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Methane emissions from southern High Plains dairy wastewater lagoons in the summer

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ABSTRACT

Methane is a greenhouse gas with a global warming potential 25-fold that of CO_2, and animal agriculture is recognized as a source of CH_4 to the atmosphere. Dairy farms on the southern High Plains of New Mexico and Texas (USA) are typically open lot, and sources of CH_4 are enteric emissions from cattle and wastewater lagoons. Uncovered anaerobic lagoons are identified by the US Environmental Protection Agency as a source of CH_4 in dairy manure management systems. Our objective was to quantify summer CH_4 emissions from wastewater lagoons of a commercial dairy farm in eastern New Mexico. Research was conducted during 8 days in August (2009) at a 3500 cow open lot dairy farm with flush alleys. Methane concentration over three lagoons (total area of 1.8 ha) was measured using open path laser spectroscopy. Background CH_4 concentration was measured using a back-flush gas chromatography system with flame ionization. Wind and turbulence data were measured using a three-axis sonic anemometer. Emissions were estimated using an inverse dispersion model. Methane concentrations in the air over the lagoons ranged from 3 to 12 ppm, and averaged 5.6 ppm, with a background CH_4 concentration of 1.83 ppm. Methane flux density (*i.e.*, emission rate/unit area) ranged from 165 to 1184 $\mu g/m^2/s$, with a mean daily CH_4 flux density of 402 kg/ha/d. Methane emission rate averaged 0.211 kg/head/d. Uncovered anaerobic lagoons were a source of CH_4 emitted from this southern High Plains dairy farm, and lagoons could be a control point for emission reductions.

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1. Introduction

Methane is second to CO_2 in atmospheric radiative forcing (*i.e.*, effect on the earth's radiation balance), providing about 20% of the positive radiative forcing of long lived greenhouse gases (IPCC, 2007). Though present in the atmosphere at a relatively low concentration (~1.8 ppm), its global warming potential is 25 times that of CO_2 over 100 years. Methane

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Abbreviations: BLS, backward Lagrangian stochastic; CO_2e, carbon dioxide equivalent; CP, crude protein; DIM, days in milk; DM, dry matter; DOY, day of year; GHG, greenhouse gas; MMS, manure management system.

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Table 1
Cattle population and composition of key feed ration components.

Cow type	Population (head)	DM intake (kg/hd/d)	Crude protein (g/kg)	Neutral detergent fiber (g/kg)	Acid detergent fiber (g/kg)	Fat (g/kg)
Milking	2541	25.1	174.5	347.4	211.9	47.0
Fresh	261	21.5	167.3	384.3	232.5	39.0
Dry (close-up)	168	13.4	151.7	418.8	311.4	21.0
Dry (far-off)	522	13.5	135.8	357.2	226.2	30.0

concentration increased from its pre-industrial concentration of 0.7 ppm to 1.7 ppm by the early 1990s. Beginning in the mid-1980s, the rate of increase of atmospheric CH_4 decreased to near zero during 2000–2006 (Steele et al., 1992; Bousquet et al., 2006). However since 2007 this trend has reversed and CH_4 concentration has increased about 7 ppb/year (Rigby et al., 2008).

Methane comprised 9.6% of US CO_2 equivalent (CO_2e) greenhouse gas (GHG) emissions in 2007 (EIA, 2008). Major sources of CH_4 emitted to the atmosphere in the US GHG inventory include fossil fuel energy production systems (39%), landfills (24%), enteric fermentation by ruminant livestock (20%) and animal waste (9%). USDA (2008) estimated that dairy cattle were responsible for 20% of the 259 Tg of livestock CO_2e emissions in 2005, second to beef cattle (65%). Dairy cattle emitted 25% of enteric CH_4 emissions, and 46% of CH_4 from managed livestock waste (USDA, 2008).

The US Environmental Protection Agency (EPA, 2009) ruled that livestock facilities with manure management systems (MMS) that emit more than 25,000 t CO_2e/year were required to report CH_4 and N_2O emissions. Manure management systems include uncovered anaerobic lagoons, liquid/slurry systems, solid manure storage and dry lots. The threshold for dairies to report is an average annual animal population of 3200. Although the MMS portion of the mandatory GHG reporting rule is not currently in force because US Federal Congress prohibited expenditure of funds to implement it, accurate and comprehensive data on GHG emissions from dairy farms are needed for potential regulatory demands and for national and international GHG inventories.

Our objective was to quantify CH_4 emissions during summer from an uncovered anaerobic wastewater lagoon at a commercial dairy farm typical of those in operation on the southern High Plains of New Mexico and Texas (USA).

2. Materials and methods

2.1. Research site and dairy management

The research was conducted from 8 August 2009 to 15 August 2009 at a commercial dairy farm located in Curry County, New Mexico (USA), which was judged to be typical of dairy farms in eastern New Mexico and western Texas (Fig. 1). Cows were housed in open lot soil/manure surfaced corrals (from 82 to 96 m × 225 m), with a total area of 22.5 ha. A 7 m × 192 m sun shade was provided in each corral. Feed lanes were surfaced with concrete, and flushed on an irregular schedule with lagoon waste water to remove accumulated manure. Flushed effluent entered a 700 m canal that flowed into a sump pit. From there effluent was pumped to a solids separator before it entered the lagoon system.

The lagoon system consisted of 4 lagoons. During the study, the first 3 lagoons (1.8 ha surface area) contained effluent and the fourth was dry. A pump that operated intermittently near the inlet of the first lagoon pumped solids back to the separator. The first lagoon (east) was connected to the second (west) by a 2 m wide surface channel, while the third lagoon (south) only received effluent that overflowed from the first lagoon. Water from the first lagoon was periodically pumped to the north end of the dry lot and recycled as flush water. Information from dairy management and random soundings indicated that water depth was generally 1–2 m and bottom sludge depth was 0.25–0.5 m.

The dairy was only populated with lactating and dry cows, ~3500, with 73% being in lactation (average 150 days in milk (DIM)), 7% fresh (average 20 DIM) and 20% dry (Table 1). Dry matter (DM) intake averaged 25.1 and 21.5 kg/head/d and crude protein (CP) was 167.3 and 174.5 g/kg (DM basis) for milking and fresh cows, respectively. The DM intake was 13.4 and 13.5 kg/head/d, and CP was 151.7 and 135.8 g/kg for close up and far off dry cows, respectively. During the study period, milk production averaged 29.2 kg/head/d.

2.2. Micrometeorological measurements and flux quantification

Methane concentration at the lagoons was measured using an open path tuned diode laser (Gasfinder 2.0, Boreal Laser, Inc., Spruce Grove, AB, Canada) deployed at a height of 1.65 m. Prevailing wind direction was southerly, so the laser path was positioned either along the north side of the lagoons (day of year (DOY) 219–223, path length 233 m) or diagonally from northeast to southwest across the lagoons (DOY 224–227, path length 239 m; Fig. 1). The laser path was changed during the morning of DOY 224 to include easterly winds. The laser measured CH_4 concentration every 35 s. The open path laser was calibrated using standard gas concentrations in the laboratory after completion of the study and a calibration factor of 1.26 used to adjust measured concentrations, which were then averaged into 15 min mean concentrations. Background CH_4 concentration was measured at a location 75 m south of the southwest corner of the open lot corrals and 680 m west of the lagoons using a back-flush gas chromatography system with flame ionization detector (Model 55I, Thermo Scientific,

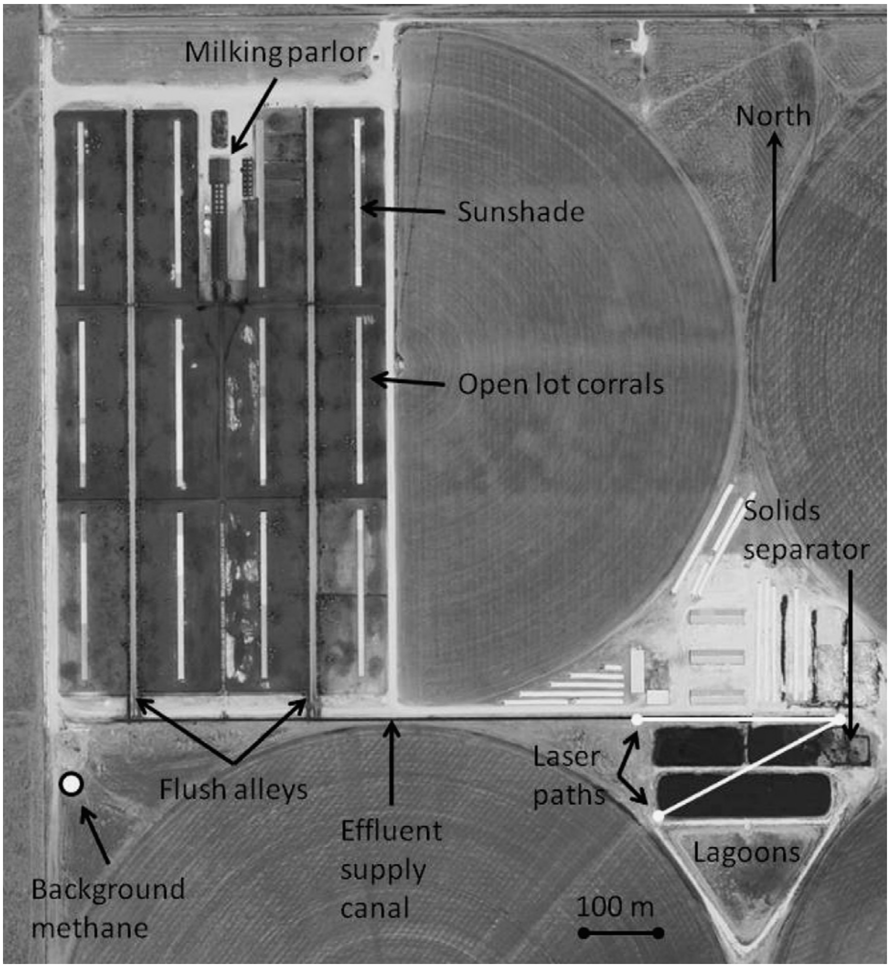

Fig. 1. Commercial dairy farm used in study. Area of open lot corrals was 22.5 ha and area of the three lagoons with effluent was 1.8 ha.

Waltham, MA, USA). The detection limit was 0.05 ppm. Background CH_4 concentration was measured once a minute and the 15 min averages were calculated. The background CH_4 system was calibrated periodically on site. Locations of the open path laser and background measurement constrained acceptable wind directions to between 100° and 270° because of possible contamination of CH_4 concentration measurements by CH_4 emissions from the open lot.

Wind and turbulence data were measured using a three-axis sonic anemometer (Model 81000, R.M. Young, Traverse City, MI, USA). The sonic anemometer was located about half way along the north side of the lagoon system at a height of 3.8 m in order to characterize southerly winds flowing over the lagoons. Data were sampled at 10 Hz frequency and 15 min means, variances and covariances of sonic temperature, and with-wind, cross-wind and vertical velocities were stored on a datalogger (CR21X, Campbell Scientific, Inc., Logan, UT, USA). Coordinate rotations were employed and wind direction, wind speed (u), friction velocity (u^*), turbulence statistics (σ_u, σ_v, σ_w), sonic air temperature, sensible heat flux, roughness length and Monin-Obukhov length (L) were calculated (van Boxel et al., 2004; Ham, 2005).

Methane emissions from the lagoons were quantified using an inverse dispersion model (Windtrax 2.0.7.9, Thunder Beach Scientific, Nanaimo, BC, Canada), methodology which is comprehensively discussed in Flesch and Wilson (2005). Gas concentration downwind of an emission source area is coupled with upwind concentration (*i.e.*, background), wind information, and a map of the source area to estimate emission rate by calculating the emission rate necessary to cause the measured increase in concentration. The inverse dispersion model uses a description of turbulent transfer based on Monin-Obukhov similarity theory, and a backward Lagrangian stochastic (BLS) model that calculates the upwind trajectories of large ensembles of gas particles from the concentration measurement location to the source area. It assumes that the atmospheric surface layer is homogeneous, that flow is stationary and that the source strength is spatially uniform. Harper et al. (2009) reported that BLS flux estimates from several studies ranged from −14 to +7% of known tracer releases. Gao et al. (2009), using open path lasers, found that BLS overestimated methane flux by 9%. The lagoon source area was mapped using geographic coordinates from a georeferenced digital orthophoto quadrangle of the dairy (MrSID Geoviewer 2.1, LizardTech, Inc., Seattle, WA, USA). Model runs were executed on input data sets with 15 min time steps using ensembles of 10,000 particles. Data

Table 2
Daily meteorological conditions during the study. Values are means of 96 15 min observations for each day, except day of year (DOY) 227, which has only 33 observations from the morning. The σ_u, σ_v, and σ_w are standard deviations of the wind velocity fluctuations, u^* is the friction velocity, and z_0 is the roughness length.

DOY	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Friction velocity (m/s)	σ_u/u^*	σ_v/u^*	σ_w/u^*	z_0 (m)
220	27.6	36	3.27	0.42	2.36	2.09	1.07	0.08
221	26.0	44	4.21	0.47	2.35	1.96	1.11	0.08
222	23.5	59	3.43	0.39	2.64	2.38	1.10	0.07
223	24.0	63	2.49	0.27	2.56	2.46	1.17	0.07
224	23.8	63	2.50	0.30	2.45	2.52	1.08	0.08
225	23.8	62	3.34	0.33	2.20	2.09	1.12	0.07
226	22.1	74	2.97	0.37	2.31	2.11	1.09	0.08
227	18.0	93	1.64	0.17	2.31	2.11	1.06	0.08

were excluded from input data sets when any of these conditions were met: $u^* < 0.15$ m/s, $|L| < 10$ (extreme atmospheric stability or instability), or wind direction was greater than 270° or less than 100°.

3. Results

3.1. General conditions and data retention

The first three days of the study were warm with southerly winds (Table 2). A thunderstorm during the evening of DOY 222 rained 29 mm in less than 2 h. Runoff from the drylot filled the two north lagoons and overflowed the berm into the south lagoon. Subsequent days had variable wind directions and tended to be cooler with higher humidity. Another rain event during the morning of DOY 224 totaled 2.3 mm. After applying data quality criteria, 389 out of 768 15 min observations (*i.e.*, 51%) were accepted for analysis. Low wind speed and unacceptable wind direction were the most common data rejection criteria.

3.2. Methane concentration and flux

Background CH_4 concentration averaged 1.83 ± 0.175 ppm during the study. Methane concentration over the lagoon ranged from 3 to 12 ppm, with the highest concentrations (*i.e.*, >10 ppm) either near sunrise or during the night. Mean daily CH_4 concentration over the lagoon was 5.6 ppm. Typically, the CH_4 concentration rose at sunrise to a daily maximum of ~8 ppm, and then decreased to 4 and 6 ppm for most of the day.

Methane flux was 170–1190 $\mu g/m^2/s$ (Fig. 2), with daily minima tending to occur during the afternoon. An exception was on DOY 223, when afternoon flux densities exceeded 700 $\mu g/m^2/s$. These higher flux densities occurred on the day following the 29 mm rain event and a large influx of water into the lagoons. A diel (*i.e.*, 24 h time period from midnight to midnight) composite (n = from 2 to 6 for the mean of each 15 min period) showed CH_4 flux minima (~300 $\mu g/m^2/s$) at about 0300 and 0900 h (Fig. 3). Mean maximum flux density (~650 $\mu g/m^2/s$) occurred 90 min either side of sunrise. Mean daily CH_4 flux density was 402 kg/ha/d, or 0.21 kg/head/d.

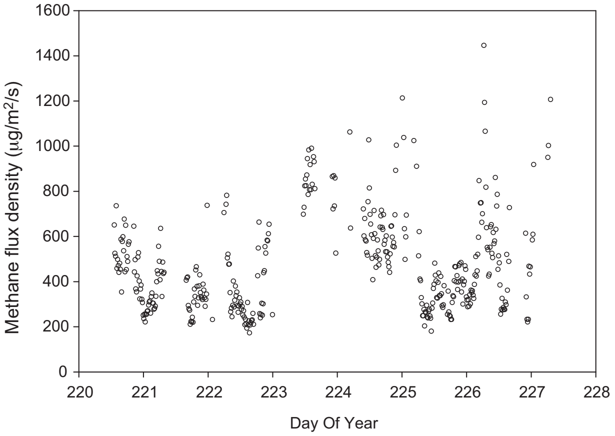

Fig. 2. Methane flux density (15 min observations) from lagoons.

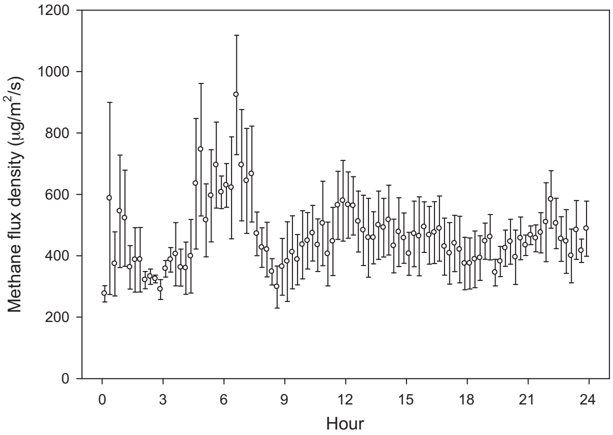

Fig. 3. Composite diel (*i.e.*, 24 h time period from midnight to midnight) methane flux density from lagoons. [Error bars are the standard error for each 15 min mean.].

4. Discussion

Methane emissions from anaerobic lagoons range widely. Khan et al. (1997), using the integrated horizontal flux method, found that CH_4 flux from a New Zealand dairy slurry pond ranged from 2 to 148 $\mu g/m^2/s$ and that daily emission rate for two days was 9.75 kg/head/d, compared with our much larger value of 402 kg/head/d. However, the New Zealand data were collected during winter and the ambient temperature was about half that during our study. Safley and Westerman (1992) found that a covered anaerobic dairy lagoon managed for biogas production produced 0.147 m^3 $CH_4/m^2/d$ over 17 mo, with a peak production of 0.52 m^3 $CH_4/m^2/d$. Mean volumetric CH_4 flux in our study was 0.057 m^3 $CH_4/m^2/d$ (0 °C, 100 kPa), only 39% of the CH_4 production measured by Safley and Westerman (1992). Sutter and Ham (2005) collected biogas emitted over 1 year from a swine lagoon, and annual CH_4 flux density was 136 $\mu g/m^2/s$, with a peak flux of 2431 $\mu g/m^2/s$ in June. Park et al. (2010) reported CH_4 flux from liquid swine manure in a tank of 1650 $\mu g/m^2/s$. In contrast, Sharpe and Harper (1999) found much lower emissions from swine lagoons, ranging from 52 $\mu g/m^2/s$ during winter to 70 $\mu g/m^2/s$ during summer. Even lower emissions reported by Sharpe et al. (2002) using a flux-gradient method were probably attributable to limited fetch (*i.e.*, upwind emission source area).

Sharpe et al. (2002) found that CH_4 emission from a swine lagoon was positively correlated with wind speed. However, CH_4 emission from our lagoons was inversely correlated with wind speed. This unexpected relationship was related primarily to the diel pattern of emissions, as we observed that every morning a scum composed of bubbles had formed over most of the surface area of the two north lagoons. This bubble scum phenomenon was also correlated with lowest wind speeds (*i.e.*, <3 m/s between 04:30 h and 07:30 h). As the sun rose and the temperature increased, the bubble scum dissipated, releasing the gases that comprised the bubbles to create a typical CH_4 burst between 05:00 h and 08:00 h. We speculate that a minor contribution to the pattern of emissions was related to oxygenation of water and its effect on methanotrophy. Higher wind speed could aerate a deeper column of water, and increase methanotrophic activity, which would reduce CH_4 emissions. Ding et al. (2004) reported that diel CH_4 emissions from a freshwater marsh peaked 4 h after sunrise and then decreased as oxygen from plant photosynthesis accumulated. The diel pattern in Fig. 3 suggests this effect, and preliminary measurements showed that daytime dissolved oxygen in lagoon water tended to be higher during day than night (*i.e.*, 0.68 mg/L *versus* 0.57 mg/L). This demonstrates the complexity of lagoon chemistry and biology, and that we need to better quantify and understand the processes occurring in lagoons at various depths.

5. Conclusions

Methane emissions from an anaerobic wastewater lagoon system at a commercial New Mexico (USA) dairy farm were quantified during 8 days in August 2009 using open path laser spectroscopy and an inverse dispersion model. Methane concentrations in air over the lagoons ranged from 3 to 12 ppm and averaged 5.6 ppm. Methane fluxes ranged from 170 to 1190 $\mu g/m^2/s$ with a mean daily CH_4 flux of 402 kg/ha/d. On a per animal basis, emission rate was 0.21 kg/d, values which tended to fall in the middle of the range of CH_4 emissions from anaerobic animal waste lagoons previously reported. Further research is needed into factors that affect CH_4 emissions from wastewater lagoons, such as lagoon chemistry, manure partitioning, volatile solids loading and temperature dependency. Measurement of CH_4 emissions throughout the year is needed to describe seasonal variability.

Conflict of interest

None.

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