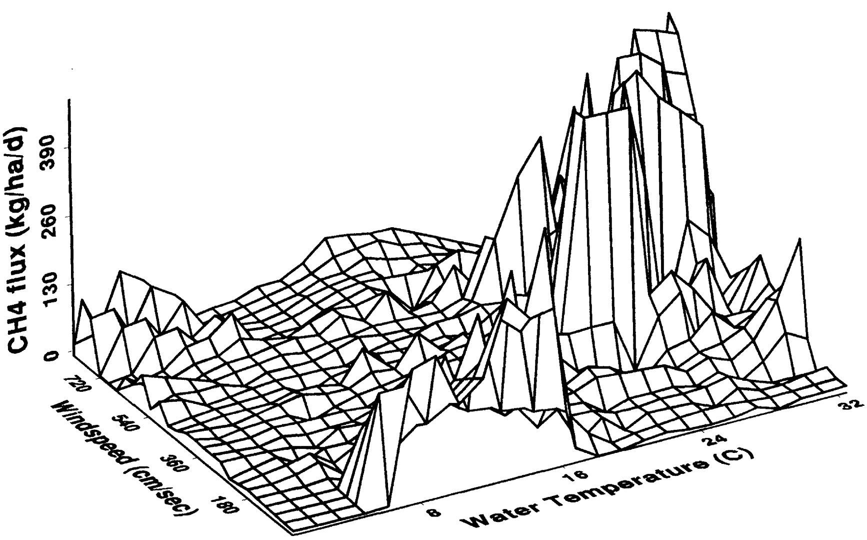

Fig. 5. Relationship between liquid effluent temperature, windspeed and CH_4 flux.

a dependence on the interrelationships of biological and physical factors. The biological factors were the effects of temperature on biological activity and to changes in the type of methanogenic bacteria present in the lagoon. Relatively large fluxes occurred between 8 and 16°C during the winter season. During this period psychrophilic methanogenic bacteria were probably dominant and these temperatures would optimize CH_4 for psychrophilic bacteria. During the warm measurement periods, mesophilic bacteria would probably be the primary methanogenic bacteria. Optimal temperatures for CH_4 production with mesophilic bacteria are 30–35°C (Cullimore et al., 1985) so lagoon temperatures of 20–24°C would be in the lower mesophilic range and thus gas production would be less. The physical effect was the ability of the wind turbulence to remove CH_4 from the water-surface/atmospheric-boundary layer. The rate limiting boundary layer was the diffusive air boundary layer and the removal of CH_4 from the boundary layer is a function of the atmospheric turbulence (windspeed) and atmospheric stability measured by Richardson's Number (Richardson, 1929).

Average daily emissions in this study ranged from 44 to 60 kg CH_4 ha^{-1} d^{-1} (Table 1). These values correspond to 0.005–0.009 m^3 CH_4 m^{-2} lagoon surface which were less than a tenth of those reported for covered lagoons (Safley and Westerman, 1988; Humenick and Overcash, 1976). Part of the discrepancy between the results in this study and those from covered lagoons was probably due to dilution of waste into lagoons 2, 3, and 4. The yearly average emission from lagoon 1 for the study was 52.3 kg CH_4 ha^{-1} d^{-1} which corresponded to about 5.6 kg CH_4 $animal^{-1}$ yr^{-1} (4 kg CH_4/45 kg animal). Methane flux measurements were not determined for lagoons 2–4 in 1996. Methane flux measurements in spring 1998 were estimated in all four lagoons using gas collection carboys submerged in the lagoons (Table 2). The large standard deviation in flux rates was probably due to the location of the gas collectors in relation to the input site. Fluxes were always greater in the collectors closest to the input site. These results were similar to those of Safley and Westerman (1988) who reported greater CH_4 emissions when lagoon areas close to the input were covered. Methane accounted for about 79% of the emitted gases in lagoon 1 to 8% of gases in lagoon 4. The large decrease in CH_4 in lagoons 2–4 was probably due to lack of C substrate, since there was no sludge accumulation in the bottom of the lagoons, and to the aeration of the effluent (Table 2). The dissolved O_2 in the effluent was < 0.5, 8.7, 18.4 and 20.0 mg O_2 l^{-1} in lagoons 1, 2, 3 and 4, respectively. Assuming similar fluxes in 1996 and 1998, then average CH_4 in lagoons 2, 3 and 4 was about 0.5 kg CH_4 $animal^{-1}$ yr^{-1}. There are about 55 800 000 swine in the United States (USDA/NASS, 1998) with 75% of the swine production systems in North America using anaerobic or liquid/slurry systems (Safley et al., 1992). Using these animal population and lagoon figures with total emissions from all four lagoons (6.1 kg CH_4 $animal^{-1}$ yr^{-1}) this study would give an estimation of about 255 000 mt yr^{-1}. Eklund and LaCosse (1995) reported emission rates of 106 kg CH_4 $animal^{-1}$ yr^{-1} in an EPA study. Using Eklund and LaCosse data with animal population and lagoon figures would result in about 4 400 000 mt yr^{-1}. The EPA estimated that 788 000 mt of CH_4 are produced each year from anaerobic swine lagoons. This estimate does not include any direct measurements of CH_4 flux and is based on maximum CH_4 producing capacity, CH_4 conversion factors, and climate adjustment factors because there are few direct measurements of CH_4 fluxes from lagoons (Safley et al., 1992). Additional studies are required to reconcile the large discrepancies in emission rates between this study, the rates reported by Eklund and LaCosse (1995), and rates reported by Safley et al. (1992) based on total CH_4 producing potential.

Table 2
Mass flux of gases emitted from the sludge layer of a four-stage swine lagoon system in 1998

Lagoon #	% CH_4	CH_4 flux kg ha^{-1} d^{-1}	% O_2[a]	O_2 flux kg ha^{-1} d^{-1}
1	79.2	125.9 ± 47.6	0.60	0.95
2	26.2	5.5 ± 2.9	1.46	0.31
3	13.1	2.6 ± 2.5	2.24	0.45
4	7.6	1.3 ± 0.7	7.52	1.28

[a]Concentrations of O_2 and CO_2 in the mass flux gas analyses are likely influenced by algae growing in the gas collectors.

4. Conclusions

Under natural conditions, CH_4 fluxes were linearly related to water temperature below 22°C. At higher temperatures emission rates are correlated with water and air temperatures and windspeed. However, the correlation could only account for about 50% of the variations in CH_4 flux and some other components of the system are major factors in controlling emissions from swine lagoons. Further research is needed to investigate differences in reported CH_4 emission measurements and to determine the environmental and/or lagoon characteristics controlling emission rates. It is evident that the United States and other countries are committed to limiting global greenhouse gas emissions and US agriculture needs accurate and reliable information on its contribution to total gas emissions and to identify possible areas for reduction.

References

Adler, J.A., 1994. International anthropogenic methane emissions: estimates for 1990. Report to Congress. EPA Report 230R93010, 332 pp.

Cullimore, D.R., Maule, A., Mansuy, N., 1985. Ambient temperature methanogenesis from pig manure waste lagoons: thermal gradient incubator studies. Agricultural Wastes 12, 147–157.

Denmead, O.T., Raupach, M.R., 1993. Methods for measuring atmospheric gas transport in agricultural and forest systems. In: Harper, L.A., Mosier, A.R., Duxbury, J.M., Rolston, D.E. (Eds.) Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. American Society of Agronomy Special Publication Number 55, Madison, WI, pp. 19–43.

Dias, G.T., Thurtell, G.W., Wanger-Riddle, C., Harper, L.A., 1996. Measuring ammonia fluxes from soil with a laser-based trace gas analyzer. Proceeding International Conference On Air Pollution from Agricultural Operations.

Dyer, A.J., Hicks, B.B., 1970. Flux-gradient relationships in the constant flux layer. Quarterly Journal Royal Meteorological Society 96, 715–721.

Edwards, G.C., Neumann, H.H., den Hartog, G., Thurtell, G.W., Kidd, G.E., 1994. Eddy correlation measurements of methane fluxes using a tunable diode laser at the Kinosheo Lake tower site during the Northern Wetlands Study (NOWES). Journal of Geophysical Research 99, 1511–1517.

Eklund, B., LaCosse, J., 1995. Field measurements of greenhouse gas emissions from the wastewater treatment systems at two farms. EPA Contract No. 68-D-0031, Work Assignment 66, U.S.E.P.A. Office of Research and Development, Washington, DC.

Harper, L.A., 1988. Comparisons of methods to measure ammonia volatilization in the field. In: Bock, B.R., Kissel, D.E. (Eds.), Ammonia Volatilization from Urea Fertilizers, pp. 93–111. Bull. Y-206, National Fertilizer Development Ctr., Tennessee Valley Authority, Muscle Shoals, AL.

Hashimoto, A.G., 1983. Thermophilic and mesophilic anaerobic fermentation of swine manure. Agricultural Waste 6, 175–191.

Hill, D.T., 1984. Methane productivity of the major animal types. Transactions American Society Agricultural Engineers 27, 530–534.

Humenik, F.J., Overcash, M.R., 1976. Design criteria for swine treatment systems. EPA Report 600/2-76-233. 291 pp.

IPCC, 1996. Climate change 1995: the IPCC second assessment Report, vol. 1 The science of climate change.

Pos, J., Eszes, R., Pavicik, V., 1985. Evaluation of two full-size mesophilic digester processing swine manure. Agric. Waste Utilization and Management. Proceedings of the fifth ISAW. ASAE 81–90.

Richardson, L.F., 1929. The supply of energy from and to atmospheric eddies. Proceedings of Royal Society 97, 354–373.

Safley, Jr, L.M., Casada, M.E., Woodbury, J.W., Roos, K.F., 1992. Global methane emissions from livestock and poultry manure. United States Environmental Protection Agency, Washington, DC.

Safley Jr, L.M., Westerman, P.W., 1988. Biogas production from anaerobic lagoons. Biological Wastes 23, 181–193.

Safley Jr, L.M., Westerman, P.W., 1989. Anaerobic lagoons biogas recovery systems. Biological Wastes 24, 43–62.

SAS Institute, 1991. SAS Users Guide: Statistics. Version 6.03. SAS Institute, Cary, NC.