Lagoon-Biogas Emissions and Carbon Balance Estimates of a Swine Production Facility

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ABSTRACT

Gaseous emissions from animal manure storage facilities can contribute to global greenhouse gas inventories. Biogas fluxes were measured for one year from a 2-ha anaerobic lagoon that received waste from a 10 500-head swine (*Sus scrofa*) finishing operation in southwestern Kansas. During 2001, ebullition of biogas was measured continuously by using floating platforms equipped with gas-collection domes. Periodically, the composition of the biogas was determined by using gas chromatography. Detailed records of feed quality and quantity and animal weights and gains also were obtained to determine the carbon budget of the facility (barns and lagoon). Flux of biogas was very seasonal, with peak emission (18.7 mol m⁻² d⁻¹) occurring in early June. Nearly 50% of the annual biogas losses occurred during a 30-d period beginning on day of year (DOY) 146. Flux patterns suggest that the start of the high biogas production period was governed by temperature, while the decline in production in mid-June was caused by substrate limitations. Average biogas composition was 0.71 L CH₄ L⁻¹. The quantity of CH₄ released from the lagoon was 86.3 Mg yr⁻¹, which represents about 38 g of CH₄ per kg of animal weight gain. The average flux density of biogas from the lagoon was 382 mol m⁻² yr⁻¹ or 725 mol yr⁻¹ per resident animal where the resident animal population was 10 500. Flux rates of CH₄ were 1.7 to 3.4 times less than predictions made with Intergovernmental Panel on Climate Change (IPCC) models. Additional research is needed on the carbon budgets of other animal feeding operations so that better estimates of greenhouse gas emissions can be determined.

Anaerobic lagoons are commonly used to store and treat manure from large-scale swine production facilities. Ultimate by-products of anaerobic digestion are methane (CH₄) and carbon dioxide (CO₂), with CH₄ making up between 60 and 70% of the biogas (Chynoweth and Pullammanappallil, 1996; Rittman and McCarty, 2001). Although some facilities have engineered systems to utilize the CH₄ for energy (Lusk, 1998; Moser, 2001; Zhang et al., 1990), most farms using anaerobic lagoons allow the CH₄ to escape into the atmosphere. Methane also is a by-product of enteric feed digestion, which is reported to be 1.5 kg yr⁻¹ animal⁻¹ in swine (Crutzen et al., 1986).

In the Great Plains region of the United States, swine are commonly contained in barns with slatted floors that allow waste material to fall and be temporarily stored into 30- to 45-cm-deep concrete-lined pits. Periodically, generally at intervals of less than 7 d, the waste in the under-floor pits is discharged into the lagoon for storage and treatment. Lagoons are commonly 2 to 6 m deep with surface areas between 0.5 and 5.0 ha (Ham and DeSutter, 2000). The primary objective of anaerobic digestion is to stabilize organic matter and, thus, reduce odors, pathogens, and the overall mass of organic solids (Parkin and Owen, 1986). The waste is converted to CH₄ and CO₂ by two groups of bacteria, acetogens and methanogens, and by a three-stage process called methanogenesis (McCarty and Smith, 1986). These three stages are defined by (i) hydrolysis and fermentation, (ii) acetogenesis and dehydrogenation, and (iii) methane formation (McCarty and Smith, 1986; Parkin and Owen, 1986). For a more detailed description of anaerobic processes, refer to McCarty and Smith (1986) and Parkin and Owen (1986).

Greenhouse gases (GHG) produced from agriculture account for 6.8% of all U.S. emissions (USEPA, 2004), and global efforts are being directed to reduce the emissions of these gases from agricultural sources (Cole et al., 1997; Desjardins et al., 2001; Minami and Takata, 1997; Oenema et al., 2001). The boom of large swine operations and subsequent increased amounts of manure production in the United States during the past 10 years have increased the need to provide the public with accurate, research-based measurements of GHG emissions from these facilities (Jungbluth et al., 2001). Only a few studies have been conducted to quantify CH₄ emissions from anaerobic swine waste lagoons (Harper et al., 2000; Safley and Westerman, 1988; Sharpe and Harper, 1999), but no studies have been conducted in the Great Plains.

Conducting a carbon budget, according to a mass-balance approach, is a unique way to quantify and trace carbon forms through agricultural systems. Currently, there are no published reports that address mass balance experiments on large-scale animal production facilities. Picot et al. (2003) recently conducted a carbon balance on an urban wastewater anaerobic digestion pond and were able to account for 99.6% of the carbon in their system. A holistic carbon balance of animal production facilities would provide valuable information about the quantity of GHG produced from the facility per mass of animal produced (i.e., emission factors). This information could then be extrapolated to regional sites with similar animal production practices and climates, and provide research-based information needed to model GHG emissions in the United States.

The objectives of this research were to (i) describe and demonstrate the performance of instrumentation used to obtain continuous measurements of biogas production and CH₄ flux from lagoons, (ii) measure biogas and CH₄ fluxes from an anaerobic-swine lagoon, and (iii) quantify the mass balance of C from the entire swine production facility.

Abbreviations: DOY, day of year; GHG, greenhouse gas.
MATERIALS AND METHODS

Biogas production was determined on a 2-ha swine-waste lagoon located within 30 km of Hugoton, KS, during 2001. The lagoon was constructed in 1996 with a 0.46-m compacted-soil liner and 4:1 side-slopes. Maximum design holding volume of the lagoon at the maximum lagoon depth of 6.1 m was 95,978 m$^3$. During the study, the lagoon was operating at a consistent depth of 4.3 m with a holding volume of approximately 58,000 m$^3$. The surface areas of liquid over the middle and edge portions of the lagoon were about 9200 and 10,800 m$^2$, respectively. The lagoon received waste from a 10-barn, 10,500-head swine finishing operation. Animals entered the barns weighing approximately 20 kg and, after about 170 d, the animals were removed weighing near 120 kg. During this growth period, the animals were fed five different diets. Animals were contained on slatted floors with under-floor pits to collect the waste. Periodically, every 5 to 7 d, waste in the under-floor pits was drained into the lagoon via a pull-plug system. A floating recirculation pump, located near the center of the lagoon, was then used to add about 5 cm of lagoon effluent back into the emptied pits. The lagoon effluent was not used for irrigation purposes during the study.

Gas Collection and Ebulition Metering Rafts

Four floating gas collection rafts were used to measure biogas production (Fig. 1). Each 2.7- × 1.5-m raft was constructed from aluminum C-channel, supporting two flotation panels (300201 and 300224; Superdeck Systems, Minneapolis, MN). Biogas from ebullition was collected by using a 0.96-m-diameter dome fabricated by cutting the endmost 0.4 m off a polyethylene applicator tank (45061; Norwesco, St. Bonifacius, MN). The dome was secured in the center of the raft so that 0.05 m extended above the waterline, creating a headspace of 3.3 L. Biogas was routed from the spherical top of the dome through 9.5-mm-t.d. tubing to a 1.0-L Krinkle Tedlar gas-sampling bag (KT20070071JN4MT; EaglePicher, Phoenix, AZ) mounted inside an environmental enclosure secured to one of the flotation panels (Fig. 2). As gas was collected, the bag gradually inflated, and its internal pressure was monitored with a pressure transducer (264, 0–622 Pa; Setra Systems, Boxborough, MA). Once the bag reached 100 Pa, a four-way valve (L01SA459B; Numatics, Highland, MI) and exhaust pump (NMP830-KNDC; KNF Neuberger, Trenton, NJ) were energized for 23 s, and the bag was evacuated. A CR10X datalogger (Campbell Scientific, Logan, UT) was used to monitor and control the pressure transducer, valve, and pump. Before field installation, each sampling bag was individually calibrated for volume by using N$_2$ gas and gravimetric methods. Calibration volumes ranged from 1.2 to 1.4 L at 100-Pa gauge pressure. In the field, the number of moles of gas was deter-
mined after each bag evacuation by multiplying the volume of the bag by the molar density of air as calculated using the perfect gas equation.

A 12-V battery and a 10-W solar panel powered sensors, control devices, and dataloggers. One raft had a cellular telephone, modem, and a coaxial multidrop interface (MD9; Campbell Scientific), whereas the remaining three rafts had only the MD9. Coaxial cable, 67 m between each raft, allowed for transmission of data to a central telephone and modem, alleviating the need for multiple cellular-phone supplies and contracts. Because of the long lengths of coaxial cable between the rafts (67 m), oval-shaped floats (OS-4SC; The Carlon Products Company, Derby, CT) were positioned every 5 m to prevent unwanted stress on the cable. The temperature at the bottom of the lagoon (4.3 m) was independently monitored from two different rafts by using type-T thermocouples. Data from the rafts were downloaded by cellular phone daily.

**Sampling Plan, Gas Analysis, and Emissions Calculations**

Gas-collection rafts were deployed between day of year (DOY) 1 and 365 of 2001, although preliminary data were collected between DOY 145 and 305 in 2000 to perfect the equipment and to characterize variability in biogas production. From the experiments in 2000, spatial variation was a concern, so a sampling plan was devised to avoid bias and obtain an areal estimate of biogas flux. The lagoon surface was divided into a $6 \times 4$ grid (Fig. 3). But, the north- and south-most grids were not used, leaving a $4 \times 4$ sampling grid that encompassed the bottom and adjacent east–west side-slopes, with each sampling grid approximately $25 \times 50$ m. A scheme was developed to periodically move the rafts within the grid to avoid sampling bias. Rafts could be moved along an east–west transect within blocks denoted A, B, C, and D in Fig. 3. Thus, Raft 1 always remained within Block A, Raft 2 always remained within Block B, Raft 3 always remained within Block C, and Raft 4 always remained in Block D. The lagoon also was divided into plot numbers, where Plots 1 and 4 encompassed the side-slope portions of the lagoon and Plots 2 and 3 were over the flat portion of the lagoon floor. During the study period, rafts were repositioned three times, over different plots within the same block (i.e., along an east–west transect). At any one time, two rafts were over the lagoon bottom and two were over the side-slopes. There was some flex in the cables used to tether the rafts, so some wind-induced movement within a block did occur.

Composition of the biogas was measured twice in 2000 and two more times in the 2001 study period. A 60-mL plastic syringe equipped with a 22-ga needle was used to extract the biogas from a sample line between the collection dome and the metering bag. Samples from the syringe were injected into

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**Fig. 3.** Diagram of the swine facility and the sampling plan used to quantify biogas production from the 2-ha lagoon.
evacuated 100-mL serum bottles (33110-U; Supelco, Bellefonte, PA) fitted with gray butyl stoppers (27232; Supelco) and aluminum crimp seals (27016; Supelco) for storage. The serum bottles were over-pressurized with the sample biogas by about 50%. After biogas samples were collected and stored, the needle piercings in the gray butyl stoppers were smeared with silicon adhesive to prevent further leakage.

Methane, CO₂, N₂, and O₂ were determined by using a gas chromatograph (GC) (8610C; SRI Instruments, Torrance, CA). The GC was equipped with flame-ionization and thermal-conductivity detectors, a methanizer for reduction of CO₂ to CH₄, and a gas sampling valve with a 0.5-mL sample loop. 

Separation was achieved by using a 0.9-m silica gel column (8600-PKC1; SRI Instruments), and He carrier gas pressure was maintained at 69 kPa. Oven temperature was maintained at 40°C for the first 2.5 min, and then increased at 20°C min⁻¹ until the final target temperature of 80°C was achieved. Using a gas-tight syringe (10MDF-LL-GT; SGE, Austin, TX), 10 mL of biogas was transferred from the serum bottle to the sample loop.

The flux of CH₄ from the lagoon at a raft location was determined to be a function of the moles of gas calculated from the perfect gas equation, concentration of CH₄ in the biogas, and area of the collection dome. The flux of CH₄ (J, in g CH₄ m⁻² d⁻¹), was calculated as:

\[ J = (nV_iM_wC)/A \]  

where \( n \) is the number of bag fills collected over the bottom or side slopes per day; \( V_i \) is the volume of the gas sample bag (m³); \( M_w \) is the molar density of air (mol m⁻³); \( M_c \) is the molecular weight of CH₄ (g mol⁻¹); \( C \) is the concentration of CH₄ in the biogas (L⁻¹); and \( A \) is the area of the collection dome (m²). Calculations of \( J \), in g m⁻² d⁻¹, were made by setting \( M_w \) equal to 16 g CH₄ mol⁻¹, \( A \) equal to 0.72 m², and \( C \) equal to 0.71 L CH₄ L⁻¹. Flux of biogas, in mol m⁻² d⁻¹, was calculated from Eq. [1] with the \( M_w \) and \( C \) terms omitted. During the study, the flux values from rafts over the bottom and the flux values from the rafts over the side-slopes were averaged, respectively. Using lagoon engineering drawings and lagoon depth measurements, the bottom and the horizontal side-slope areas (m²) were determined so that the respective flux measurements could be scaled to represent the whole lagoon.

Waste, Sludge, and Feed Analysis

Lagoon liquor was sampled seven times between DOY 194 of 2000 and DOY 365 of 2001 with a 1.2-L Kemmerer-style sampler (3JF-223484; Ben Meadows, Janesville, WI). Analysis of the waste was performed by Servi-Tech Laboratories (Dodge City, KS). Total N was determined by USEPA Method 351.3, total ammoniacal N was determined by USEPA Method 350.2, nitrate N was determined by USEPA Method 353.2, and chloride was determined by USEPA Method 325.2, and pH was determined by USEPA Method 9040B (Csuros, 1997). Subsamples of the five diets were analyzed for total C and total N by combustion (CN2000; LECO Corporation, St. Joseph, MI) following Nelson and Sommers (1996) and total P was determined to be a function of the moles of gas calculated from the perfect gas equation, concentration of CH₄, and a gas sampling valve with a 0.5-mL sample loop. 

Separation was achieved by using a 0.9-m silica gel column (Nelson and Sommers, 1996), and total P by a sulfuric acid–hydrogen peroxide digestion by the Soil and Plant Testing Laboratory at Kansas State University.

Standard Methane Emission Estimates

Calculated CH₄ emission from the lagoon was compared with two CH₄ emission calculation methods adopted by the Intergovernmental Panel on Climate Change (2001). These methods are referred to as Tier 1 and Tier 2 approaches for calculating CH₄ emissions from manure management. For the Tier 1 approach, the standing animal population of 10 500 was multiplied by 14 kg CH₄ head⁻¹ yr⁻¹, the emission factor for this region (Intergovernmental Panel on Climate Change, 2001). For the Tier 2 approach, the following equation was used to determine the emission factor for this facility:

\[ E = VS \times B \times MCF \times (0.662 \text{ kg CH}_4 \text{ m}^{-3} \text{ CH}_4) \]  

where \( E \) is the annual emissions of CH₄ for a defined animal population (kg CH₄ yr⁻¹); \( VS \) (volatile solids) is the total annual VS (kg yr⁻¹); \( B \) is the maximum methane-producing capacity for manure produced by an animal in m³ CH₄ kg⁻¹ of VS added; and \( MCF \) is the CH₄ conversion factor. The assumptions used for determination of total annual VS were a VS rate of 5.4 kg d⁻¹ 1000 kg mass⁻¹ (USEPA, 2004), an average animal weight of 70 kg, and a standing population of 10 500. The assumptions for \( B \) and \( MCF \) were 0.48 (Intergovernmental Panel on Climate Change, 2001) and 0.63 (USEPA, 2004), respectively.

RESULTS AND DISCUSSION

Biogas Composition

Biogas sampled from the rafts in 2001 contained approximately 0.71 L of CH₄ L⁻¹ of biogas (Table 1). Good agreement was observed between CH₄ concentrations sampled over the middle and edge portions of the lagoon. Almost identical results, 0.73 L L⁻¹, were obtained from samples collected in 2000 (Table 1). Methane concentrations were about 1.2 times higher than those reported by Hashimoto (1984), but similar to that reported by Safley and Westerman (1988). Results from Harper et al. (2000) were variable, with concentrations of CH₄ ranging from 0.08 to 0.79 L L⁻¹. Carbon dioxide concentrations in the domes were only about 0.07 L CO₂ L⁻¹ of biogas (Table 1). Safley and Westerman (1988) reported larger CO₂ concentrations (0.05–0.35 L CO₂ L⁻¹ biogas). When initially produced at the microbe, CO₂ concentrations are about 30 to 40% of the biogas (Chynoweth and Pullamanappallil, 1996; Rittman and McCarty, 2001), but after the CO₂ traveled to the surface and collected in the domes the concentrations were much lower.
Table 1. Concentrations of CH₄, CO₂, N₂, and O₂ in biogas collected from ebullition collection domes during 2000 and 2001.

<table>
<thead>
<tr>
<th>Day of year</th>
<th>Raft</th>
<th>Location†</th>
<th>CH₄</th>
<th>CO₂</th>
<th>N₂</th>
<th>O₂</th>
<th>L L⁻¹</th>
</tr>
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<tbody>
<tr>
<td>194</td>
<td>1</td>
<td>M</td>
<td>0.728</td>
<td>0.065</td>
<td>0.069</td>
<td>0.030</td>
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</tr>
<tr>
<td>220</td>
<td>1</td>
<td>E</td>
<td>0.722</td>
<td>0.058</td>
<td>0.052</td>
<td>0.030</td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>1</td>
<td>E</td>
<td>0.722</td>
<td>0.052</td>
<td>0.058</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>145</td>
<td>1</td>
<td>M</td>
<td>0.708</td>
<td>0.051</td>
<td>0.069</td>
<td>0.030</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>E</td>
<td>0.724</td>
<td>0.067</td>
<td>0.066</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>E</td>
<td>0.724</td>
<td>0.052</td>
<td>0.061</td>
<td>0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>0.714</td>
<td>0.076</td>
<td>0.071</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>E</td>
<td>0.721</td>
<td>0.087</td>
<td>0.071</td>
<td>0.025</td>
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</tr>
<tr>
<td>4</td>
<td>M</td>
<td>0.693</td>
<td>0.086</td>
<td>0.071</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.709</td>
<td>0.068</td>
<td>0.071</td>
<td>0.025</td>
<td></td>
</tr>
</tbody>
</table>

† The terms M and E represent the middle and edge areas, respectively, of the lagoon.

Flux of biogas was seasonal, characterized by a sharp increase around DOY 130 that steadily increased until about DOY 160 (Fig. 4). During this 30-d period, biogas emissions increased to about 19 and 5 mol biogas m⁻² d⁻¹ from the middle and edge portions of the lagoon, respectively. A sharp decline in biogas flux after DOY 160 continued until about DOY 210. During the peak period of biogas production, the middle portion of the lagoon yielded about 0.4 m³ of biogas m⁻² d⁻¹, which corresponded to about 330 daily bag fills per raft (Fig. 1 and 2). During the entire calendar year, 535 and 252 mol biogas m⁻² were lost from the middle and edge portions of the lagoon, respectively. About 50% of the annual biogas emissions occurred during the 30-d peak emission period between DOY 146 and 176. During the first 190 d of the experiment, Rafts 1 and 3 were positioned in Plots 3 and 2 over the bottom portion of the lagoon, albeit over different blocks, and detected 459.7 and 462.5 mol biogas m⁻², respectively. During the 30-d peak emission period, Rafts 1 and 3 detected 284.5 and 361.5 mol biogas m⁻², when both were over the lagoon bottom. The average biogas flux density on an annual basis was 382 mol m⁻² yr⁻¹ or 728 mol yr⁻¹.
per resident animal where the resident animal population was 10,500.

Biogas production was dependent on lagoon temperature. Biogas steadily increased when temperatures in the bottom sludge layer reached between 10 and 15°C, but peaked on DOY 161, about 40 d before maximum lagoon temperature was reached. This observation is in close agreement with the findings of Safley and Westerman (1988). Lagoon temperature steadily declined after DOY 210 to about 4°C near DOY 1. Although Bitton (1999) reported methanogenesis at temperatures as low as 0°C, biogas production can be initiated between 3 and 9°C (Cullimore et al., 1985). Although temperature was the only other ancillary measurement monitored continuously at this lagoon, other parameters such as supply of organic solids, organic acid concentration, microbial population, and balance between fermenters and methanogens may have contributed to the sharp decline in biogas production. Safley and Westerman (1988) reported a good relationship between a drop in biogas production and decline in total organic acid concentrations, even though lagoon temperature was increasing.

It is important to reiterate that the production of biogas is concentrated in about 90 d of the year even though waste is continually flushed from the barns into the lagoon. The pattern of biogas flux from the lagoon is somewhat driven by the relationship between the storage of manure solids and lagoon temperature. Carbon from the barns is continually flowing into the lagoon throughout the year. In the winter months, low temperatures inhibit anaerobic digestion, which causes organic carbon to accumulate in the lagoon. Once temperatures begin to rise in the spring, increased microbial activity and population growth drive the rapid decomposition of stored organic matter. After the reservoir of surplus organic carbon is consumed, anaerobic digestion may become substrate limited and decline even before the maximum temperature is reached.

The biogas data can be used to estimate CH₄ flux by assuming that the concentration of CH₄ in the biogas was 0.71 L CH₄ L⁻¹ of biogas during the study (Table 1). Methane flux values peaked at about 210 and 60 g CH₄ m⁻² d⁻¹ from the middle and edge portions of the lagoon, respectively. These maximum flux rates corresponded with the period of maximum biogas production. Studies of swine lagoons by Harper et al. (2000) and Safley and Westerman (1988) determined maximum CH₄ flux rates to be about 13 and 61 g m⁻² d⁻¹, respectively. During the entire study period (i.e., 1 yr), 55,710 and 30,638 kg of CH₄ were lost from the middle and edge portions of the lagoon, respectively. These losses correspond to an annual average flux density for the whole lagoon of 4.3 kg CH₄ m⁻² yr⁻¹ or 8.3 kg CH₄ yr⁻¹ resident animal (i.e., 10,500 head).

**Sludge Depth and Waste Chemistry**

Sludge depth varied spatially across the lagoon. Depths ranged from 0 m near the upper edges of the shoreline to about 0.4 m at the lagoon floor (Fig. 5). The overall average areal depth was 0.19 m, which corresponded to an accumulation rate of 0.06 m yr⁻¹. This rate was considerably less than the predicted accumulation rate of 0.53 m yr⁻¹ (USDA, 1992). Sludge depths were less where waste inlet pipes were located because incoming waste forced the sludge away from the flow of waste. Bulk density of the sludge was about 1100 kg m⁻³. Phosphorus concentration in the sludge was 51 g kg⁻¹ and total C and N concentrations were 228 and 29 g kg⁻¹, respectively. The C to N ratio of 7.9:1 was similar to that reported for sludge from swine lagoons by USDA (1992).

Total N concentrations in the lagoon liquor ranged from 1000 to 1240 mg L⁻¹, whereas NH₄–N ranged from 900 to 1100 mg L⁻¹ (Table 2). Ammonium N was about 89 to 97% of the total N in the liquor. Because no NO₃–N was detected in any of the samples, the remaining nitrogen would be considered organic. Chloride concen-
Feedings ranged from 525 to 757 mg L⁻¹. A slight increase in Cl was observed during each year. The pH was consistently near 8.0 during the study. Overall, lagoon-liquor characteristics remained relatively constant.

Carbon Balance

The carbon balance was constrained by knowing the total carbon inputs in the feed (C_feed). Carbon balance can be defined as:

\[
C_{\text{feed}} = C_{\text{animal}} + C_{\text{barn}} + C_{\text{lagoon}} + S
\]

where \(C_{\text{animal}}\) is the carbon accumulated in the animals, \(C_{\text{barn}}\) is gaseous losses of carbon from the barns, \(C_{\text{lagoon}}\) is carbon lost from the lagoon as gas (\(\text{CO}_2\) and \(\text{CH}_4\)), as well as that removed by pumping for irrigation, and \(S\) the change in carbon storage (e.g., accumulation of sludge and dissolved \(\text{CO}_2\)), all in Mg C yr⁻¹. Feeding cycles were about 170 d long, with about 1 wk between cycles when the barns were vacant. During each feeding cycle, nearly 3000 Mg of feed was consumed by the 10 500 animals (Table 3). The animals were fed five diets during the feeding cycle where the total amounts ranged from 380 to 1033 Mg, with the bulk of the feedstuffs consumed in the first and last diets. On average, carbon represented 44% of the feedstuffs by mass.

The average size and number of animals and the quantities of feed consumed at the facility differed among calendar years, depending on the start dates of the feeding cycles. Averaging population, animal mass, and quantity of feed consumed over four years provided the best estimate of \(C_{\text{feed}}\) and \(C_{\text{animal}}\). Thus, on an annual basis, about 23 000 animals were finished from this facility, while consuming 6566 Mg yr⁻¹ of feed (Table 4). During each 170-d feeding cycle, each animal consumed about 280 kg of feed and gained 100 kg, yielding a feeding efficiency of 36%. During the study year, nearly 2889 Mg of C (6566 Mg yr⁻¹ × 0.44) was consumed while animals gained nearly 2300 Mg of mass.

The total carbon entering the animals as feed was either retained as body mass, lost through respiration, or lost through excretion. A detailed accounting of Eq. [3] was prepared (Table 4) according to the following assumptions: (i) the animals contain 200 g C kg⁻¹ of mass (C.D. Fulhage, personal communication, 2003); (ii) the amount of \(\text{CO}_2\) lost from the lagoon can be determined by assuming that biogas produced under anaerobic conditions contains essentially only \(\text{CH}_4\) and \(\text{CO}_2\); and (iii) the amount of \(\text{CH}_4\) and \(\text{CO}_2\) emitted from the barns through respiration was 4.0 g \(\text{CH}_4\) animal⁻¹ d⁻¹ and 1654 g \(\text{CO}_2\) animal⁻¹ d⁻¹ (T.M. Brown-Brandl, personal communication, 2003; Brown-Brandl et al., 1998). Given that 2889 Mg of carbon entered the site and 86.5 Mg of \(\text{CH}_4\) was quantified from the lagoon, 2.2% of the carbon that entered the site in the form of feed was lost as \(\text{CH}_4\) from the lagoon through anaerobic digestion. Nearly 60% of the input carbon left the barns in the form of animal respired \(\text{CO}_2\), whereas only 16% of the input carbon was retained in the animals. Sludge accumulation accounted for about 11% of the carbon inputs, and lagoon biogas \(\text{CO}_2\) and respired \(\text{CH}_4\) accounted for about 1% of the carbon inputs. Use of the collected data and scientific assumptions provided herein produced a carbon budget for this facility that underestimated carbon outputs by 9.6%. Determining the \(\text{CH}_4\) and \(\text{CO}_2\) produced from the digestion of wastes in the under-floor storage pits would have helped quantify the underestimation of carbon outputs from the facility (Sharpe et al., 2001). A source of carbon output from the lagoon that was not determined was diffusion of \(\text{CH}_4\) from the lagoon surface. However, we expect \(\text{CH}_4\) losses from diffusion to be small because of the low solubility of \(\text{CH}_4\) in water (Parkin and Owen, 1986). Also, the C balance did not account for changes in soluble \(\text{CO}_2\). However, for this term to be significant there must be annual changes in lagoon depth and/or lagoon temperature (i.e., gas solubility) over the course of the experiment. Lagoon depth remained relatively constant during the year and lagoon temperature changed less than 2°C from the start to the conclusion of the experiment (Fig. 4).

The GHG contribution of \(\text{CH}_4\) (assume a radiative forcing potential of 21 times that of \(\text{CO}_2\) on a CO₂-
equivalent basis from the lagoon and from animal respiration for one year was approximately 1812 and 344 Mg, respectively. Because about 23,000 animals were finished during 2001, while gaining 2300 Mg of body mass, and total CH_{4} contributing CO_{2} equivalents of 2132 Mg were produced from the lagoon and animal respiration, then approximately 93 kg of CO_{2}-equivalent GHG was produced for each finished animal (100 kg of body mass gain). Although not attempted here, a complete GHG emissions inventory from the facility needs to consider the CO_{2} that was fixed into the feed that was fed to the animals and any CO_{2} and CH_{4} produced in the underfloor storage pits and lagoon.

Estimates of CH_{4} emissions from the lagoon in 2001 according to the Intergovernmental Panel on Climate Change (2001) were about 147 and 290 Mg yr^{-1} for the Tier 1 and Tier 2 approaches, respectively. These values are much greater than the actual CH_{4} determined by using the floating platforms (86.3 Mg; Table 4). However, the Intergovernmental Panel on Climate Change approach attempts to quantify the CH_{4} production from all manure sources and this study did not attempt to quantify CH_{4} losses from the barn storage pits, which may be as high as 37 g CH_{4} d^{-1} animal^{-1} during the summer months (Sharpe et al., 2001).

CONCLUSIONS

Results suggest that the floating gas-collection rafts are a reliable way to quantify the flux of CH_{4} from anaerobic lagoons, but are not suited for determining CO_{2} flux because of the high solubility of CO_{2} in water. Estimated CH_{4} fluxes were characterized by a sharp springtime increase in production that peaked near DOY 161, at which time the maximum flux value was 210 g CH_{4} m^{-2} d^{-1}. Total CH_{4} exhausted from the lagoon in 2001 was 86.3 Mg, of which 50% was released between DOY 146 and 176. The contribution of CH_{4} from both lagoon and animal respiration to GHG inventories was about 2132 Mg of CO_{2} equivalents, of which 85% was from lagoon emissions. Thus, even though swine are not considered large contributors of CH_{4} through respiration or flatulence, there is a potential for substantial GHG contributions when animal waste is stored and treated in anaerobic lagoons.

APPENDIX

A Comment on Gas–Liquid Exchange in the Ebullition Measurement Raft

Ebullition of CH_{4} can be measured using a bubble collection dome (Fig. 1) if there is negligible methane exchange between the chamber headspace and the water surface after a bubble has been trapped. Depending on the rate of ebullition, trapped molecules may temporarily reside in the dome headspace, for 5 min to several hours, before being forced into the metering mechanism (Fig. 2). Gas exchange at the gas–water interface is governed by the concentration gradient and the solubility of the gas in water (Smith, 1985). A laboratory study was conducted to examine the potential for gas–water transfer of biogas trapped in the headspace. The bottoms were removed from fifteen 100-mL septum-equipped serum bottles. Bottles were submerged in a water bath, and 112 mL of imitation biogas (0.60 L CH_{4} L^{-1} and 0.40 L CO_{2} L^{-1}) was added to emulate bubbles trapped in the headspace of a collection dome. The water bath had been allowed to equilibrate with room air for several days before the experiment. Gas samples were collected at 1, 3, 6, and 24 h after injection and were analyzed for CH_{4}, CO_{2}, O_{2}, and N_{2} with a gas chromatograph.

Laboratory Evaluation of Biogas Trapped by a Chamber

Laboratory analysis showed that the composition of biogas can change appreciably once trapped in the headspace of a floating chamber. Carbon dioxide rapidly diffused into the water, decreasing headspace concentration to 0.281 L L^{-1} after 3 h and 0.055 L L^{-1} after 24 h (Fig. 6). Conversely, the headspace concentration of CH_{4} increased to 0.691 L L^{-1} after 3 h and 0.861 L L^{-1} after 24 h. As CH_{4} moved into the water, the volume of air in the bottle decreased and caused an increase in CH_{4} concentration. Offsetting some of the losses of CO_{2} was an increase in both O_{2} and N_{2} from zero to 0.023 and 0.042 L L^{-1}, respectively, after 24 h, indicating the need for careful interpretation of data when collected with a dome-style chamber. The different response of CO_{2} and CH_{4} is caused by differences in their solubilities; CO_{2} has a solubility in water 29 to 22 times greater than that of CH_{4} between 0 and 30°C, respectively (Fogg and Gerrard, 1991). Clearly, one cannot measure the ebullition of CO_{2} by using chamber methods unless the water is known to be CO_{2} saturated. However, the lower solubility of CH_{4} makes bubble-trapping measurements possible. Also, the volume of the chamber headspace should be minimized to reduce the residence time in which gas is exposed to the air–water interface. Ideally, one would eliminate the headspace completely. This was not possible in our design because pitching of the rafts in wind-driven waves forced water into the gas metering hoses if some headspace was not allowed.

REFERENCES

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