Short communication

Methane emissions from swine lagoons in Southeastern US

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Abstract

Concentrated animal production can have a significant effect on the atmospheric environment. Methane (CH4) emissions from two swine waste holding lagoons were determined periodically in 1997 and 1998. Emission rates from the lagoons were measured under ambient conditions with little disturbance to the natural environment. One farm (NC10) used a periodic 'flush' to remove wastes (8 h cycle). The second farm (NC20) used a 'pull-plug' system with a 1 week cycle time. In general, flux rates followed a diurnal pattern with greater fluxes during the day when both temperature and windspeed were greatest. Methane emissions from the lagoons were related to windspeed, effluent temperature and volatile solid loading into the system. Average emissions from NC10 ranged from 20 to 115 kg CH4 ha−1 per day. Greatest emissions were during the spring period when the sludge depth was deepest. Emissions from NC20 were much less (5.3–10.7 kg CH4 ha−1 per day) due primarily to fewer number of animals and type of manure handling system. Emissions followed a diurnal pattern with greatest emissions during the day when effluent temperature was greatest. The average flux for the year from the two lagoons were 62 and 8 kg CH4 ha−1 per day which corresponded to 6.0 and 1.6 kg CH4 per animal per year, respectively. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Concentrated animal production is increasing in the United States. Concentrated production results in increased production efficiency, improved economics and a better industry support system. High animal concentrations, however, increase problems of storage and waste disposal. 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 (Salley et al., 1992). Anaerobic lagoons, open pits about 3 m deep, which produce significantly more CH4 than solid systems account for about 61% of the total North American CH4 emissions from animal waste (Adler, 1994). Total CH4 emissions from the decomposition of animal manure in North America are about 2,300,000 metric tons per year with about 40% of the total from swine (Adler, 1994).

Current estimates of CH4 emissions are based on biogas production from anaerobic digesters and covered lagoons or on the CH4 production potential of animal waste. Most anaerobic digesters are operated at constant mesophlic or thermophilic temperatures (Hill, 1984) and CH4 production rates of about 1.1 m3 gas m−1 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; Humenik and Overcash, 1976). Sharpe and Harper (1999) reported that CH$_4$ emissions from the primary lagoon of a 4-stage lagoon system in south Georgia ranged from 1 to 500 kg CH$_4$ ha$^{-1}$ per day with an average flux for the year of 52.3 kg CH$_4$ ha$^{-1}$ per day.

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 anaerobic swine waste holding lagoons under natural conditions, to compare these emissions to those determined for other lagoons under different management and environmental conditions and to those determined for covered lagoons.

### Materials and methods

#### Lagoon characteristics

The swine production units studied (designated as NC10 and NC20) are located in the Coastal Plains of North Carolina. Their waste disposal systems are anaerobic lagoons with the animal house waste emptied directly into the lagoon. Farm and lagoon characteristics are shown in Table 1. The NC10 production facility uses a periodic ‘flush’ to remove wastes (about an 8 h cycle) and NC20 uses a ‘pull-plug’ system with a cycle time of about 1 week. Water used in the flushing is recycled wastewater from the lagoon. Other water entering the lagoon is from normal cleaning and washing loss from the drinking system, urine, and rainfall. The quantity of waste water entering the lagoon was not measured but the loading rate into the lagoon was calculated from the quantity of feed at each farm and assuming a feed dry matter content of 88 and 19% of the feed dry matter being excreted (Hall et al., 1988; Jongbloed, 1991). Total feeding rations were 7,567,000 and 3,161,000 kg at NC10 and NC20, respectively.

#### Atmospheric measurements

Micrometeorological instrumentation was located on a platform ‘barge’ 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 surface area: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

### Table 1
Management characteristics for swine production facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Farm type</th>
<th>Lagoon size (ha)</th>
<th>Number of animals</th>
<th>Weight per animal (kg)</th>
<th>Lagoon depth (cm)</th>
<th>Manure depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC10</td>
<td>Farrow to finish</td>
<td>2.7</td>
<td>13700</td>
<td>58</td>
<td>121</td>
<td>29</td>
</tr>
<tr>
<td>NC20</td>
<td>Farrow to wean</td>
<td>2.4</td>
<td>4300</td>
<td>63</td>
<td>232</td>
<td>19</td>
</tr>
</tbody>
</table>
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, 0.315, 0.505, 1.26, and 2.0 m) above the lagoon.

2.3. Methane measurements

Methane concentration profiles were measured at the 0.315 and 1.26 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 to 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 ppb. The TDL’s electronics 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 per second 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 reference gases to the barge to calibrate the laser spectrometer.

Nineteen data collection periods (24 h period) were made during three measurement seasons at NC10 and 12 periods were measured during two seasons at NC20. 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

\[
C = K_{mb} \frac{\Delta n}{\Delta z}
\]

where \(C\) is the CH\(_4\) flux densities (kg CH\(_4\) ha\(^{-1}\) per day), \(n\) the atmospheric CH\(_4\) concentration (\(\mu g\) 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

\[
K_{mb} = \frac{k}{2} \ln \left( \frac{z_2 - z_d}{z_1 - z_d} \right) \Psi^2
\]

where \(k\) is the von Karmon constant, \(\mu\) the windspeed (cm s\(^{-1}\)), \(z_d \approx 0\) (cm) for a water surface, \(\Psi\) the stability correction factor (Dyer and Hicks, 1970). The flux gradient technique assumes that momentum, energy and gases are transported identically and potential errors associated with the technique include measurement errors and thermal stability corrections. These errors, usually considered to be 15–20%, have been discussed by Harper (1988) and Denmead and Raupach (1993). Data were analyzed using the stepwise regression procedures of SAS (SAS Institute, 1991).

2.4. Lagoon sampling

Spatial sampling of the lagoons, both horizontally (in three locations) and vertically (at the surface and in the sludge layer), was accomplished using a remotely actuated, closed sampler to obtain samples representative of each of the vertical layers. The sample containers were lowered from a boat to the appropriate depths, opened for sample collection, then closed before bringing them to the surface for sample retrieval and storage. Samples were also obtained periodically during the measurement season from the input pipes into the lagoons. The samples were frozen immediately and shipped to a laboratory for analysis of total organic carbon, volatile solids and pH. Dissolved \(O_2\) (YSI 55 DO meter, YSI) and 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.

3. Results and discussion

Lagoon pH, temperature, and CH\(_4\) emissions and concentrations of total organic carbon (TOC) and volatile solids (VS) from the waste water entering the
Table 2
Lagoon temperature, pH, concentration of VS and TOC of waste entering lagoons, and CH₄ emissions during each sample perioda

<table>
<thead>
<tr>
<th>Facility</th>
<th>Measurement dates</th>
<th>Lagoon temperature</th>
<th>pH</th>
<th>VS (mg l⁻¹)</th>
<th>TOC (mg l⁻¹)</th>
<th>CH₄ emissions (kg ha⁻¹ per day)</th>
<th>CH₄ emissions (g per animal per day)</th>
<th>CH₄ emissions (kg AU⁻¹ per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC10</td>
<td>May 2-8, 1997</td>
<td>18.3 ± 3.5</td>
<td>7.8</td>
<td>4500 ± 2500</td>
<td>520 ± 140</td>
<td>115.3 ± 71.2</td>
<td>30.8</td>
<td>74.8</td>
</tr>
<tr>
<td></td>
<td>August 9-13, 1997</td>
<td>24.0 ± 3.6</td>
<td>8.1</td>
<td>2500 ± 160</td>
<td>360 ± 130</td>
<td>49.9 ± 1.4</td>
<td>13.3</td>
<td>32.4</td>
</tr>
<tr>
<td></td>
<td>January 20-30, 1998</td>
<td>6.7 ± 3.5</td>
<td>8.1</td>
<td>2000 ± 410</td>
<td>380 ± 160</td>
<td>20.3 ± 15.8</td>
<td>5.4</td>
<td>13.2</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>8.0</td>
<td>8.1</td>
<td>2667 ± 420</td>
<td>61.8 ± 16.5</td>
<td>61.8 ± 16.5</td>
<td>16.5</td>
<td>40.1</td>
</tr>
<tr>
<td>NC20</td>
<td>April 24-May 1, 1997</td>
<td>15.6 ± 3.9</td>
<td>7.7</td>
<td>1440 ± 620</td>
<td>240 ± 180</td>
<td>10.7 ± 7.7</td>
<td>6.0</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>February 1-6, 1998</td>
<td>7.7 ± 3.4</td>
<td>7.9</td>
<td>5300 ± 550</td>
<td>210 ± 60</td>
<td>5.3 ± 7.3</td>
<td>3.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>7.8</td>
<td>7.8</td>
<td>1350 ± 225</td>
<td>8.0 ± 4.5</td>
<td>8.0 ± 4.5</td>
<td>4.5</td>
<td>8.4</td>
</tr>
</tbody>
</table>

*a Animal units (AU) based on animal weight of 454 kg.
lagoon are shown in Table 2. Average emissions were much less during the winter than the spring or summer measurement periods at both lagoons. Lower CH₄ production has been reported for anaerobic digesters (Cullimore et al., 1985) and covered lagoons (Safley and Westerman, 1989) at lower temperatures. In a previous study with open lagoons, Sharpe and Harper (1999) also reported lower CH₄ emissions during the winter, but the differences in emissions rates between seasons was not as great as in this study. The differences may have been due to higher winter temperatures in the previous study. The much greater emission rates from NC10 than NC20 are partially due to fewer animals at NC20 which would lower input rates into the lagoon. Calculated annual loading rates were 1,265,000 and 528,500 kg of solid waste for NC10 and NC20, respectively. Even when rates are calculated on a per animal basis, emissions rates were greater at NC10 (12.2 g CH₄ per animal per day) than at NC20 (4.3 g CH₄ per animal per day). The lower emissions may also have been due to the type of waste disposal system at the two farms. The periodic ‘flush’ system at NC10 emptied wastes into the lagoon every 8 h while the waste at NC20 remained under the houses for 1 week before removal into the lagoon. This would allow lower decomposition and greater CH₄ emissions in the houses and thus less available carbon for emissions from the lagoon. In a previous study (Sharpe and Harper, 2001), CH₄ emissions from houses at NC20 were found to be more than twice those from houses at NC10. Total VS loading was about twice as great in the NC10 lagoon while emissions were about eight times greater. Although the lagoons are considered to be anaerobic, there are small quantities of dissolved O₂ in the water (0.03 to 0.024 mg l⁻¹), allowing for some aerobic decomposition. The greater surface area per animal at NC20 would increase aerobic decomposition and thus decrease CH₄ emissions in relation to NC10.

During each individual measurement season, both windspeed and effluent temperature influenced CH₄ emission rates (Fig. 1). In general emission rates followed a diurnal pattern with greater fluxes during the day when both temperature and windspeed were greatest. However, when all the data from both farms was combined the correlations between emission rates and windspeed were poor (r = 0.25). Windspeed (turbulence) would not directly affect CH₄ production but during short term periods, when other factors are static, high windspeed would increase mixing in the sludge lagoon and may result in the release of trapped gas pockets. Windspeed would not be expected to have a direct influence on CH₄ emissions, but high winds would physically stir the waste water which could result in the release of CH₄ trapped in the sludge layer. Average emission rates during the spring were more than twice those during the summer at NC10 although temperature was about 6 °C cooler. The greater emissions rates during the spring then summer may have been due to a accumulation of organic material during the winter. Manure (sludge) depth was not measured during the winter 1997 and summer 1998 measurement periods but was from October 1998 to November 1999. Sludge depth in 1999 was almost twice as deep than during the spring (33 cm) than during the summer (17 cm).

The information obtained over three seasons at both farms was combined to develop a statistical model for emissions. Sharpe and Harper (1999) presented seasonal data of CH₄ emissions from a swine lagoon in the Coastal Plains of Georgia. They concluded that CH₄ emissions were generally a function of windspeed, air temperature and lagoon temperature, but these factors could not consistently explain season to season variation in emissions (R² = 0.36). In this study, concentration of VS in the input plus windspeed and effluent temperature resulted in an R²-value of 0.65. The predictive relationship is

$$E_{CH₄} = -57 + 0.10μ + 2.33T eff + 0.01VS (3)$$

where $E_{CH₄}$ is lagoon emissions (kg CH₄ ha⁻¹ per day), $μ$ the windspeed (cm s⁻¹), $T_{eff}$ the effluent temperature (°C), and VS is volatile solids in the input (mg l⁻¹).

Daily emissions at NC10 ranged from 20 to 115 kg CH₄ ha⁻¹ per day which corresponded to 0.003–0.002 m³ CH₄ m⁻² per day. These emission rates were less than those reported by Safley and Westerman (1988) for two partially covered lagoons (0.04–0.10 m³ CH₄ m⁻² per day). The difference in emissions between the studies was probably due to effluent temperature, VS loading rate and measurement techniques. In the Safley and Westerman (1988) study, the VS loading was 0.04 and 0.05 kg m⁻³ per day and effluent temperatures were 24–30 °C. In this study calculated VS loading was 0.02–0.03 kg m⁻³ per day and effluent temperature ranged from 2 to 30 °C. In
addition, the micrometeorological techniques used in this study measure atmospheric CH₄ profiles developed from a relatively large footprint area downwind from the sensors. Safley and Westerman (1988) used floating covers positioned within 15 m of the discharge pipe. Methane emissions would be maximized in these areas due to the greater loading rates close to the pipes.

Methane emission factors (kg CH₄ per animal per year) are often used to calculate total regional and national emission rates (EPA, IPCC). Emission factors from this study were 6.0 and 1.6 kg CH₄ per animal per year at NC10 and NC20, respectively. Basing emissions on animal units (AU) of the same size may be a more useful method of comparison. On an AU basis (AU = 454 kg animal) average yearly emissions were 40.1 and 8.4 kg CH₄ AU⁻¹ per year. These values, particularly from NC20, probably underestimate total emissions from the farms since they do not
include losses from the houses. The emission factor from NC10 would be comparable to those developed from a swine facility in the Coastal Plains of Georgia (Sharpe and Harper, 1999) since both facilities were farrow to finish farms with similar waste disposal systems and emission factors were based on lagoon emissions only. The emission factor calculated from the Georgia farm was 6.1 kg CH$_4$ per animal per year, which was slightly greater than for NC10. Two US Environmental Protection Agency (USEPA) estimated much greater emission factors for swine manure. Eklund and LaCosse (1995) reported emission rates of 106 kg CH$_4$ per animal per year and in a more recent study (USEPA, 1999) emission factors were revised to 19 kg CH$_4$ per animal per year. The EPA estimates do not include any direct measurements of CH$_4$ flux and are 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 Jr., 1989). In a previous study (Sharpe and Harper, 2001), CH$_4$ emissions from houses were determined for both NC10 and NC20. Average house emissions from NC10 was about 7.3 kg per animal per year, no yearly average house emission was determined for NC20. Combining house and lagoon emissions for NC10 would result in an emission factor of 13.3 kg per animal per year which is about 30% less than the most recently reported EPA report (USEPA, 1999).

4. Conclusions

Under natural conditions, CH$_4$ emissions from lagoons are related to windspeed, air and water temperature and VS loading into the system. These factors could explain 66% of the variation in emissions from the lagoons. The much lower emissions from NC20 then NC10 were due to the number of animals and the type of waste management system used at the farm. Waste at NC20 was held under the houses for 7 days, which would allow much greater decomposition and CH$_4$ losses from the waste before emptying into the lagoon. The much lower emission factors and the differences between NC10 and NC20 would indicate that both lagoon and housing losses are required to obtain accurate emission factors for swine production facilities.

References


