Final Report

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Post-AMMP Dairy Emissions of GHG, Ammonia and Hydrogen Sulfide from a Pastured Dairy and Compost-Bedded Pack Barn Project

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Abstract

California is the national leader of milk production. According to the California Air Resources Board (CARB), methane emissions inventory for California in 2020 were estimated to be 115 million metric tons of carbon dioxide equivalent ($MMTCO_2e$). Methane emissions from dairy manure and enteric fermentation represented nearly half of all methane emissions in California, with dairy manure accounting for 26% (30 $MMTCO_2e$), and enteric fermentation accounting for 29% (33 $MMTCO_2e$). A majority of dairy farms in California utilize manure lagoons, in which organic matter in manure undergoes a biochemical degradation process that creates methane. Anaerobic digesters, which mitigate methane emissions and produce bioenergy in the form of biogas, have been installed on 1.3% of dairy farms in California, a number still relatively low due to high installation costs. As a result, Alternative Manure Management Program (AMMP) practices are considered by some as a cost-effective set of solutions to reduce methane emissions on California dairies.

These AMMP practices include technologies and farm management procedures (e.g., mechanical separators for manure solids, and increase pasture time) that remove part of the organic matter from manure prior to it being stored in manure lagoons. However, the effectiveness of AMMP practices on the reduction of methane emissions is not well understood. In the present project, the emissions of methane and selected gases were measured on two dairies that employed AMMP practices. The first dairy (study name Charlie) used a compost-bedded pack barn. The second dairy (study name Foxtrot) used two practices – a mechanical separator to treat flushed manure and grazing milking cows on pasture for eight months per year.

The utility of various emission models, including the Intergovernmental Panel on Climate Change (IPCC)/CARB, the Dairy Gas Emissions Model (DairyGEM), and the Manure Denitrification-Decomposition (Manure-DNDC) model were studied to identify the most useful one for California dairy conditions. Our work has shown that both the DairyGEM and Manure-DNDC models are in need of major model modifications to be applicable for multiple stages in manure storage (settling basin and lagoon as separate emission sources) and manure processing using different AMMP technologies. The agreement between predicted and measured methane emissions from the lagoons, using IPCC/CARB, varied across the AMMP practices and farm management.

Surprisingly, the measured methane emissions from the lagoons on both dairies post-AMMP practices were relatively higher than those measured pre-AMMP practices. However, this does not suggest that AMMP practices are not effective. The studied AMMP practices in this project are expected to reduce emissions from manure lagoons, as they divert significant amounts of volatile solids that have undergone microbial conversion to produce methane in settling basins and lagoons. The higher methane emission determined post-AMMP may be due to: 1) unknown amounts of manure delivered to the lagoon in both dairies pre- and post- AMMP practices; 2) the change of the lagoon microbial dynamics based on flow rates and characteristics of manure, and cleaning out of the lagoon; and 3) the unknown quantity and quality (i.e., organic matter contents) of manure withdrawn from the lagoon when lagoon water is used for irrigation. On the Foxtrot dairy, the mechanical separator was not properly applied: not all manure delivered to the lagoon was treated with the separator (i.e., lagoon was also fed with manure without passing over the

mechanical separator). However, better system design and management are needed to achieve emission reduction after the implementation of AMMP practices. Moreover, more research is needed to determine the best operation and management procedures when applying these practices.

Executive Summary

The dairy industry represents California's largest agricultural commodity generating approximately $6.3 billion dollars out of a total $50 billion in agricultural production in 2019. However, methane emissions from dairy manure account for 26% of the 115 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) that was the total methane emissions inventory in California in 2020 (CARB, 2015). Relative to anaerobic digesters, Alternative Manure Management Program (AMMP) practices are considered by some to be a more feasible solution as they require less capital investment and are easier for dairy farmers to operate as they strive to reduce methane emissions. These practices include technologies and farm management procedures to remove part of the organic matter from manure prior to anaerobically storing manure. However, the effectiveness of these practices on methane emission reduction is not well known. Therefore, there is a need to understand the impacts of AMMP practices on greenhouse gas (GHG) and other gas emissions from dairy farms in California. The objectives of this project were to conduct emissions measurements on two selected dairies post-application of an AMMP practice and evaluate the utility and accuracy of selected modeling tools for predicting the emissions from dairy manure management practices. Three models were evaluated for their suitability to predict the emissions of methane from manure on these two farms and four other dairy farms that were also measured through a separate contract with the California Air Resources Board (CARB) (agreement # RD-17RD017). The models included Intergovernmental Panel on Climate Change (IPCC)/CARB, Dairy Gas Emissions Model (Dairy GEM), and Manure Denitrification-Decomposition (Manure-DNDC) model.

The first dairy (in this study called Charlie) employs a compost-bedded pack barn for milking cows and the second (in this study called Foxtrot) employs a mechanical separator to treat flushed manure from the free stalls and also grazes milking cows on pasture for eight months of the year. In the pre-AMMP, the animal housing at Charlie dairy was open corrals with shades, and Foxtrot dairy had freestalls with milk cows grazing for at least half of the time in summer. Gas emissions were measured from the lagoons on both dairies for at least three days. The gas emissions from manure collected from the compost-bedded pack barn were measured for two days. At Foxtrot dairy, the emissions were measured from the settling basin for one day and from the mechanical separator solids for one day. The DairyGEM and Manure-DNDC models need a major model development to be applicable for manure storage in which there are multiple settings as separate emission sources, such as settling basin and lagoon, and there is manure processing using different AMMP technologies. Therefore, the IPCC/CARB model was used to predict gas emissions from the lagoons on both monitored farms and the settling basin on the Foxtrot dairy. The same model was also used for the lagoons and the settling basins from the other four dairies under the complementary project (agreement # RD-17RD017) that will be reported elsewhere.

For Charlie dairy, average emission rates of methane (CH_4) and ammonia (NH_3) from the lagoon measured at 17.03 and 0.03 $g/m^2/hr$, respectively. They were 0.66 and 10.13 $mg/m^2/hr$, for nitrous oxide (N_2O) and hydrogen sulfide (H_2S), respectively. The average emission rates of CH_4 and NH_3 from manure collected from the barn were 1.07 and 0.04 $g/m^2/hr$, respectively. They were 1.20 and 2.22 $mg/m^2/hr$, for N_2O and H_2S, respectively. For Foxtrot, the average emission rates, from the lagoon, of CH_4 and NH_3 were 7.89 and 0.15 g/m^2/hr, respectively. They were 16.66 and 0.06 mg/m^2/hr, for N_2O and H_2S, respectively. The average emissions rates from the settling basin, of CH_4 and NH_3 were 13.82 and 0.19 g/m^2/hr, respectively. They were 2.74 and 0.12 mg/m^2/hr, for N_2O and H_2S, respectively. The average emission rates from solids separated by the mechanical screen separator, of CH_4 and NH_3 were 10.41 and 1.66 g/ton/hr, respectively. They were 39.05 and 0.33 mg/ton/hr, for N_2O and H_2S, respectively.

The measured methane emissions from the lagoons on both dairies post-AMMP practices were relatively higher than those measured pre-AMMP practices. The calculated emissions of methane from the lagoon pre-AMMP were 1,054 and 403 g/animal unit/day at Charlie and Foxtrot dairy, respectively. While, for post AMMP, they were 1,475 and 662 g/animal unit/day, respectively. This might be due to: 1) though there was relatively constant number of animal heads on the studied dairies, amounts of manure delivered to the lagoon in both dairies pre- and post-AMMP practices were not known ; 2) the change of the lagoon microbial dynamics based on flow rates and characteristics of manure, and cleaning out of the lagoon can affect the rate and yield of methane production; and 3) the unknown quantity and quality (i.e., organic matter contents) of manure withdrawn from the lagoon when lagoon water is used for irrigation (i.e., removing small amounts of organic matter during irrigation could increase the emissions from lagoons as it can undergone microbial conversion into methane). At Foxtrot dairy, the mechanical separator was not properly applied. Ideally, flushed manure is delivered to a processing pit wherein manure is mixed and then pumped to the separator. The separated manure (i.e., liquid fraction) is then delivered to the lagoon. However, on the studied dairy, flushed manure was delivered to the settling basin first and then part of it was fed to the mechanical separator. Moreover, as a result of how the system was operated, not all manure delivered to the lagoon was treated with the separator during the measurements (i.e., lagoon was also fed with manure without passing over the mechanical separator). This operational and management issue needs to be modified to increase the effectiveness of the system in reducing emissions from the lagoon. Although there were higher methane emissions post-AMMP application that does not suggest that these practices are not effective. The studied AMMP practices in this project, if designed and employed properly, should reduce the emissions from the lagoon because they divert significant amounts of volatile solids from lagoons, that would otherwise undergone biological conversion into methane. More research is needed to determine the best operation and management procedures when applying these practices. Long term and seasonal measurements of emissions, along with a determination of amounts and characteristics of manure are needed for pre- and post-AMMP to accurately determine the effectiveness of AMMP practices in reducing the emissions from lagoon.

The modeled emissions from the lagoons and settling basin, using IPCC/CARB model, varies among the studied dairies. While some of the modeled emissions using this model were comparable to the measured ones, others were not. This might be due to the assumptions used for the amounts and composition of manure delivered to the settling basin and lagoon. More accurate estimations of the amount and characteristics of manure and bedding material delivered to storages should be carried out. Long term measurements of emissions are needed to determine the effect of seasonal temperature variations and the AMMP practices on the emissions of different gases. These measurements could also be used to validate model results. Compared with IPCC/CARB model, the DairyGem and Manure-DNDC models are more mechanistic models that need many input parameters. However, they need a substantial code modification to include both settling basins and lagoons as two sequential treatment systems. They also need to be modified to include different AMMP practices on dairies.

Introduction

The California Air Resources Board (CARB) approved the Short-Lived Climate Pollutant Reduction Strategy (SLCP Strategy) in March 2017 to reduce emissions of methane (CH_4), which include emissions of manure CH_4 from California dairies and other SLCPs. SB 1383 (Lara, Chapter 395, Statutes of 2016) requires CARB to begin implementation of the SLCP Strategy by January 1, 2018, and specifically requires a 40% CH_4 emission reduction from 2013 levels by 2030 for the dairy and livestock sector (https://ww2.arb.ca.gov/resources/documents/slcp-strategy-final).

California is the national leader of milk production. The total sale of milk and its products represents about $6.3 billion annually out of the $50 billion generated from all agricultural production in the state (CDFA, 2019). There were 1,331 dairies in California in 2017, with an average of 1,304 cows per dairy (CDFA, 2018). According to CARB (2015), the 2020 methane emissions inventory from California was estimated to be 115 million metric tons of carbon dioxide equivalent ($MMTCO_2e$). Methane emissions from dairy manure and enteric fermentation represented nearly half of all methane emissions in California, with dairy manure accounting for 26% (30 $MMTCO_2e$), and enteric fermentation accounting for 29% (33 $MMTCO_2e$). Most dairy farms in California, if not all, have manure lagoons in which organic matter in manure undergoes a biochemical degradation process, which results in the production of methane. Anaerobic digesters, which mitigate methane emissions by producing bioenergy in the form of biogas, have only been installed on 1.3% of dairy farms in California due to high installation costs. As a result, Alternative Manure Management Program (AMMP) practices that require less capital investment and are easy to operate, are sought for use on livestock operations that for one reason or another, don't have a digester. These practices include technologies and farm management procedures (e.g., increase pasture time) to remove part of the organic matter from manure prior to storing it. However, the effectiveness of AAMP practices on the reduction of methane emissions is not well known. Therefore, there is a need to understand the impacts of AMMP practices on GHG and other gas emissions from dairy farms in California.

This project is complementary to projects funded by CDFA (contract #16-0747-SA) and CARB (agreement # RD-17RD017) to measure the pre-AMMP practice GHG emissions from six (6) sites and post-AMMP practice GHG emissions from four (4) of the same six (6) sites. The present project aimed at 1) post-installation gas emission monitoring on the additional two (2) dairies that employ AMMP practices (i.e., compost-bedded pack barns, and mechanical separator and pastured dairy); and 2) estimating post-AMMP practice emissions on six (6) dairies using three (3) different modeling tools described in the following sections.

The objectives of this project were to:

1) Conduct emissions measurements on two (2) selected dairies post application of AMMP practices. This process quantifies how effective changes in manure management practices are from pre- to post-AMMP installation, by comparing the results of the two companion projects. This specific objective was achieved through identification and recommendation

of the best measurement practices for farm-scale dairy manure emissions monitoring. A protocol was developed to measure GHGs (CH_4 and N_2O), as well as NH_3, and H_2S. Measurements were conducted on two dairies that adopted AMMP practices to establish a better understanding of post-project emissions benchmark data, which were then be compared to pre-AMMP practice results (assessed in the separate CDFA funded companion project).

2) Evaluate the utility and accuracy of selected modeling tools for predicting the emissions of methane from dairy manure management practices. The modeling tools included the Intergovernmental Panel on Climate Change (IPCC)/CARB, Dairy Gas Emissions Model (DairyGEM), and Manure-DNDC model. The models were employed to predict the emissions of GHGs from the six dairies (two in this project and the other four that were funded by CARB in the companion project) after the application of AMMP practices. The predicted emission rates from the three models were validated using the measured emission rates from the six sites.

3) Analyze, report, and disseminate project results and findings. The data from the monitoring study were synthesized to benchmark the post-project emissions of CH_4, N_2O, NH_3, and H_2S from the two selected farms. The final report was written to summarize project findings and recommendations for future research, dairy manure management practices, and policy considerations.

The CDFA funded pre-AMMP project and the present CARB post-AMMP project will be the first to investigate the impacts of the AMMP practices on GHGs and other pollutant emissions. These tandem projects enabled the evaluation of the utility and accuracy of existing farm-scale dairy manure management emissions models for California dairies, as the models have not been calibrated for California dairies in the past. Moreover, the results of this project can be used as a basis in developing selection criteria for different manure management practices in California, helping to improve the economics of milk production while maintaining a clean and healthy environment for animals, farmers, and the public.

Literature Review

The two dairies that were monitored for emissions in this study were named Charlie and Foxtrot. In the pre-AMMP, the cows at Charlie dairy were housed in open corral with shades. Flushed manure from feed lanes and milking parlor was delivered directly to a lagoon. Foxtrot dairy had a freestall barn and flushed manure was delivered to a settling basin and then to a lagoon. In addition, cows at the Foxtrot dairy were grazed on pasture for at least half of the time in summer. The other four dairies that were modeled are named Alpha, Bravo, Delta, and Echo. Those four dairies had freestall barns and flushed manure was delivered to setting basins and then lagoons. The AMMP practices at Charlie was a compost-bedded pack barn for milking cows. Flushed manure was delivered to the lagoon. While Foxtrot employed a mechanical separator and increased pasture time to eight months of the year. Alpha dairy employed a mechanical separator. Bravo dairy employed a vacuum truck to remove manure from the barn, to a screw press for dewatering. The liquid fraction was delivered to the settling basin and then to the lagoon. Delta dairy employed a vacuum scraping of manure for one day per week. The vacuumed manure was then sun dried on a concrete pad. Echo dairy employed a one-cell weeping wall. The liquid seepage from the weeping wall was delivered to the lagoon. When the weeping wall was full, the flushed manure was delivered to the settling basin and then to the lagoon.

Mechanical separators

Mechanical separators are common systems used to remove manure solids prior to storing manure in lagoons. By doing so, they can reduce the emissions of methane and other gases produced under anaerobic storage conditions. Several technologies are currently used on dairies throughout California, including single-stage horizontal scraped screen separator, single-stage sloped screen separator, and two-stage sloped dual-screen separator. In addition, a rotary drum separator system is employed at a few dairies in California. The performance of the mechanical screen separators depends on manure characteristics and system design and management. Most California dairies use some method of solids separation. According to Meyer et al. (2011), 30%-40% of the dairies they surveyed in California use settling ponds or basins, and approximately 30% use mechanical separators, with or without settling basins. There is no exact inventory that details different manure management technologies employed at all dairies in the state. Table 1 shows the major AMMP practices that are used on California dairies. Some of these technologies are included in the AMMP quantification methodology (CARB, 2019). The methodology was developed by CARB staff to provide guidance for estimating the reductions of GHG emissions after employing different AMMP practices. The efficiency of total solids (TS) removal depends on the technology type. Table 2 shows the solids removal efficiency of several screen separators for dairy manure as reported in the literature.

Table 1. Mechanical separators used at California dairies (Meyer et al., 2019; Williams et al., 2020).

Separator type	Relative occurrence on California dairies*	Included in AMMP quantification methodology
Sloped Screen	Most common	Yes
Two-stage Sloped Screen	Several, likely less than 10	No
Drag Flight Conveyor	Less common but significant	No
Rotary Drum Separator	One	Yes
Centrifuge	None	Yes
Screw press	Several, likely less than 10	Yes
Roller Press	None	Yes
Weeping Wall	Several, likely less than 10	Yes

Table 2. A comparison of selected screen separators for dairy manure

Type of separator	Screen size (mm)	Flow rate (m^3/min)	TS of inflow (%)	Dry matter removal (%)	Reference
Rotary screen	0.75	0.41-0.75	0.52	5	Hegg et al., (1981)[1]
		0.45-0.97	0.81	10	
		0.78-0.91	1.14	4	
		0.08-0.34	2.95	14	
Sloped screen				67	Graves et al. (1971)
Inclined stationary screen	1.5		3.83	60.9 (62.8*)	Chastain et al. (2001)[1]

1: Calculated based on the difference in the concentration.
*: Reduction of volatile solids.

A literature review focusing on both flush manure and solid separation treatments, showed to varying degrees methane potential from manure after some solids are removed to be in the range of 15% to 40% as shown in Table 3. Screens and presses were used for solid separation in these studies.

Table 3. Relative methane production potential from solids-separated dairy manure compared to untreated manure.

Separation method	Relative methane potential (Treated / raw manure, %)		Reference
	Filtrate (after solids separation)	% of initial VS in filtrate	
Screening	85%	54%	Hills (1985)
Screening	72%	62%	El-Mashad and Zhang (2010)
Screening	60%	48.7%	Rico (2007)
Screw Press	70%	~30%	Witarsa (2015)
Roller Press	70%	~50%	Pain et al. (1984)
Screw Press	63%	~50%	Amon et al. (2006)

Hills (1985) investigated and compared the methane production potential of untreated and filtered dairy manure (with 10 mesh screen), using 4 L laboratory digesters operated continuously at 35° C for 100 days. Their results showed that solid separation by screening reduced the methane production potential by 15%. El-Mashad and Zhang (2010) screened manure using a screen with 2-mm openings and conducted anaerobic digestion assays of the untreated manure and the coarse and fine fractions of the removed solids using 1 L laboratory batch digesters operated at 35°C for 30 days. Their results showed 28% reduction in methane production potential of the manure after filtration. Rico (2007) reported on the methane production potentials of solid and liquid dairy manure fractions. Manure at 8% solids was collected followed by screening of a portion of the manure with a screen with 1-mm openings. The methane production potential for raw and screened manure (filtrate) was determined using 2.5 L batch laboratory reactors operated at 35°C for 45 days. Their results showed that the screened manure produced about 40% less methane than the untreated manure. Witarsa (2015) investigated methane production potential of flush manure and solid separation treated dairy manure under psychrophilic digestion conditions (< 25°C). Manure was collected before and after a screw press that removed about 70% of the total solids. Methane potential was determined in 250 ml reactors held at 24°C. Methane production potential from the filtrate was about 30% less than the raw manure. Pain et al. (1984) operated two 125 m^3 mixed tank mesophilic digesters at a dairy with one fed with 7% TS dairy manure slurry and the other digester used the filtrate (4% TS) from roller press screen separator. They found that the methane production from the filtrate was about 30% less than the raw manure. Amon et al. (2006) measured GHG emissions from different treatments of stored, then land-applied dairy slurry manure (untreated slurry, liquid and solids fraction separation w/ screw-sieve, digestate from slurry digester, slurry w/ straw cover and aerated slurry). Approximately 10 m^3 of each treatment type was stored in a concrete in-ground tank with a loose wooden cover for 80 days (mean slurry temperature was 17°C) and then land-applied. Relative GHG emissions reduction (for storage and land application combined) of the separated and aerated slurry treatments were 37% and 42%, respectively, of that from the untreated slurry. Zhang et al. (2019) evaluated solid removal efficiency and methane potential reduction of five mechanical separation technologies at California dairies. Some of the systems were evaluated over the four seasons by measuring manure inflow rate to the systems and weighting the solids removed. The efficiencies of the systems for solid removal and methane potential reduction were dependent on manure characteristics (i.e., total solid contests), system design (e.g., screen size and orientation), separator operation and management (manure flow rate), and manure processing pit type and configuration. Table 4 shows the determined average solid removal efficiencies and methane potential reduction.

Recently, Williams et al. (2020) recommended values for manure solid removal, that are different from the default values currently used in AMMP quantification methodology default (Table 5).

Table 4. Solid removal efficiencies and methane reduction potential of some mechanical separation technologies installed at California dairies (Zhang et al., 2019).

Parameter		**Single-stage horizontal scraped screen separator**	**Single-stage sloped screen separator**	**Single-stage sloped dual-screen separator**	**Two-stage sloped dual-screen separator**	**Advanced multistage separator system**
Screen size (mm)	1st stage	2.39	Top 1/3: 0.381 Middle 1/3: 0.635 Bottom 1/3: 0.889	Top 2/3: 0.508 Bottom 1/3: 0.635	Top 2/3: 0.508 Bottom 1/3: 0.635	Separation zone: 3.175 Dewatering zone: 3.175
	2nd stage	NA	NA	NA	Top 2/3: 0.254 Bottom 1/3: 0.381	Separation zone: 0.533 Dewatering zone: 3.175
Influent flow rate (m^3/m)		2.99-5.7	1.12-2.57	3.18-4.12	2.63-3.53	3.55-5.74
TS removal efficiency (%)		4.7-8.0	20.1-38.4	27.7-48.9	37.6-60.2	64.2-78.8
VS removal efficiency (%)		6.5-12.1	26.4-48.8	35.5-58.4	41.4-72.8	62.7-79.6
CH_4 potential reduction (%)		1.4-8.4	28.9-42.2	38.2-57.2	28.2-73.1	69.0-83.4

Table 5. Recommended values for solid removal using selected manure management technologies (Williams et al., 2020).

Separator type	Recommendation	Current AMMP quantification methodology default (solids removal)
Sloped screen	30-35% default solids removal	17%
Screw press	50% Default for Scrape/Vacuum Systems	25%
Weeping wall	50%-80% (average (65%)	45%

Weeping wall

A weeping wall system is defined as a settling basin with a large dewatering surface area (Meyer et al., 2004). Compared to mechanical separation technologies, a weeping wall can provide several advantages, including: lower energy, minimum equipment requirements, and lesser repair and maintenance cost (Mukhtar et al., 2011). Well designed and operated weeping walls also do not have operational downtimes. They provide flexibility in managing manure hauling tasks and extended storage periods for manure solids; and they could save 5 to 10 hours of labor per week (Sustainable Conservation, 2005). Nooyen (2018) mentioned that weeping walls are the most cost-effective system for dairy operation and they do not require additional energy, equipment, or labor. In the U.S., weeping walls can provide storage for manure solids for up to three months.

Generally, the weeping wall system consists of multiple cells, usually 2-4. Each cell is a standalone structure that has concrete floors. Three sides of the cell are constructed using slotted concrete, horizontal wooden slats, or screens supported by concrete pillars (Mukhtar et al., 2011; Houlbrooke et al., 2011). The fourth side is used as an entry ramp for filling and emptying the cell. While the liquid manure travels along the cell, the solids accumulate inside the cell and the water is drained out of it. The drained water is usually stored in lagoons until it is used for irrigation. The accumulated solids in the cell act as a filter that helps in capturing more solids.

Once a cell is filled with solids, it is left to continue to drain and dry for a designated period of time, usually for two weeks. While the filled cell is draining, the flushed manure from the barn is directed to another empty cell. After dewatering, the accumulated solids are removed using an excavator or a front loader. Then, the solids are transported to fields or to a composting area on the dairy farm.

Laubach et al. (2015) mentioned that weeping walls are increasingly popular as a pre-treatment step for dairy manure. They also mentioned that a weeping wall could achieve a solid removal of up to 50%. The accumulated solids inside the weeping wall cells are generally removed once or twice per year and applied to pasture or crops. A two-stage weeping wall system was evaluated for its solids and nutrient retaining/capturing capabilities at a dairy in east central Texas (Mukhtar et al., 2011). The weeping wall system comprised of primary and secondary weeping walls. The effluent from the primary chambers was collected in a storage tank and pumped and delivered to secondary chambers. The primary system consisted of four parallel chambers. The secondary weeping wall system consisted of two parallel chambers. Each chamber in the primary and secondary systems had a storage capacity of 60-90 days, and 21 days, respectively. In the primary chamber, the estimated capture efficiencies for total solids (TS), volatile solids (VS), total Kjeldahl Nitrogen (TKN), Phosphorus (P), and Potassium (K) were 67%, 67%, 60%, 55%, and 54%, respectively. Overall capture efficiencies for TS, TVS, TKN, P, and K were 88%, 89%, 84%, 86%, and 84%, respectively. Meyer et al. (2004) evaluated the effectiveness of a weeping wall on a 1,100 cow commercial dairy in California by sampling manure over four sampling events: three events in March and one in July. The influent mean TS concentration was 1.52%. Fixed solids ranged from 37% to 46% of the TS. The weeping wall removed manure particles that are greater than 0.125 mm. The average TS removals were in the range of 49% to 63%. No sampling was conducted for the solids retained in the weeping wall. Nooyen (2018) mentioned that the Tri-Bar weeping wall system could effectively remove 60% - 85% of total solids and up to 70% of sand. NRCS (2014) reported a solid removal efficiency of the weeping walls in the range of 50%-85%. Zhang et al. (2019) measured the efficacy of solid removal by a weeping wall system on a dairy in California. The system consisted of four cells that were alternately filled. The filling time ranged from 14-20 days, and the draining time ranged from 22 to 34 days. Two cells were evaluated by measuring manure inflow rate and weighing the solids separated by the weeping wall at the end of draining time. The efficiency of solid removal was in the range of 78-82% and volatile solids 79%-82%. Based on the volatile solid removals and the methane production potential, the authors estimated the reduction of methane potential of 75%-81 Williams et al. (2020) recommended a 65% solids retention default with a methane conversion factor (MCF) of 0.22 for weeping wall systems in the quantification methodology. The proposed MCF was calculated based on the average times of 43, 49, 7 days; and the MCF values of 0.1, 0.32, and 0.16 for the filling, storage and seepage, and excavation periods, respectively. The authors mentioned that retention of 65% of solids in the weeping wall reduced overall methane emissions by 46%.

Compost-bedded pack barns

Compost-bedded pack barns are a housing system for dairy cows that has been recently adopted in many states. They can increase cow comfort, as cows have an open bedded pack area for resting and exercise. Bedding materials are usually used cows and mixed with manure. The best materials for the compost-bedded pack barns should have good physical structure, good water absorption capacity, less than 25% initial moisture, and should be less than 2.5 cm long (Barberg et al., 2010). Barberg et al. (2010) described different bedding materials used in compost-bedded pack barns. The materials include: pine sawdust, corn cobs, pine woodchip fines, and soybean straw. Each of these materials is used individually or mixed with other materials. Saw dust was the preferred choice of material to use as bedding in compost barns. In California, straw, dried manure, or nut shells are typically employed.

Shane et al. (2010) evaluated several materials as bedding for compost bedded pack barns. Experimental bedded packs each with 16 cows were used. The materials included pine sawdust (control), corn cobs, pine woodchip fines, and soybean straw. Some of these materials were evaluated as mixtures on a 2:1 volume-to-volume ratio. These mixtures included: woodchips

/sawdust, woodchips/soybean straw, and soybean straw/sawdust. Moisture content was measured twice a month, and C:N ratios and pH were analyzed monthly. Temperatures of each pack were measured weekly at various depths (15.2, 30.5, 45.7, and 61.0 cm). Cows were scored for hygiene (1=clean, 5=dirty) twice a month. Moisture contents were 59.7, 44.5, 60.6, 58.2, 60.7 and 60.6 for saw dust, corn cob, woodchips/sawdust, soybean straw/saw dust, woodchips/soybean straw, and soybean straw, respectively. The pH values were 8.7, 7.7, 8.6, 8.6, 8.3, and 8.6, respectively. The C:N ratios were 37.3, 29.2, 47.5, 25.6, 31.0, and 22.8, respectively. Hygiene scores of cows were 2.4, 2.7, 2.5, 2.9, 2.6, and 2.8, respectively. It was concluded that with proper bedding management, any of the tested materials would work as a bedding material in compost-bedded pack barns.

Although the system could potentially increase the risk of poor cow hygiene, properly managed compost-bedded pack barns can provide a health-promoting, dry, and comfortable surface that allow a cow to lie, stand, and walk (Leso et al., 2020). Animal walking and laying may compact the manure surface and reduce air (e.g., oxygen) exchange with manure so that the rate of manure decomposition is reduced. Barberg et al. (2010) mentioned that bedding can accumulate in the pack up to 1.2 m deep. The bedding is usually tilled using cultivator, rotary tiller, or chisel plow. The depth of tilling is usually approximately 25 cm. The bedding should be properly managed to promote microbial activity. The number of times a bed is tilled, ranges from one to three depending on the weather conditions, type of bedding, area available for each cow in the barn, and farm management. Stirring and ventilation is usually applied to keep the pack surface dry (Barberg et al. (2010)). Black et al. (2013) surveyed 42 farms in Kentucky that were applying a compost-bedded pack to characterize herd performance, describe system management and operation, and satisfaction of producers. Results showed that system benefits included cow comfort and cleanliness and low maintenance requirements. Pack temperatures, measured at 20.3 cm, increased with the increase in stirring frequency, stirring depth, and ambient temperature. Compost-bedded pack barns had lower investment than freestall housing systems. However, their variable costs (e.g., bedding costs) may be higher. For data collected from eight compost-bedded pack barns in Kentucky dairies, Eckelkamp (2016) found that compost internal temperature increased and compost moisture content decreased with increasing maximum barn temperature. Herd hygiene score decreased with increasing barn temperature and compost moisture content. The growth of staphylococci, streptococci, and bacilli decreased with the increase of compost internal temperature while the growth of coliform species increased.

Emissions from compost-bedded pack barns

In compost-bedded pack barns, Rotz (2018) mentioned that ammonia can be emitted from fresh and non-fresh manure. Ammonia emission from a manure surface involves five processes: urea hydrolysis, dissociation, diffusion, aqueous-gas partitioning, and mass transport away from the manure surface to the atmosphere. For the emissions of ammonia from fresh manure, urea in urine is converted into ammoniacal nitrogen via urease enzyme present in the feces. A portion of the organic fecal nitrogen (N) can also transform to ammoniacal N during extended manure storage (composting). The Michaelis-Menten kinetics model was used to describe the degradation of urea by the urease present in feces (Muck, 1982). The distribution of total ammoniacal N (TAN) between ammonia (NH_3) and ammonium (NH_4^+) in a solution such as manure was modeled using thermodynamic equilibrium principles (Stumm and Morgan, 1996; Montes et al., 2009). Henry's law was employed to relate the ammonia in a solution to that in a gas phase equilibrium with the solution. The movement of ammonia away from the manure surface into the surrounding atmosphere was described using a mass transfer model. Mass transfer coefficient was derived using a two-film model and ammonia properties and air as the transfer media. The mass transfer coefficient was modeled as a function of the air friction velocity and the Schmidt number (Mackay and Yeun, 1983). The same equations used for fresh manure were also used for estimating hourly ammonia emission rates from non-fresh manure areas. However, ammonium adsorption was considered in calculating the ammonia fraction in TAN due to its higher degree of organic matter decomposition. As organic matter decomposes, the adsorption capacity of the manure pack increases (Bernard et al., 2009; Waldrip et al., 2012), which then gives more sites to adsorb cations that can include ammonium. The model also includes an equation for urine absorbed by the bedding material. The absorption of urine by the bedding material can reduce ammonia emission (Misselbrook and Powell, 2005; Gilhespy et al., 2009). The moisture content of the bedded pack was predicted using models of soil water component (Jones and Kiniry, 1986). The amount of water evaporated was modeled based on the difference in moisture concentrations between ambient air and the air layer right above the bedded pack surface (Black et al., 2013). The prediction of N_2O emissions involved processes such as mineralization, nitrification, and denitrification and leaching. Mineralization rate of manure organic N was modeled as a function of temperature, moisture content and a mineralization rate coefficient. Ammonium in manure is nitrified to nitrate which can undergo leaching that was modeled based on the Nitrate Leaching and Economic Analysis Package model (Shaffer et al., 1991). Modeling of nitrification, denitrification and leaching processes are based on relationships from the DAYCENT model (Parton et al. 2001; DAYCENT, 2007; Bonifacio et al., 2015). The temperature model for compost-bedded pack barns is adapted from Cekmecelioglu et al. (2005). Methane emissions from bedded pack was modeled using the tier 2 approach from the IPCC (2006), in which emission on a given day was determined as a function of the ambient barn temperature and a methane conversion factor.

In the compost-bedded pack barns, the aerobic and anaerobic conditions within the manure pack lead to much greater CH_4 and N_2O emissions (Rotz, 2018). Ayadi et al. (2015) measured the ammonia and greenhouse gas at surfaces of simulated beef cattle bedded manure packs using corn stover or soybean stubble as bedding. Results showed that NH_3, CO_2, CH_4, and N_2O concentrations increased with the increase of storage temperature. Nitrous oxide and NH_3 concentrations were similar across bedded manure pack ages. Methane concentrations doubled with increased age of the pack. Ayadi (2015) developed a mathematical model based on Integrated Farm Systems Model (IFSM) to simulate N_2O emissions, NH_3 emissions, TN, TP and TK concentrations from compost-bedded pack barns on beef farms. Evaporation was the main process for water movement inside the bedding. The model for ammonia emissions included degradation of urea in the urine in the bedding and mass transfer of ammonia from the bedding surface. Nitrous oxide was predicted based on denitrification losses. There was not a good agreement between predicted and measured values of ammonia and nitrous oxide emissions. The model could adequately predict N-P-K fertilizer concentration for bedded manure packs.

In the Netherlands, Van Dooren et al. (2016) measured gaseous emissions from four bedded pack dairy farms and a concrete slatted floor housing system that acted as a reference system. One of the bedded pack farms used wood chips as bedding material, the other three used green waste compost. The ammonia emissions from the wood chip bedded barn were 190.4 $mg/m^2/hr$ and the compost-packed bedded barn ranged from 44.3 to 754 $mg/m^2/hr$. Emissions of ammonia per cow were 175%-475% higher compared to the reference system. But the emission per square meter were lower due to the large area per cow in the bedded pack farms. Emissions of nitrous oxide from the wood chips bedded barn were 7.3 $mg/m^2/hr$ while they ranged 10.3 to 33.4 $mg/m^2/hr$ for the barns bedded with compost. These emissions values were 3.5 to 25 times higher than that of the reference system. Emissions of methane from the wood chips bedded barn were 82.1 $mg/m^2/hr$ while they ranged from 165.8-186.7 $mg/m^2/hr$ for the barns bedded with compost. Methane emissions, however, ranged from 6% to 25% of the reference system. For the wood chips bedding, temperature at depth 20-40 cm were higher than those of the compost bedded barns. The temperature of the former reached a maximum of 50°C.

Wolf (2017) measured the emissions of N_2O, CH_4, and CO_2 from a compost-bedded pack barns at the University of Kentucky Coldstream Dairy. Sawdust was used as the bedding material. The bed temperature and moisture content at 20 cm depth were 48.5°C and 49% (wet basis). Emissions were high directly after tillage and stabilized with time. The emission rates of methane were 0.21, 0.013, 0.082 g/m^2 /hour, respectively at 20, 40, 60 min after tillage. The emissions of CO_2 were 100.2, 24.1, 26.4 g/m^2 /hour, respectively. Emissions of N_2O were 0.0031 g/m^2 /hour at 20 minutes after tillage. Then emissions were negligible. Külling et al. (2001) mentioned that straw additions to dairy slurry decreased NH_3 emission and increased N_2O emission. It was found that NH_3 emissions were positively related to the crude protein content of the diet. Similar results were obtained by Gilhespy et al. (2009), who found that increasing straw in bedding of cattle and pig farms decreased the emissions of ammonia. For a pack-bedded barn in the Netherlands, de Boer (2014) estimated that 63% of the carbon in wood chip bedding, and the feces excreted on the bedding, was lost to the atmosphere in the form of CO_2 and CH_4. Galama et al. (2015) calculated the mass balance of nitrogen in six bedded pack barns in the Netherlands. Wood chips, green waste compost, and straw were used as bedding materials. The losses of nitrogenous gases from the barns ranged from 19% to 63% of the nitrogen excreted by the cows, and from 17% to 35% of the total nitrogen input on the barn floor (manure and bedding material). The nitrogen losses per kg of milk was the lowest for the barns bedded with wood chips and using aeration systems. The barns that applied aeration blowing had lower emissions than from the barns that applied aeration by suction. The authors measured the emissions of ammonia, nitrous oxide, and methane using a flux chamber in some of these barns. Results showed that ammonia emissions per square meter for the barns bedding with wood chips, compost, and straw were lower than from a free stall that was as a reference system. The emissions of ammonia, measured with Innova, ranged from 70.5 to 593.6 $mg/m^2/hour$. The average emission of ammonia from the bedding were 3,224, 6,396, and 5,033 mg/animal/hr for wood chips, compost, and straw bedding, respectively. The emissions of nitrous oxide were 8 to 16 times higher than that from the reference systems. The emissions of nitrous oxide from the beddings ranged from 1.4 to 41.1 $mg/m^2/hr$. Methane emissions were considerably lower than that from the reference system. The emissions of methane from the beddings ranged from 6.1 to 1795.9 $mg/m^2/hr$. Galama (2014) described three compost-bedded pack barns in Netherlands. The first farm used fresh wood chips as bedding and an aeration system that consisted of perforated tubes between the concrete slabs to simulate the composting process. The compost material on other two farms was organic waste compost, from a composting company. In the first farm, cows were fed on the bedded pack by movable feeding troughs. Therefore, all the manure is excreted on the bedded pack. While on the other two farms, about half of excreted manure is stored as liquid manure in manure pits under the slatted floor and the walking area. In all of the three farms, an area of 12-15 m^2 bedded pack space for each cow was sufficient to achieve a dry hygienic top layer throughout the year. For the first farm, the barn started using a new bedding material in November, and bedded material was added three times per year to resulting in about 5 ton per cow at a thickness of 50 cm. The temperature in the bedded pack ranged reached 55 ºC after three months of operation and the normal range was from 40 to 50 ºC at a depth of 20-40cm. Bedding material was removed from the barn after about a year when the C:N ratio was less than 15:1. The surface was made of concrete. New compost was added every 3 months in the summer and every three weeks in the winter. The temperature of the pack was in the range of 16-18 ºC. Approximately 8.3 tons of compost was used per cow. The pack was mixed once a day with a rotary harrow.

Emission models

Intergovernmental Panel on Climate Change (IPCC)/CARB model

California's GHG emissions from dairy manure storage systems are currently estimated by CARB and generally follow the Tier 2 methods and sources of the U.S. EPA and the Intergovernmental Panel on Climate Change (IPCC). CARB's model can be used to estimate CH_4 emission from manure treatment and storage, and from manure deposited on pastures. IPCC uses methane emission factors on an per animal per year basis (CARB, 2014).

Dong et al. (2006) described the IPCC model in detail as summarized below. The IPCC includes three tiers to estimate CH_4 emissions from livestock manure. The Tier 2 of the IPCC model is a more complex method than Tier 1 for estimating methane emissions from manure management, using emission factors for different management methods. It requires detailed information on animal characteristics, and manure management methods. This information is used to develop emission factors for manure management under different conditions in a country. The emission factors are affected by manure characteristics and the characteristics of manure management systems. Manure characteristics include the quantity and biodegradability of volatile solids (VS) and maximum methane yield (B_o). The quantity and biodegradability of the VS depends on animal breed, stage of life, and feed intake, and digestibility. B_o varies by animal species and diet regimen. The modelled values for B_o do not include the effect of bedding materials (straw, sawdust, chippings, etc.). However, the effect of the bedding materials on methane emissions from liquid manure might not be significant on the farms applying manure separation systems. Yet, the bedding material may be significant in solid manure storage. Manure management system characteristics include the types of systems used to manage manure that in turn reflects the portion of B_o that is achieved. The values of B_o are measured values using the standard methods under specific temperatures. In addition to these parameters, MCFs for each manure management practice are used. The values of MCFs vary with manure management system and temperature. They represent the degree to which B_o is achieved. Although the IPCC have default values for B_o, VS, and MCF, measurements are needed for each climate region to replace the default MCF values. Measurements should consider the following parameters: timing and length of manure storage/application; feed and animal characteristics at the measurement site; characteristics of manure at influent and effluent of manure management systems; the amount of manure left in the storage facility (methanogenic inoculum); and daily and seasonal temperature fluctuation and temperature in manure storage. The implementation of the Tier 2 method requires the collection of the data of the portion of manure managed in each manure management system.

In the CARB model, the van't Hoff-Arrhenius equation is used to determine the effect of temperature on the proportions of VS that are biologically available for conversion to CH_4. The CARB model has been used to estimate GHG emissions from dairy farms before and after application of anaerobic digestion, and to estimate GHG emission reductions after the application of manure solid-liquid separation.

Integrated Farm Systems Model (IFSM)/Dairy Gas Emissions Model (DairyGEM)

Several models and computer software tools for estimating the GHG emissions and carbon footprint of dairy production systems have been developed over the past three decades as led by USDA researchers. IFSM is a computer model that integrates the major biological and physical processes of a crop, livestock, or dairy farm to predict performance, economics, and environmental impacts including various GHG and other gas emissions and a partial LCA of carbon, energy, water, and reactive nitrogen footprints of the feed, meat, or milk produced (Rotz et al., 2015). The quantity and nutrient content of the manure produced is a function of the feed consumed. Nutrient flows through the farm are modeled to predict nutrient accumulation in the soil and loss to the environment. Whole-farm mass balances of nitrogen, phosphorus, potassium and carbon are determined as the sum of all nutrient imports and exports. The DairyGEM model is a subset of the IFSM model that can be used to determine the emissions of GHGs, NH_3, and H_2S from different components of dairy farms. GHG emissions include those from enteric fermentation, the barn floor, manure storage, and feces deposited in pasture. The model uses empirical and process-based models to estimate GHG emissions. A carbon footprint is determined through a partial Life Cycle Analysis (LCA) of the production system, which includes the secondary emissions that occur during the manufacturing or production of resources used on farms. Results of the DairyGEM model were validated using emission data from the US dairy farms. Figure 1 shows a flow chart of different components of the IFSM and DairyGEM modeling tools.

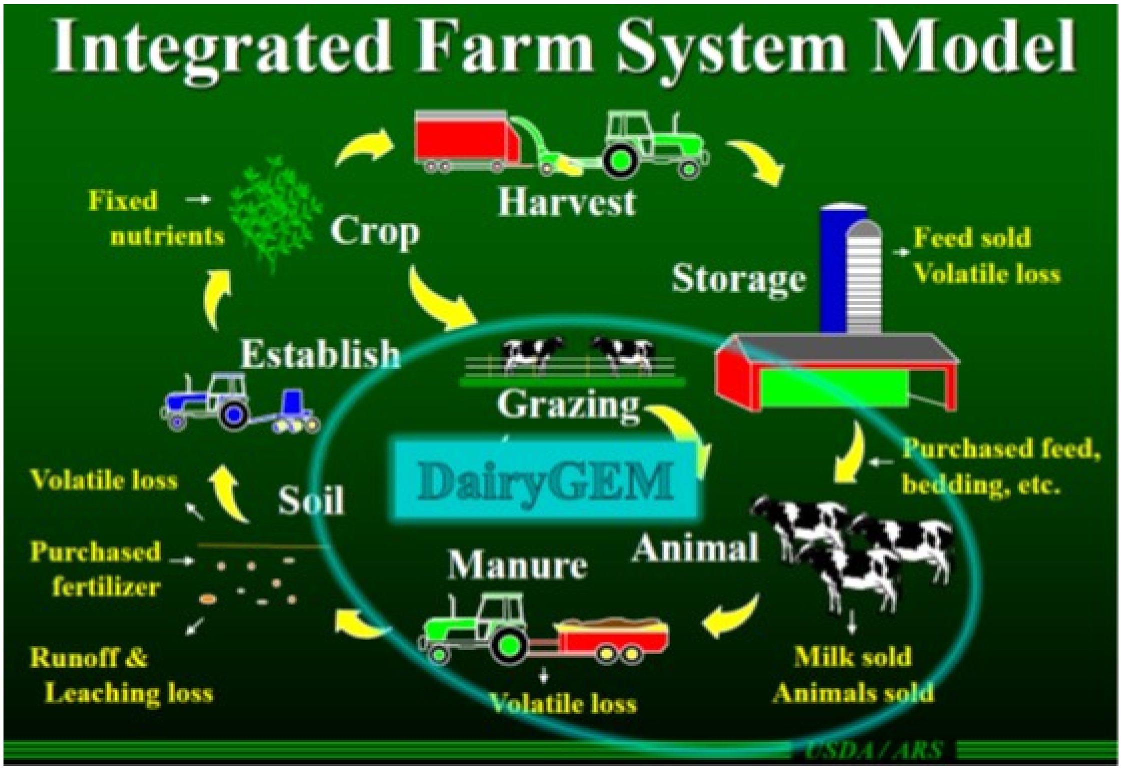

Figure 1. IFSM and DairyGEM modeling tools.

Manure-DNDC Modeling tool

The Denitrification-Decomposition (DNDC) model was originally developed for quantifying C sequestration and trace gas emissions for U.S. agroecosystems (Li et al., 1992; Li et al., 1994; Li, 2000). The DNDC is a process-based model that has several sub- models as shown in Figures 2 and 3. The DNDC sub-models of manure management were later developed as a dedicated model called Manure-DNDC (Figure 2). The Manure-DNDC is a biogeochemical process model to predict GHG and NH_3 emissions from manure management systems (Li et al., 2012). It includes cattle housing (barns or outdoor corrals), manure storage/treatment facilities (lagoon, tank, compost and anaerobic digester) and field application. The effect of Eh, pH, temperature, moisture content, the concentrations of dissolved organic carbon (DOC) and CO_2 are used as drivers to quantify CH_4 production in Manure-DNDC. In addition, the model involves the oxidation of CH_4 when it is diffused into the aerobic microsites. The framework of Manure-DNDC was developed based on the manure life cycle within the farm. Results of the Manure-DNDC model were validated using emissions data from several dairies in the USA.

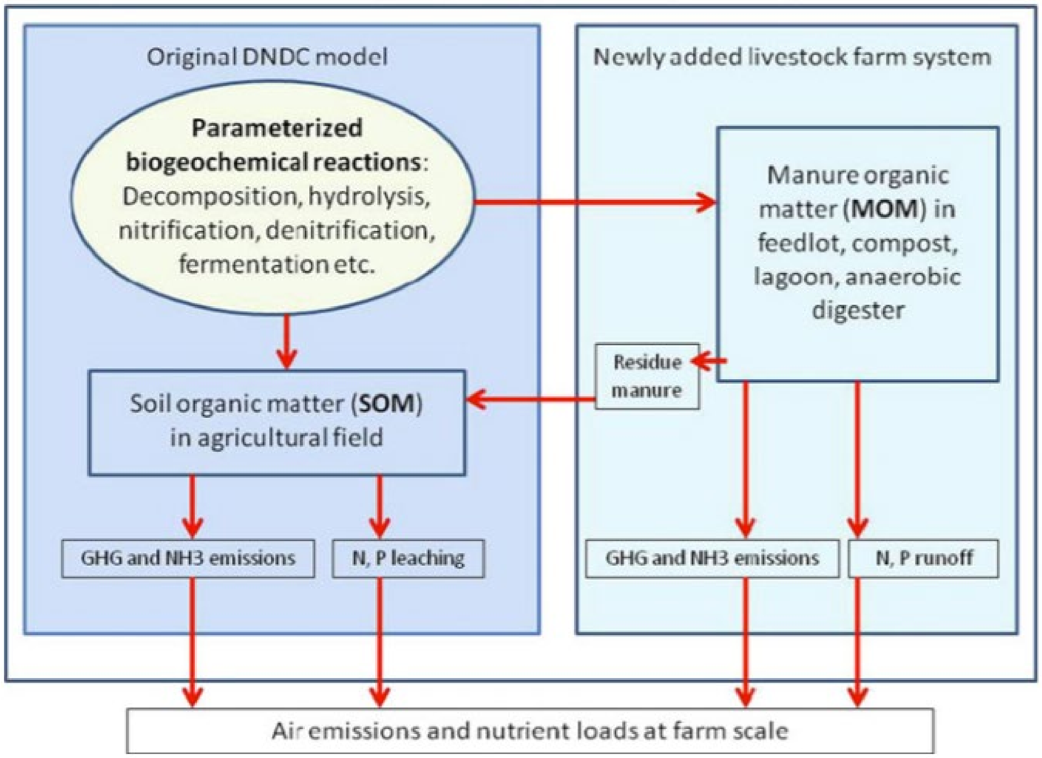

Figure 2. DNDC Model (Li et al., 2012).

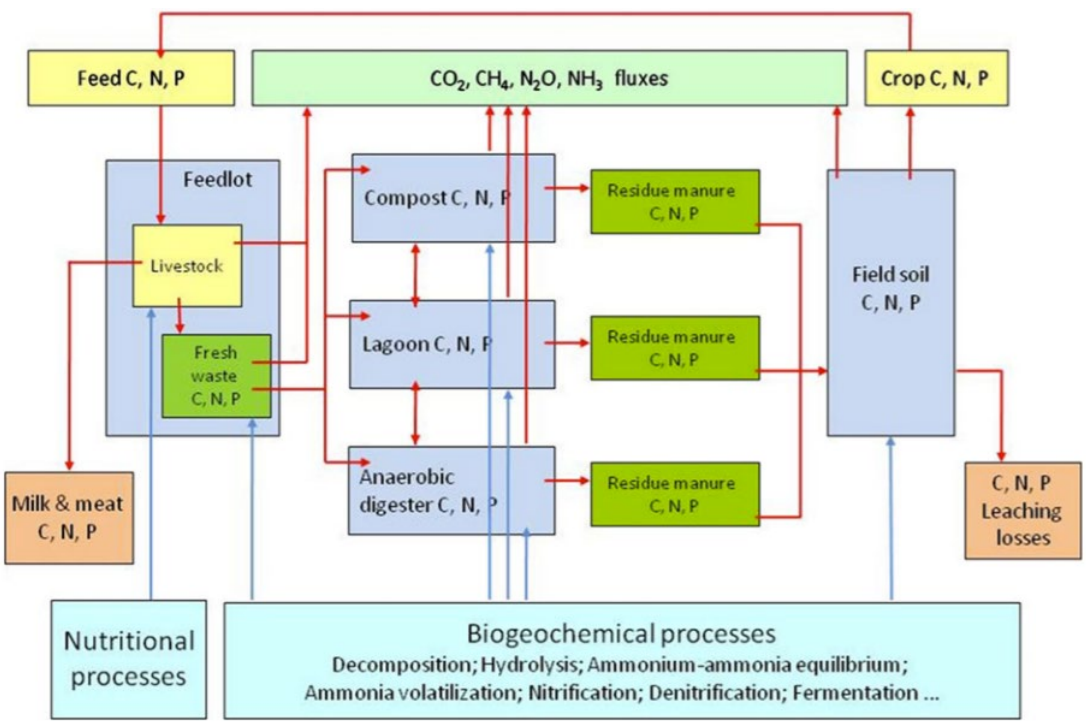

Figure 3. Manure-DNDC Model (Li et al., 2012).

Compared with the IPCC/CARB model, DairyGem and Manure-DNDC models are more mechanistic models that use empirical and process-based sub-models to estimate the emissions of GHG. These sub-models need many input parameters that are not frequently provided by dairies. For example, DairyGem requires detailed rations (e.g., amounts of silage, hay, high moisture grains, dry grains, and feed supplements) that are not usually provided by dairy farmers. The IPCC/CARB model needs fewer number of input parameters such as ambient temperature, number of animals, amount of bedding, and amount of manure delivered to the lagoon. The DairyGEM and Manure-DNDC models do not have the capability to predict emissions from the settling basins and lagoons when they are arranged in series. They do not also have the capability to predict emissions after employing all manure management practices. Both models need a substantial code modification to include both settling basins and lagoons as two sequential treatment systems. They also need to be modified to include different AMMP practices on dairies.

Objective 1: Conduct emissions measurements for selected dairies that adopt AMMP practices.

Task 1a: Selection of AMMP and study sites, and development and recommendation of measurement plans.

Selection of the studied sites

Greenhous gas emissions were measured on two dairies in the present project and four others in the accompanied project funded by CARB. The study names, locations and the type of AMMP technologies employed on each dairy are shown in Table 6.

Table 6. The names, locations, and types of AMMP technologies on each studied dairy.

Dairy	Location	AMMP technologies
Alpha	Lodi	Mechanical separator
Bravo	Tulare	Scraping and screw press
Charlie	Visalia	Mechanical separator
Delta	Turlock	Partial scrape with windrow drying
Echo	Gustine	Weeping wall
Foxtrot	Ballico	Mechanical separator and increased pasture time

Description of manure management on the studied dairies

Alpha dairy

Alpha dairy was located in Lodi, California. The dairy had 1,580 milking cows, 290 dry cows, 300 heifers, and 250 calves. The cows were housed in freestall barns. The average milk yield was 94 lbs./cow/day. Milking center wastewater and lagoon water was used to flush the barns six times a day; during the summer, fresh water was used for flushing, while recycled lagoon water was used the remainder of the year. Barn effluent flowed to a sand settling lane where sand separated from manure by gravity. Sand-lane effluent flowed to a processing pit in which manure was mixed and then pumped to a mechanical separator, which is the AMMP technology. On the occasions that the mechanical separator is not used, manure from the sand lane flowed to two settling basins that were estimated to be 69 ft (21 m) wide and 584 ft (178 m) long each. The dimensions of the settling basins and lagoons for all the studied dairies were estimated using Google Maps. The settling basin had an estimated storage capacity of six months. The settling basins were used alternately – a settling basin used until filled then sand lane effluent flowed to the second basin. Settling basin effluent flowed by gravity to a 125 x 689 ft (38 m x 210 m) lagoon. The liquid fraction from the mechanical separator was delivered to the lagoon. Lagoon water was usually stored until it was used for irrigation or barn flushing. The solids removed from the settling basin and from the mechanical separator were sun dried and used as stall bedding and soil amendment. Figure 4 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3. No information was available on the date of the last time the lagoon was cleaned.

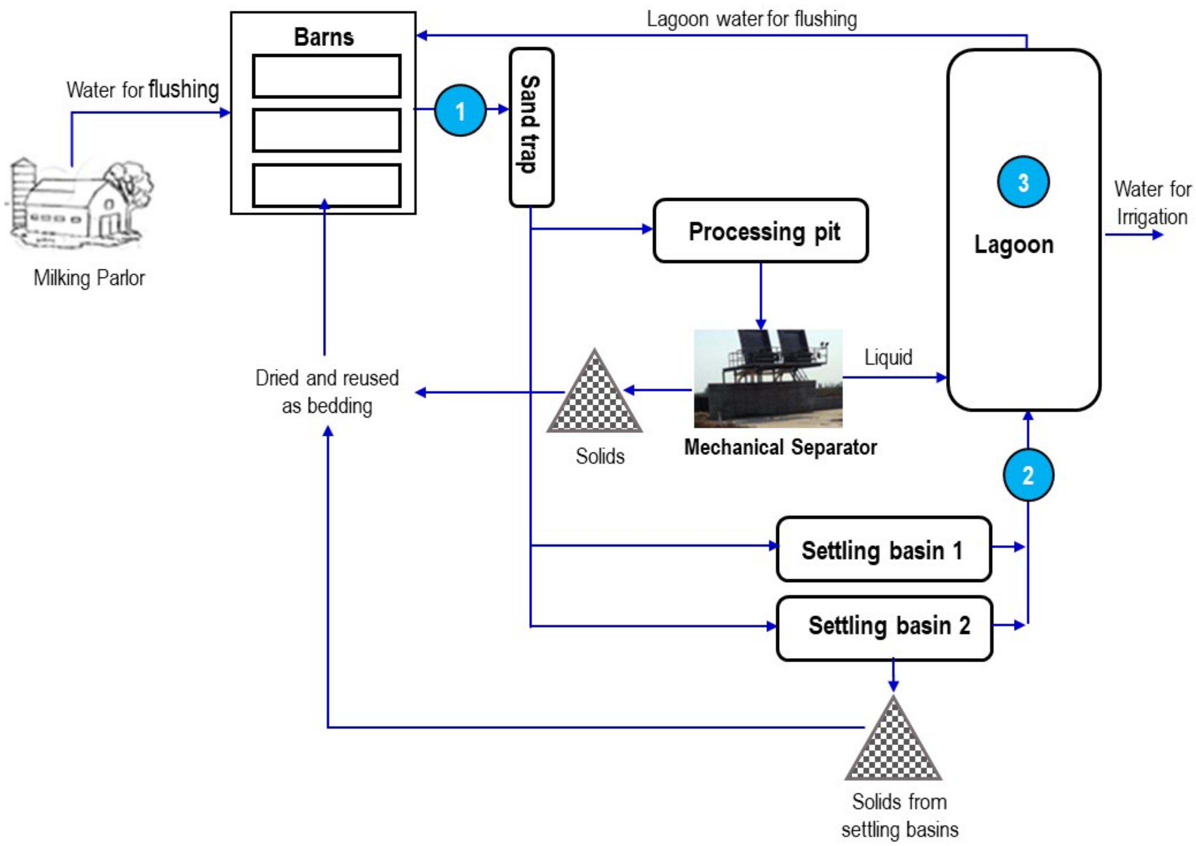

Figure 4. Single-line flow diagram for the manure management system on Alpha dairy.

Bravo dairy

Bravo dairy was located in Tulare, California. The dairy had 850 milking cows and 40 dry cows. The cows were housed in freestall barns. The AMMP technology included a vacuum truck to remove manure from the barn to a screw press for dewatering. The liquid separated from the screw press flowed to two settling basins. The first settling basin had a width and length of 49x150 ft (15 and 46 m), respectively. The second settling basin had a width and length of 49 and 135 ft (15 and 41 m), respectively. On the occasions the AMMP technology was not used, the barns were flushed using milk center wastewater and fresh water three times a day. The flushed manure was flowed to the settling basins. The settling basins were used alternately: a settling basin used until filled then effluent was allowed to flow to the second one. Each settling basin was used for six months. Settling basin effluent flowed to the lagoon that had an estimated width and length of 55 and 185 m, respectively. Lagoon water was stored until used to irrigate available cropland cultivated with winter wheat, corn, and sorghum. The solids from settling basins and the separators were sun dried and used as bedding and soil amendment. No information regarding the frequency of lagoon solids cleanout was available. The solids removed from the settling basin were sun dried and used for stall bedding. Figure 5 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

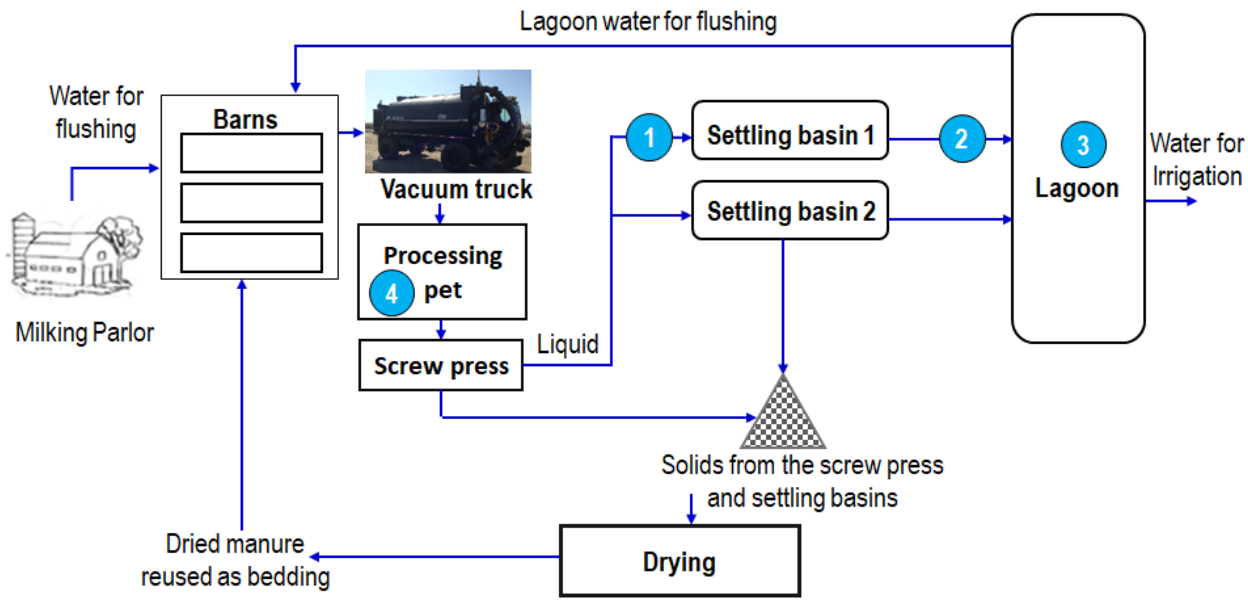

Figure 5. Single-line flow diagram for the manure management system on Bravo dairy.

Charlie dairy

Charlie dairy was located in Visalia, California. The dairy had 1,700 milking cows, 200 dry cows, and 700 heifers. The average milk yield was 80 lbs/cow/day (36.4 kg/cow/day) with a fat content 3.4%, respectively. The cows were housed in compost-bedded pack barns that were installed as AMMP technology. Dried manure and almond shells were used as bedding. Approximately 30% of manure is pumped to the lagoon and 70% was pumped to corrals. Manure feed lanes were flushed using milking center wastewater twice daily, and effluent was pumped to a lagoon that had an estimated width and length of 150 ft and 900 ft (46 m and 275 m), respectively. Lagoon water was stored (100-150 days) until used for cropland irrigation. The dairy had 600 acres that were cultivated with wheat and corn. Prior to using lagoon water for irrigation, it was pumped over a single-stage screen separator to remove the solids. The solids removed were sun dried and used as bedding material. No information was available on the frequency of lagoon-settled solids removal. However, the farmer reported that they excavate around lagoon corners every couple of years. Manure solids are typically spread to fields between crops. Corrals are also cleaned at the same time to move manure once. Figure 6 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1 and 2.

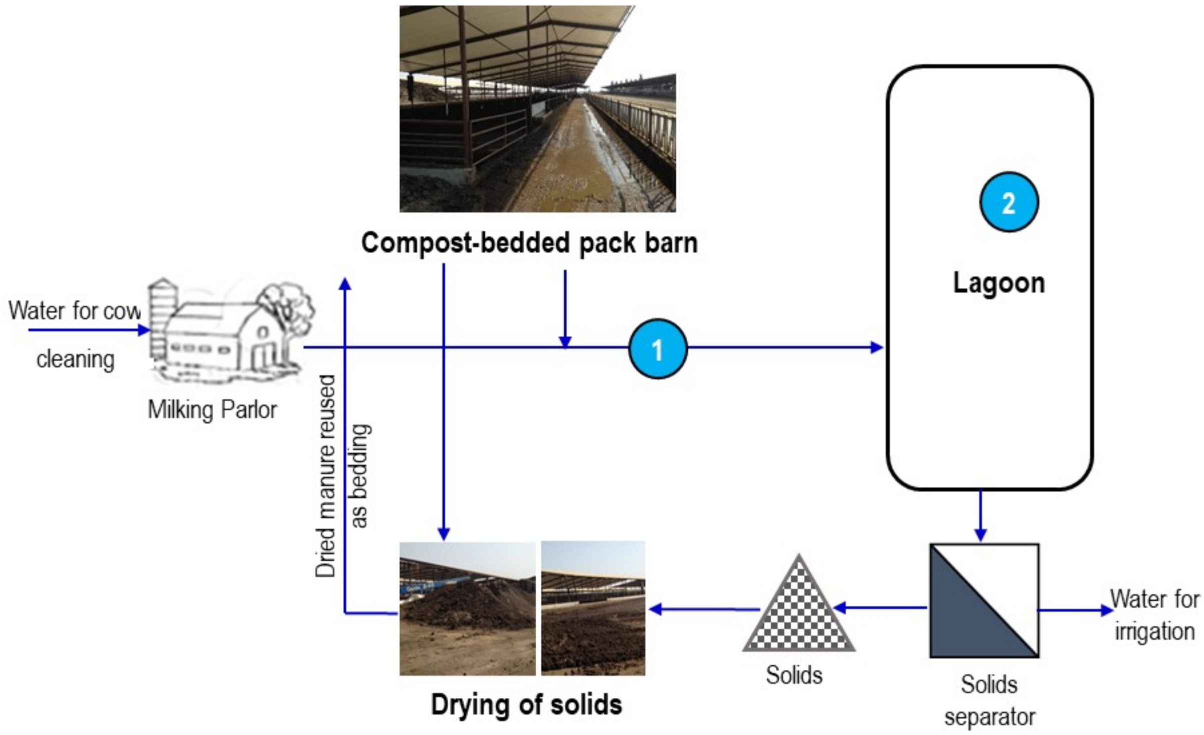

Figure 6. Single-line flow diagram for the manure management system on Charlie dairy.

Delta dairy

Delta dairy was located in Turlock, California. The Dairy had 2,563 milking cows, 426 dry cows, 150 heifers, and 400 calves. The cows were housed in freestall barns flushed twice a day. Each freestall has a summer corral. In addition, the dairy has 4 bedded pack barns for cows with special needs. Milk production of each cow was 105 lbs per day with 3.65% fat and 2.96% protein. Late lactation and low production cows are transported to another dairy that is owned by the same family. In the winter, barns were flushed using lagoon water and milking center wastewater, while in the summer (May to late September/early October), milking center wastewater and lagoon water mixed with fresh water was used for manure flushing. Barn effluent was pumped to two settling basins for six days a week. While, on the seventh day, a vacuum truck was employed to clean manure lanes. The first settling basin had a width and length of 1,110 x 145ft (338 x 44 m) and the second was 1,110 x 150 ft (338 x 46 m), respectively. The settling basins were used alternately: a settling basin used until filled then barn effluent was directed to the second one. Each settling basin had a storage capacity of six months. Setting basins are cleaned once per year. Settling basin effluent flowed to the lagoon that had an estimated width and length of 1,015 x 140 ft (309 x 43 m), respectively. Lagoon water was stored until used for cropland irrigation.

The AMMP technology is vacuum scraping. The AMMP operation was designed to use the vacuum truck for 120 days per year and solar drying on concrete pad. However, during the period of emissions monitoring, the AMMP technology was employed only on Thursdays. The solids collected from the settling basins were also dried and mixed with the vacuumed manure.

Setting basins were cleaned once per year. Manure is dried in a few steps: first the vacuum manure is spread over the concrete pad for about one week, then collected in small piles for a few more days, then later stacked into bigger piles. Manure solids are turned with wheel loader to help drying. The dried manure is not used as bedding due to the high sand and rocks contents. It is transported to farmland that does not receive lagoon water from the dairy. Figure 7 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, 3, and 4.

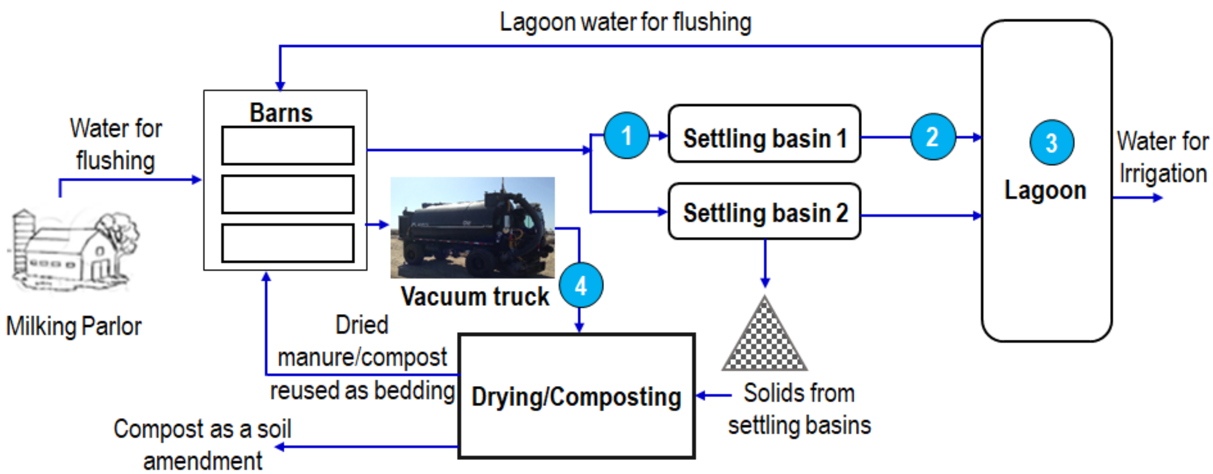

Figure 7. Single-line flow diagram for the manure management system on Delta dairy.

Echo dairy

Echo dairy was located in Gustine, California. The dairy had 1,450 milking cows, 200 dry cows, 1,100 heifers, and 300 calves. The cows were housed in freestall barns. The average milk yield was 70 lbs/cow/day with fat content of 4.6% and protein content of 3.65%. Milking center wastewater and lagoon water were used to flush the barns when there wasn't any irrigation occurring. The AMMP was a one cell weeping wall. This in fact is a pitfall of the design of this weeping wall. When this single cell was full, the farmer used the settling basin for separating solids prior to the lagoon until the manure dried in and removed from the weeping wall. Essentially, the farmer was using the conventional manure management system that he was employing prior installing the AMMP technology. Barns were flushed four times per day; barn effluent was pumped to a sand lane to remove sand. Sand lane effluent was pumped to the weeping wall for 4 months (i.e., weeping wall capacity is to hold solids from flushed manure for four months). The weeping wall drying and emptying time was 1-2 months. During the drying and emptying time of the weeping wall, manure from the sand lane is pumped to a settling basin that had a width and length of 55 and 1,186 ft (16.8 and 361.5 m), respectively.

Manure solids were excavated out of the settling basin two times per year and then windrowed to produce compost that was used as bedding and soil amendment. Settling basin liquid effluent and water seepage from the weeping wall flowed to a lagoon that had a width and length of 400 and 1,186 ft (121.9 and 361.5 m), respectively. Lagoon water was stored and agitated until used for irrigation. During the irrigation season, fresh water was pumped to the lagoon, and the mixture was used for irrigation. The dairy had 307 acres that were cultivated with winter forage, Sudan grass, and corn. Solids removed from the settling basin and the weeping wall were moved to a composting production area where a composter turner was used weekly to turn solids to produce compost. The produced compost was used as stall bedding. Compost was also exported outside the farm as a soil amendment. Figure 8 shows a single-line flow diagram for the manure management system on Echo dairy. Samples were collected at points 1, 2, and 3.

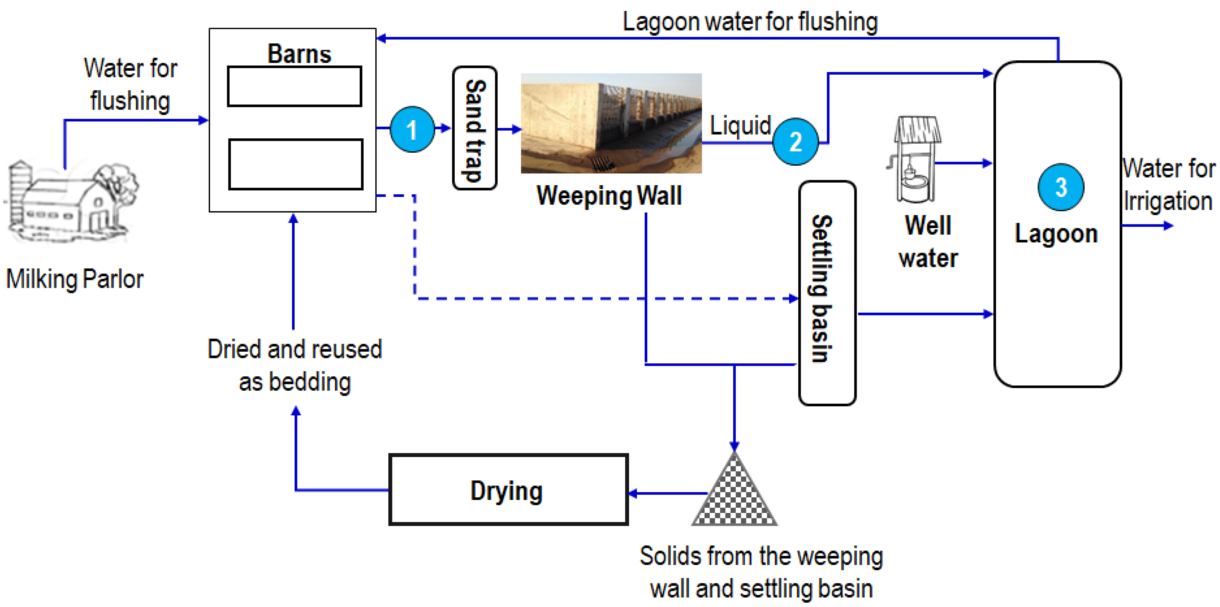

Figure 8. Single-line flow diagram for the manure management system on Echo dairy.

Foxtrot dairy

Foxtrot dairy was located in Ballico, California. The dairy had 650 milking cows, 101 dry cows, 385 heifers, and 250 calves. The cows were housed in freestall barns. The average milk yield was 70 lbs/cow/day. The AMMP technology included increased pasture time and a mechanical separator. In summer, the cows were on pasture for half of the time. Milking center wastewater and lagoon water were used to flush the barns two times a day in the summer and three times a day in the winter. Barn effluent was pumped to settling basin that had a width and length of 49 x 646 ft (15 and 197 m), respectively. Solids were removed from the settling basins every four months and were composted for bedding and soil amendment. After the settling basin, manure was flowed to the lagoon that had an estimated width and length of 131 and 436 ft (40 and 133 m), respectively. Part of the settling basin effluent was pumped through the mechanical screen separator. The separator was operated for 7.5 and 5 hours per day, in the winter and summer, respectively. Screened manure flowed to the lagoon. The separator lagoon water was stored until used to irrigate 200 acres. Most of the available land is used as pasture where cows are pastured for 8 months. During the irrigation season, fresh water was pumped to the lagoon to help meet the pasture's irrigation water demand. The solids removed from the settling basin were composted with the solid separated from the mechanical separator. The produced compost is used as a soil amendment in the grazing land and used as bedding material. Excess compost, beyond the need of Foxtrot farm, was sold to other farmers. Figure 9 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

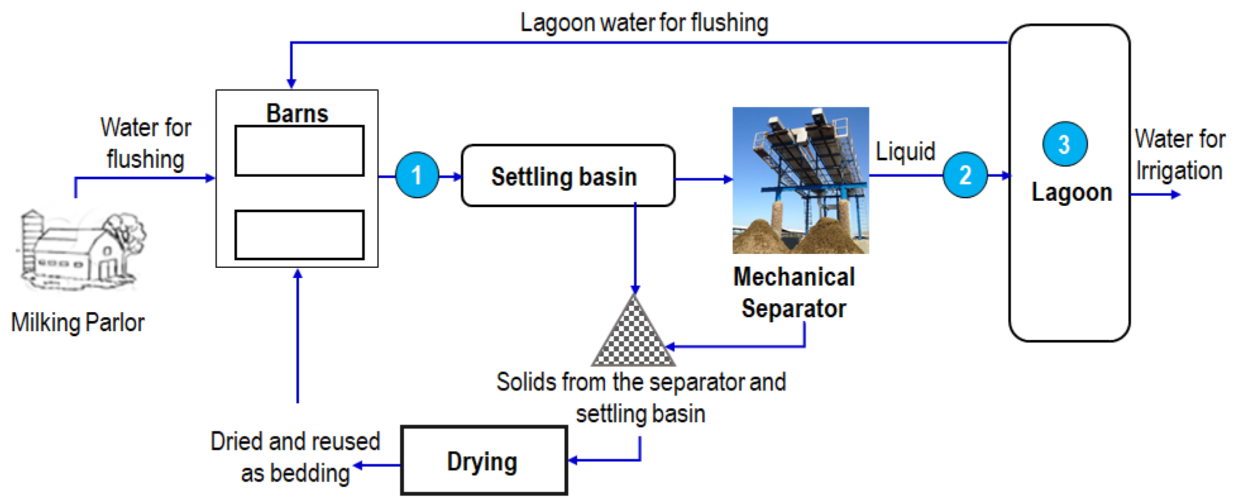

Figure 9. Single-line flow diagram for the manure management system on Foxtrot dairy.

Task 1b: Measurement of post-AMMP emissions from selected dairies

Measurement Methods

Mobile Air Quality Laboratory (MAQ Lab) and equipment

Measurements and sampling plans were developed. The concentrations of CH_4, N_2O, NH_3, and H_2S were measured using state-of-art devices such as a 55i methane analyzer, an INNOVA 1412 analyzer, and a TEI 17i NH_3 analyzer. These devices were housed in the UC Davis Mobile Air Quality Laboratory (MAQ Lab). In addition to these emission analyzers, the MAQ Lab had other supporting equipment and software that are required to measure and record the emissions on different dairies. The devices on the MAQ Lab were remotely monitored and controlled. The MAQ Lab and other equipment were prepared and moved to the selected dairies for use. The on-farm measurements of the emissions from the lagoons and settling basins were carried out according to the schedule shown in Table 7. After moving the MAQ Lab to the intended site, the set-up of the measurements was carried out including connecting the required gas cylinder for operating different measurement devices, calibration of the measurement devices, and preparing and floating the wind tunnel. The analyzers and other equipment were powered with 120/240 volts alternative current. An electricity generator was used to provide the required electricity for the research analyzers and equipment. Figure 10A shows the MAQ Lab and electricity generator. Figure 10B shows different analyzers and equipment onboard the MAQ Lab. Mitloehner et al. (2018, unpublished data) conducted on farm measurements of the emissions of GHG and ammonia from dairy lagoons and settling basins on six dairies pre-AMMP practices. A floated wind tunnel was used to continuously collect air samples from the lagoon surfaces. The collected air samples were analyzed using the state-of-the-art gas analyzers that are housed in the MAQ Lab. On all dairies but Charlie, the MAQ Lab was parked on a location that is close to the lagoon and settling basin. At Charlie dairy, the MAQ Lab was parked close to the lagoon as there was not a settling basin.

Figure 10. (A) The Mobile Air Quality Laboratory (MAQ Lab) and engine-generator set; (B) different analyzers and supporting equipment onboard of the MAQ Lab.

Wind tunnel measurements

A wind tunnel equipped with floatation was used to collect air samples from the surface of lagoons and settling basins. The float raft was made of two 4-inch diameter PVC pipes. The main parts and dimensions of the wind tunnel are shown in Figure 11.

The wind tunnel was made of stainless steel. The bottom portion covered 0.32 m^2 of emitting surface area of lagoon, settling basin, or manure solids. The wind tunnel had a small chamber for holding filter media. The tunnel had three sampling ports to sample the inlet air, air post the filter and the outlet air. However, for this study, no filter media were used and only the concentration of select gases were measured in the inlet and outlet air.

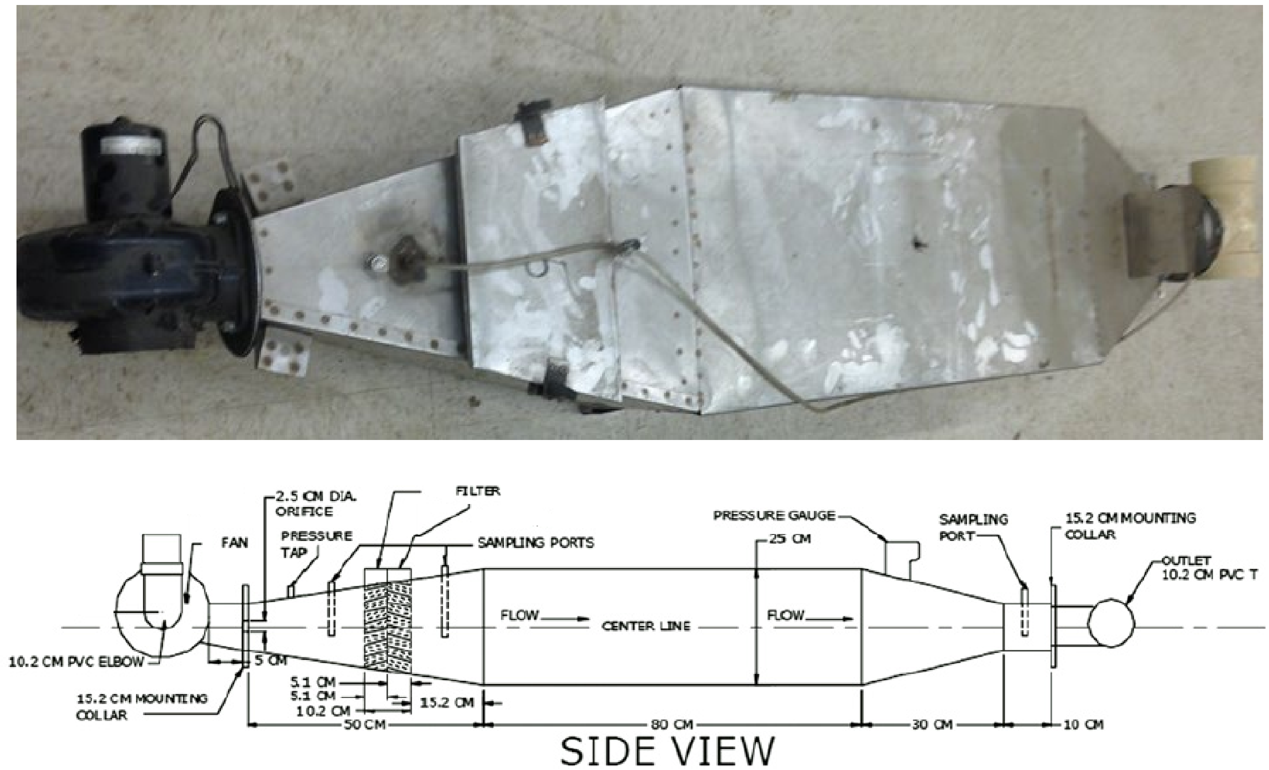

Figure 11. Main parts and dimensions of the wind tunnel (adapted from Kumar et al., 2011).

The wind tunnel inlet was connected to a blower powered with a DC motor (12 volts /36 watt). The blower was used to blow a certain flow rate of air over sampling surfaces. The blower inlet was connected to a corrugated pipe with a length of 100 ft (30.4 m) and diameter of 4 inches (10 cm) to draw air from above the banks of the lagoons and the settling basins. The wind tunnel outlet had a T-shaped baffle that avoided back pressure caused by ambient wind during sampling. Air blown through the tunnel was mixed, and transported the surface emissions towards the outlet where air samples were withdrawn and analyzed.

To move the wind tunnel over the lagoons, the research team used long ropes to pull and guide the wind tunnel to the intended location. The emissions were measured in at least two different locations on each lagoon. The wind tunnel was kept in its location on the lagoon surface for one day before moving to another spot on the next day. For the emissions measurements from the settling basins, the wind tunnel was set up on one location. If needed, when floated solids accumulated on the settling basin surfaces, the dairy mangers helped the research team to remove the solids so that the wind tunnel edges could be submersed under the liquid surface.

The air flow rate inside the wind tunnel was calculated after measuring the air velocity in the 4-inch (0.1016 m) PVC tube that was connected to the corrugated pipe. During the measurements, the wind tunnel was located in the lagoon or the settling basin at distance of about 200 ft (60.96 m) from the MAQ Lab, and at approximately 75 ft (22.86 m) from the lagoon banks.

Figures 12-19 show the wind tunnel during the emission measurements of lagoons and settling basins on the dairies that were monitored in this study.

Calculation of emission flux

The emission flux rate was calculated using the equation:

$E = Q \times (C_{out} - C_{in}) / A$

Where:

E = Gas emission rate from the wind tunnel, $g/m^2/hr$
Q = Air flow rate inside the wind tunnel, m^3 /hr

Cout = Mass concentration in the wind tunnel exhaust air, g m^{-3}
C_{in} = Mass concentration in the wind tunnel inlet air, g/m^3, and
A = Area of the emission surface covered by the wind tunnel, m^2

The air rate inside the wind tunnel was calculated after measuring the air velocity in the inlet pipe of the wind tunnel. The diameter of the inlet pipe was 4 inches. Air velocity was measured, using a hot wire anemometer (WYER® anemometer, Model No. 471-B), at least twice at each location of the wind tunnel (i.e., directly after moving the wind tunnel to a location and before moving it to the following location). Air velocity was measured in the inlet pipe at two different location across the pipe diameter at different depths. The average air velocity from different measurements was used in calculating the emission rates from the wind tunnel. The average air speed inside the inlet pipe was 3.07±0.20 m/s. Occasionally, the air flow rate was measured from the outlet of the wind tunnel to assure that there were no air leaks.

The emissions were measured on the studied dairies during 2019 and 2020. Table 7 shows monitored sources and schedule of emissions measurements on the studied dairies.

Table 7. Monitored sources and schedule of emissions measurements on the studied dairies.

Site ID	Monitored sources	Schedule and work status
Delta	Lagoon, settling basin, and vacuumed manure	• The MAQ Lab and other equipment was moved to Delta dairy on 9/14/2019 • The measurements system was set up on 9/14/2019 • The emissions from the lagoon were measured from 9/14/2019 to 9/17/2019 • The emissions from the settling basin were measured on 9/18/2019 • The emissions from vacuumed manure were measured on 9/19/2019

		• The MAQ Lab and other equipment were demobilized on 9/20/2019
Foxtrot	Lagoon, settling basin, and manure solids	• The MAQ Lab and other equipment moved to Foxtrot dairy on 9/21/2019 • The measurements system was set up on 9/21/2019 • The emissions from the lagoon were measured from 9/21/2019 to 9/24/2019 • The emissions from the settling basin were measured on 9/25/2019 • The emissions from manure solids were measured on 9/26/2019 • The MAQ Lab and other equipment were demobilized on 9/27/2019
Echo	Lagoon, settling basin, and weeping wall	• The MAQ Lab and other equipment moved to Echo dairy on 9/22/2019 • The measurements system was set up on 9/22/2019 • Due to the uncompleted emptying the weeping wall, the emissions measurements were postponed till 10/26/2016 • The filling of the weeping wall started on 10/3/2019 • The emissions from the lagoon were measured from 10/26/2019 to 10/29/2019 • The emissions from the settling basin were measured on 10/30/2019 • The emissions from weeping wall were measured on 10/31/2019-11/1/2019 • The MAQ Lab and other equipment were demobilized on 11/2/2019
Bravo	Lagoon, settling basin, and manure solids	• The MAQ Lab and other equipment moved to the Bravo dairy on 11/16/2019 • The measurements system was set up on 11/16/2019. The monitoring of emissions from the lagoon was started on 11/16/2019. However, due to some technical problem, the monitoring was measured again from 11/20/2019 to 11/24/2019 • Due to the maintenance in the screw press, the monitoring system was stopped until the separator was fixed • The emissions from manure solids were measured on 12/15/2019 • The emissions from the settling basin were measured on 12/16/2019 • The MAQ Lab and other equipment were demobilized, and all equipment were returned to UC Davis until Charlie dairy was ready for monitoring

Charlie	Lagoon and solids	• The MAQ Lab and other equipment were moved to the Charlie dairy on 9/19/2019 • The measurements system was set up on 9/19/2020 and the measurements started on the same day. Due to a technical issue, the emissions from the lagoon started again on 9/21/2020 until 9/24/2020 • The emissions from manure solids were measured from 9/24/2020 to 9/27/2020 • The MAQ Lab and other equipment were demobilized on 9/27/2020
Alpha	Settling basin and lagoon	• The MAQ Lab and other equipment were moved to the Alpha dairy on 9/27/2020 • The measurements system was set up on 9/29/2020 • The emissions from the lagoon were measured from 9/29/2020 to 10/2/2020 • The emissions from the settling basin were measured on 10/3/2020 • The emissions from the solids were measured on 10/4/2020. • The MAQ Lab and other equipment were then demobilized and returned to UC Davis on 10/5/2020

Monitored emission sources in different dairies

The measured emissions from different sources at the Alpha dairy

The emissions from lagoon, settling basin, and manure solids separated by the mechanical separator were measured. The wind tunnel was floated over the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for an entire day at each location. Figure 12A shows the wind tunnel floating over the surface of the lagoon. After measuring the emissions from the lagoon surface, the wind tunnel was moved to the settling basin. To float the wind tunnel on the settling basin, the dairyman helped to remove the scum layer on its surface using an excavator (Figure 12B and C). Figure 12D shows the wind tunnel floating over the surface of the settling basin. The emissions from manure solids were also measured for one day. Fresh solids were collected from the mechanical separator as shown in Figure 13A. To measure the emissions of different gases from manure solids, an amount of 10.1 kg of the solids were spread, over a plastic sheet, on an area of 25×85 cm (Figure 13B) prior putting the wind tunnel over the solids (Figure 13C). The wind tunnel sides were sealed with manure solids to prevent the leakage of air blown inside the wind tunnel. The thickness of manure solids was approximately 5 cm. The emissions from solids were measured for one day.

Figure 12. (A) The wind tunnel floating on the lagoon; (B and C) removing the scum layer from the surface of the settling basin; and (D) floating the wind tunnel on the settling basin at the Alpha dairy.

Figure 13. (A) Collecting manure solids after the screen separator; (B) manure solids over a plastic sheet before placing the wind tunnel; and (C) the wind tunnel placed over manure solids at the Alpha dairy.

The measured emissions from different sources at the Bravo dairy

The emissions from the lagoon, settling basin, and manure solids separated by the screw press separator were measured. The wind tunnel was floated over the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for one day at each location. Figure 14A shows the wind tunnel floating over the surface of the lagoon. After measuring the emissions from the lagoon surface, the wind tunnel was moved to the settling basin. To float the wind tunnel on the settling basin, the scum layer was removed with the help of the dairy farmer, using a steel bar attached to a front loader (Figure 14B). Figure 14C shows the wind tunnel floating over the surface of the settling basin. The emissions from manure solids were also measured for one day. Fresh solids were collected after the screw press separator as shown in Figure 15A. To measure the emissions from manure solids, an amount of 10.5 kg of the solids were spread, over a plastic sheet, on an area of 25×85 cm (Figure 15B) prior putting the wind tunnel over the solids (Figure 15C). The wind tunnel sides were sealed with manure solids to prevent the leakage of air blown inside the wind tunnel. The thickness of manure solids was approximately 5 cm. The emissions from solids were measured for entire day.

A B C

Figure 14. (A) The wind tunnel floating on the lagoon; (B) removing the scum layer from the surface of the settling basin; and (C) floating the wind tunnel on the settling basin at the Bravo dairy.

A B C

Figure 15. (A) Collecting manure solids after the screen separator; (B) manure solids over a plastic sheet before placing the wind tunnel; and (C) the wind tunnel placed over manure solids at the Bravo dairy.

The measured emissions from different sources at the Charlie dairy

The emissions from the lagoon and manure collected from the compost-bedded pack barn were measured. The manure in the compost-bedded pack barn included feces, urine, and bedding material. The wind tunnel was floated over the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for one day at each location. Figure 16A shows the wind tunnel floating over the surface of the lagoon. After measuring the emissions from the lagoon surface, the wind tunnel was moved to measure the emissions from manure. Two batches of manure were collected by the farmer and delivered by a front loader to the location of MAQ Lab. The exact amount of manure was not measured. Manure batches were leveled, using a shovel, to maintain a thickness of approximately 30 cm that was the measured thickness of manure in the compost-bedded pack barn during the measurements period. The wind tunnel sides were sealed with manure solids to prevent the leakage of air blown inside the wind tunnel. Figure 16B shows the wind tunnel during the measurement of emissions from manure. Manure thickness under the wind tunnel was 28-30 cm that matched the thickness of manure on the compos-bedded barn. Two batches of manure solids were monitored for gas emissions each for one day.

A B

Figure 16. (A) The wind tunnel on the lagoon; and (B) the wind tunnel over manure collected from the compost-bedded pack barn at Charlie dairy.

The measured emissions from different sources at the Delta dairy

The emissions from the lagoon, settling basin, and vacuumed manure were measured. The wind tunnel was floated over the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for one day at each location. Figure 17A and B show the wind tunnel floating over the surface of the lagoon, and the settling basin. The scum layer on the settling basin surface was thin and easy to be pushed by the wind tunnel. After measuring the emissions from the lagoon surface, the wind tunnel was moved to the settling basin where the emissions were measured for one day. Then an amount of vacuumed manure was collected from the vacuum truck (Figure 18 A) and used for the emission measurements.

To measure the emissions of different gases from the vacuumed manure, an amount of 16.1 kg of the vacuumed manure was spread, over a plastic sheet, on an area of 25×85 cm (Figure 18 B) prior putting the wind tunnel over the manure (Figure 18 C). The wind tunnel sides were sealed with vacuumed manure solids to prevent the leakage of air blown inside the wind tunnel. The thickness of manure solids was approximately 5 cm. The emissions from the vacuumed manure were measured for one day.

A B

Figure 17. (A) The wind tunnel on the lagoon; and (B) the wind tunnel on the settling basin at the Delta dairy.

Figure 18. (A) Collecting vacuumed manure; (B) Manure in containers; (C) vacuumed manure over a plastic sheet before placing the wind tunnel; and (D) the wind tunnel over vacuumed manure at the Delta dairy.

The measured emissions from different sources at the Echo dairy

The emissions from lagoon, settling basin, and weeping wall were measured. The wind tunnel was floated over the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for one day at each location. Figure 19A shows the wind tunnel floating over the surface of the lagoon. After measuring the emissions from the lagoon surface, the wind tunnel was moved to the settling basin where the emissions were measured for one day. A thin layer of scum was found on the settling basin surface. It was removed manually using a wood board (Figure 19B). Figure 19C shows the wind tunnel floating over the surface of the lagoon. The emissions from the weeping wall were measured for two days. To place the wind tunnel over the manure accumulated in the weeping wall, two screens were removed from the middle of the weeping wall side that is close to the lagoon (Figure 20A). Then the surface of manure was leveled off using a shovel (Figure 20B). Finally, the wind tunnel was placed on the manure surface as shown in Figure 20C. The emissions from the weeping wall were measured for two days.

Figure 19. (A) The wind tunnel on the lagoon; (B) scum layer was manually removed from the settling basin; and (c) the wind tunnel on the settling basin at the Echo dairy.

A B C

Figure 20. (A) two screens were removed from the weeping wall side; (B) leveling manure surface inside the weeping wall; and (C) the wind tunnel on the manure surface inside the weeping wall at the Echo dairy.

The measured emissions from different sources at the Foxtrot dairy

The emissions from lagoon, settling basin, and manure solids separated by the mechanical separator were measured using similar procedures of those employed for the Alpha dairy. The wind tunnel was floated over the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for one day at each location. Figure 21A shows the wind tunnel floating over the surface of the lagoon. After measuring the emissions from the lagoon surface, the wind tunnel was moved to the settling basin. To float the wind tunnel on the settling basin, the scum layer was removed with the help of the dairy farmer, using a steel bar attached to a front loader (Figure 21B). Figure 21C shows the wind tunnel floating over the surface of the settling basin. The emissions from manure solids were also measured for one day. Fresh solids were collected from the mechanical separator as shown in Figure 22A.

To measure the emissions from manure solids, 15.2 kg of the solids were spread over a plastic sheet on an area of 25×85 cm (Figure 22B) prior putting the wind tunnel over the solids (Figure 22C). The wind tunnel sides were sealed with manure solids to prevent the leakage of air blown inside the wind tunnel. The thickness of manure solids was approximately 5 cm. The emissions from solids were measured for one day. It should be mentioned that different amounts of manure solids were used in different farms for monitoring the emissions due to the differences in moisture content and bulk density across studied dairies.

A B C

Figure 21. (A) The wind tunnel floating on the lagoon; (B) removing the scum layer from the surface of the settling basin; and (C) floating the wind tunnel on the settling basin at the Foxtrot dairy.

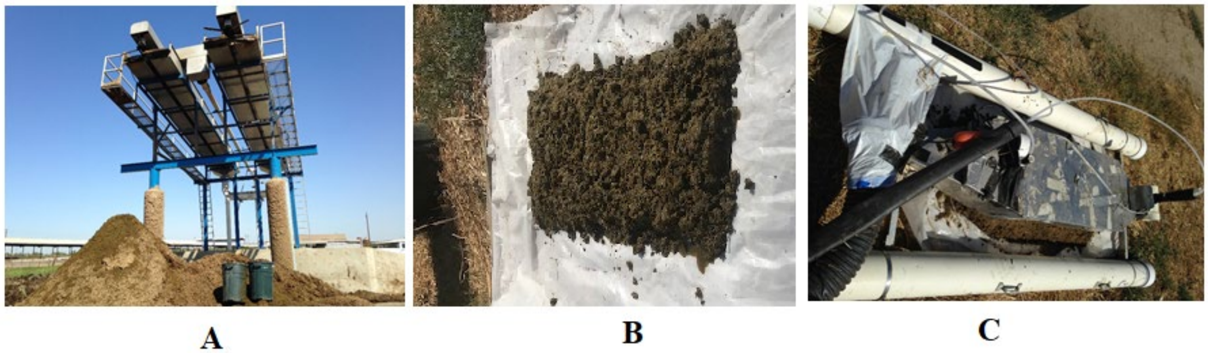

Figure 22. (A) Collecting manure solids after the screen separator; (B) manure solids over a plastic sheet before placing the wind tunnel; and (C) the wind tunnel placed over manure solids at the Foxtrot dairy.

Manure sampling

During the emissions measurements at the Charlie and Foxtrot dairy, flushed manure samples were collected for three days from the manure flushed from feed lanes. For each day, the flushed manure was sampled every two minutes over an entire flushing event of manure. Samples were also collected from the lagoon surface (10 -15 inches depth (25.4-38 cm)) for three days. Samples were also collected from the settling basin effluent at Foxtrot for three days. For each day, manure samples were collected every ten minutes for one hour (six samples per day). Then composite samples were prepared for the analyses of different components and elements. At least two samples were collected from the manure solids (used in the emissions measurements) for two days and one day at Charlie and Foxtrot, respectively. All liquid samples were collected in plastic bottles with a volume of 500 ml. Manure solids were collected in double Ziploc bags. Manure samples were then transported on ice, to UC Davis where they were stored frozen until the analysis. Sampling points are shown in Figures 4- 9. For each sampling day, two composite samples were produced from each sampling point. These composite samples were analyzed for were characterized for total and volatile solids (TS and VS), pH, ammonium (NH^+_4), total Kjeldahl nitrogen (TKN), volatile fatty acids (VFAs), dissolved organic carbon (DOC), organic carbon (OC), and total carbon (TC).

For the Foxtrot dairy, the TS, VS, and pH of manure samples were measured at UC Davis in duplicates according to the standard methods (APHA, 1998). The VFAs were also analyzed at UC Davis using a gas chromatography equipped with a flame ionization detector as described by El-Mashad and Zhang (2007). Manure samples from Charlie dairy were analyzed for TS, VS, and pH by Ward Laboratories, Inc. (http://www.wardlab.com). VFAs were analyzed using gas chromatography by Dairy One Cooperative, Inc. (https://dairyone.com/). The samples were mixed 1:1 ratio with 0.06 M oxalic acid containing 100 ppm trimethylacetic acid (internal standard). Samples injected into a Perkin Elmer Clarus 680 Gas Chromatograph containing a Supelco packed column with the following specifications: 2m x 2mm Tightspec ID, 4% Carbowax 20M phase on 80/120 Carbopack B-DA.

For both, Foxtrot and Charlie dairies, the analyses of NH^+_4, TKN, DOC, OC, and TC were analyzed by Ward Laboratory (https://www.wardlab.com/).

Dairies Questionnaire

A questionnaire was designed and administrated by the research team for the studied dairies to collect farm and activity data including number of cows, ration, length of manure storage, frequency of cleaning of lagoon and settling basin, amount of manure delivered to lagoon, and bedding material type and applied amount. The main objectives of the questionnaire were to collect the data needed to conduct the model simulations; get more information about the AMMP practices that are employed by each of the study dairies; and get the dairyman's opinion on the AMMP practices. The research team obtained the answers of the questionnaire from four of the studied dairies (Charlie, Delta, Echo, and Foxtrot). While Alpha and Bravo have not responded to the research team request, required information for the modeling was obtained by CARB. A copy of the questionnaire survey questions is enclosed in the appendix.

Temperature-dependent Correction of Emissions

To compare the measured CH_4 emissions after installing the AMMP technologies with those that were measured on the same dairies in our previous project funded by the California Department of Food and Agriculture (CDFA), the measured values pre-AMMP were corrected for the average temperature during the measurements post-AMMP. The correction for temperature was conducted as follows (Petersen et al., 2016):

$$ln\left(\frac{k_2}{k_1}\right) = -\left(\frac{E_a}{R}\right)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Where k_1 is the measured CH_4 emission rates ($CH_4/m^2/hr$) pre-AMMP, k_1 is the corrected CH_4 emission rates ($CH_4/m^2/hr$), Ea is activation energy (81 J mol^{-1} (Elsgaard et al. (2016)), R is the universal gas constant (8.314 J K^{-1} mol^{-1}), and T_1 and T_2 are the average daily ambient temperatures (K), pre- and post-installation of the AMMP technologies, respectively. The average daily ambient temperature was calculated by averaging the daily ambient temperature during the period of the emissions measurements plus one month prior the emission measurements. The period of one month was selected based on the fact that the minimum retention time in covered lagoon in California to achieve 60% reduction in the VS should be 38-40 days (NRCS, NHCP, 2017).

Modelling of methane emissions

IPCC/CARB model

The daily emissions of methane from the settling basin and lagoons of the monitored dairies were also predicted using the IPCC/CARB model. The model equations are described by the California Air Resources Board (CARB, 2014). These equations were used to estimate the daily emissions of methane from the settling basins and lagoons. The modeled daily values were determined based on volatile solids degraded in the settling basin and lagoon separately. The ICPP/CARB model depends on the accumulation and degradation of VS. Mostly the values of VS destruction and methane yields are derived from anaerobic digester processes. There are a few literature values for the VS destruction and methane yields from dairy lagoons (Lory et al., 2010). In the current study, a maximum methane yield of 240 L/kg VS added was used. Using VS destructions in settling basin and lagoon of 44%, and 57%, respectively (Chastain, 2006), a methane yield of 545 and 421 L/kg VS [destructed] could be determined. These values of methane yield per each kg of VS destructed were used in the models of the settling basins and lagoons, respectively. The studied dairies did not have records for the exact amount and composition (VS content) of bedding materials used. Therefore, a value of 1.36 kg of bedding/milking cow/day, that represent approximately 12% of the manure VS, was used in the model. This amount was a more conservative value than the bedding amounts (2.5 to 3.5 kg VS per head per day) reported by Arndt et al. (2018) and represented at least 32% of the manure VS. The weights of milking cows, dry cows, heifers, and calves were 680, 684, 407, and 118 kg, respectively. The average daily amounts of the VS for these animal types were 11.41, 5.56, 8.44, and 7.7 kg/1000 kg mass/day, respectively. Weather data required for conducting the model calculations were obtained from weather stations that are near the studied dairies (https://www.visualcrossing.com/weather/weather-data-services#/viewData). For modeling of the emissions from the lagoons, it was assumed that the lagoon was ran for two consecutive years and remaining of solids from the first year was carried over to the second year, in which we compared the measured with the predicted values.

Not all manure on dairies is collected as liquid manure or slurry storage due to application on land and corrals. Different factors (i.e., default values) are employed in the AMMP Quantification Methodology to qualify the amount of manure deposited on land. For lactating cows, these default values are 20%, 70%, and 90% for freestall, open lot, and pasture housing/management, respectively. For dry cows, the default value is 70%. The study by Meyer (2019) on four California dairies indicated that the fraction of manure deposited on land for lactating cows ranged from 10% to 18% for freestall and from 51% to 57% for open lot access housing. While for dry cows, it ranged from 79% to 64%. The values for the percentages of manure delivered to the settling basin and then to the lagoons, were based on the values reported by the dairymen based on their experience. No accurate records or measurements were available at the dairies.

For the dairies that have settling basins, the amount of TS removed by the settling basin was calculated to be 33.5% of the influent TS and the remaining (66.5%) was stored in the lagoons. This value was an average of those reported by Sweeten and Wolfe (1994) and Chastain et al. (2001). Based on the data collected from the surveys, the storage time in the settling basins was 12 months at the Delta dairy. Therefore, in the model, it was assumed that the settling basin started at zero accumulation in January. The farmer indicated that 80% of the manure produced from milking cows was pumped to the lagoon and remaining 20% was deposited in the corrals. Because the vacuum truck was used only one day per week (Thursday) during the monitoring period, in the model the amount of manure that goes to the lagoon on Thursdays was assumed zero.

To model the emissions from the settling basin and lagoon at Delta dairy, the amount of manure that was delivered to the settling basin was assumed to be zero on Thursdays when the vacuum truck was used to remove manure from the barns. The farmer indicated that they completely clean the settling basin once per year. Therefore, in the model, it was assumed that the settling basin was cleaned out in December (i.e., no solids carryover to January). According to the survey, 80% of the manure produced on the farm was delivered to the settling basin and then to the lagoon and 20% of the manure stayed in corrals.

For the Alpha and Bravo, it was assumed that 85% and 87% of manure of the milking cows was treated with the AMMP practices. For Charlie dairy, the farmer reported that 30% of manure goes to the lagoon. Therefore, in the model it was assumed that 30% of manure of the milking cows was flushed to the lagoon and the remaining stayed in the compost-bedded pack barn.

For the Echo dairy, because the settling basin was used during the drainage and drying times of the weeping wall, the emissions of methane from the settling basin was modeled assuming that the settling basin started clean both in January and July. To model emissions from the lagoon, it was assumed that the lagoon received the seepage manure from the weeping wall when it is receiving manure and from the lagoon when it is cleaned and dried. During the monitoring period at the farm, the weeping wall started to be filled on October 3, 2019. Therefore, the model simulated the operation of the settling basin and the lagoon as shown in Figure 23. Based on the information provided by the dairyman, in the modeling of the settling basin and the lagoon, it was assumed that 85% of the manure produced from the milking cows was delivered to the lagoon.

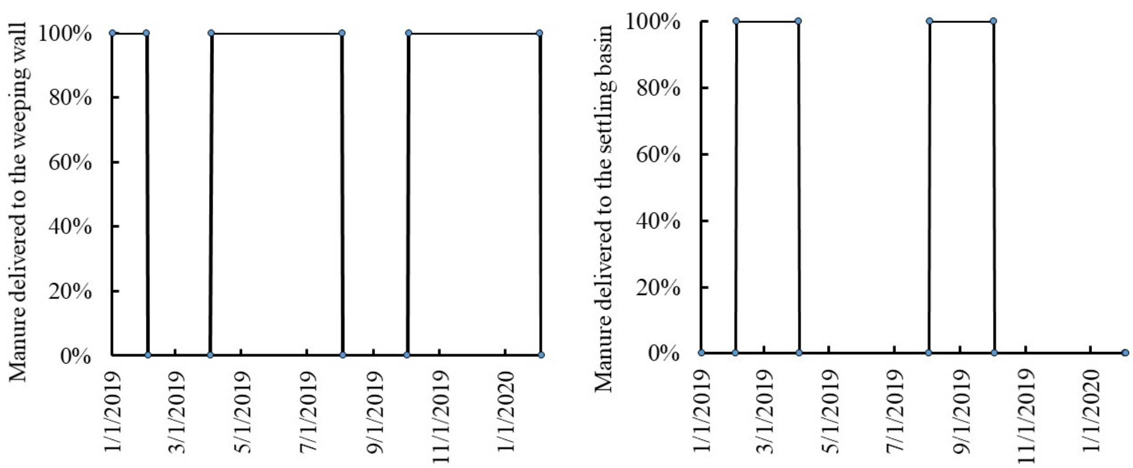

Figure 23. Percentage of manure delivered the weeping wall (A) and settling basin (B) at Echo dairy.

For Foxtrot, the cleaning of the settling basin is carried out in January, May and September. For this the accumulated manure in the settling basin was considered zero at the beginning of January, then 80% of the accumulated manure at the end of April and August. The pasture time was 8 hours per day from March to September. Therefore, in the model, it was assumed that 66% of manure volatile solids was deposited on the flushed lane and corral during the period (March-September). According to the survey, the farmer reported that 55% of manure goes to the lagoon. Therefore, in the model, a collection manure factor of 0.55 was used to determine the amount of flushed manure that was pumped to the settling basin. To determine the amount of the volatile solids that goes to the lagoon, an efficiency of 30% for total solids removal was used for the mechanical separator (Williams et al., 2020) This value is different from the value used in the AMMP quantification methodology. The value reported by Williams et al. (2020) was based on recent studies that were conducted on California dairies.

DairyGEM model

The DairyGEM model was used to model the emissions from Charlie dairy. The housing for lactating cows and heifers was selected to be bedded pack barn and freestalls and open lot, respectively. To predict the emissions, the model needs detailed feed ration for the cows. For unknown reasons, the farmer did not provide detailed information on the composition of ration after implementing the AMMP practice. However, in the survey he indicated that he usually used a typical ration (silage, hay, minerals, and various byproducts). Therefore, to apply the DairyGEM after installing the AMMP practices, it was assumed that the ration per each milking cow was similar to that used during the monitoring of the emissions pre-AMMP practices (a project funded by CDFA). Table 8 shows the type, estimated amount, and composition of major components of the feed used on Charlie dairy. DairyGEM does not give daily emissions rates from each source of emissions on the dairy. Therefore, the annual average emission rate from manure storage (i.e., lagoon) was used to estimate the daily emissions from the lagoon as a portion of the total emissions from the barns and the lagoon.

The DairyGem model provides simulation results in the form of figures and summary tables. To further process the results in the figures obtained from the DairyGem model and to predict daily emissions rates, the DairyGEM figures were digitized using an online application called WebPlotDigtizer (https://automeris.io/WebPlotDigitizer/).

Table 8. Type, amount and composition of major components of the feed used on Charlie dairy.

	Composition						
Feed type	**Annual amount, short dry ton**	**Dry matter (DM), %**	**Crude protein, %DM**	**Degradable protein, %CP**	**Acid detergent insoluble protein, %CP**	**Net energy of lactation, Mcal/lb DM**	**Neutral detergent fiber, %DM**
High quality silage	1,150.4	33.3	12.0	70.0	1.0	0.5	59.9
High quality hay	1,132.0	88.0	20.2	60.0	1.6	0.6	39.6
Low quality hay	609.2	88.0	20.2	60.0	1.6	0.6	39.6
Corn silage	5,146.7	39.0	8.4	65.0	5.9	0.6	47.0
High moisture grain	9,103.3	88.9	25.5	52.8	5.4	0.9	22.8
Dry grain	9,358.7	89.5	13.2	53.2	2.5	1.0	28.5

Results and discussion

Emissions measurements

Emissions from the lagoon on Charlie dairy

The emission rates of CH_4, NH_3, N_2O, and H_2S from the lagoon on Charlie dairy are shown in Figures 24, 25, 26, and 27, respectively. High emission rates of CH_4 and H_2S were calculated during the last day of monitoring probably due to the location of the wind tunnel that was closer to the lagoon inlet. The emissions were higher during the daytime than night times. The emission rates of NH_3 were relatively constant during the monitoring period. Low emission rates with some peaks of N_2O were calculated.

The emission rates of CH_4, and NH_3 ranged from 0.58 to 69.69 and from 0 to 0.09 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 10.06, and from 0 to 35.78 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 17.03 and 0.03 g/m^2/hr, respectively (Table 9) and the emission rates of N_2O and H_2S were 0.66 and 10.13 mg/m^2/hr, respectively. The daily emission of CH_4, NH_3, N_2O, and H_2S were 1,475.1, 2.6, 0.06, and 0.88 g/ animal unit/day, respectively (Table 10).

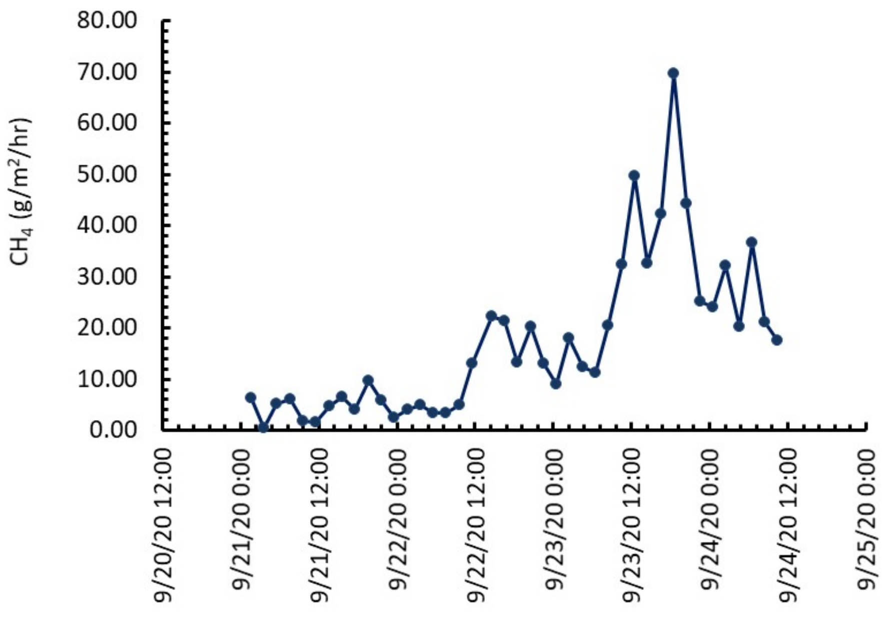

Figure 24. Emission rates of CH_4 from the lagoon at Charlie dairy.

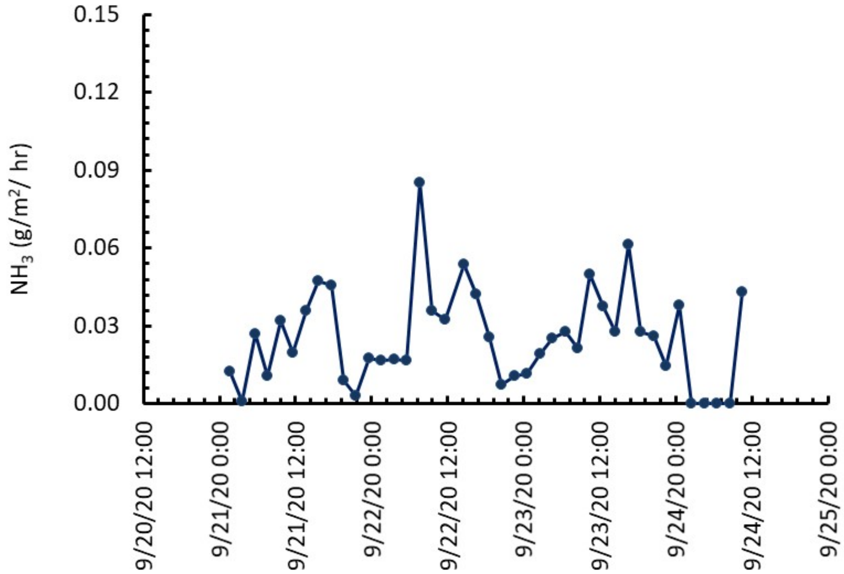

Figure 25. Emission rates of NH_3 from the lagoon at Charlie dairy.

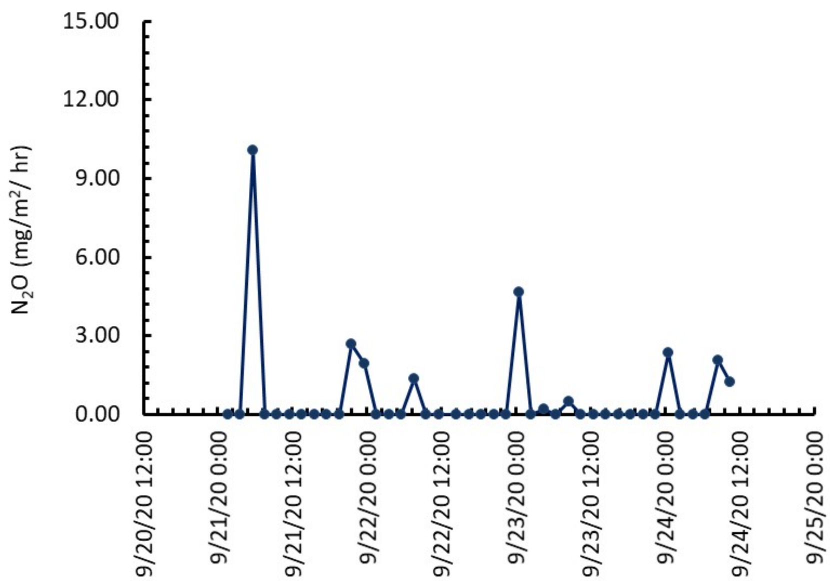

Figure 26. Emission rates of N_2O from the lagoon at Charlie dairy.

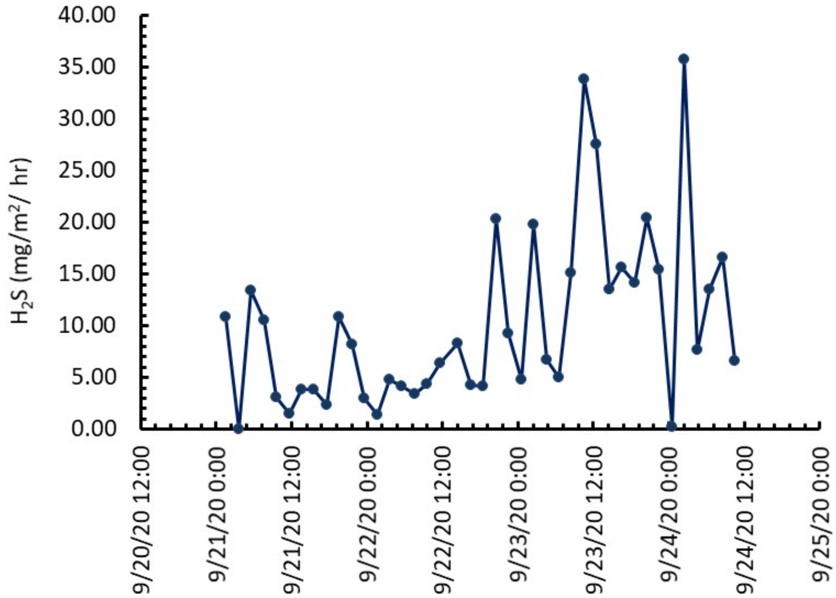

Figure 27. Emission rates of H_2S from the lagoon at Charlie dairy.

Emissions from manure solids on Charlie dairy

The emission rates of CH_4, NH_3, N_2O, and H_2S from manure solids at Charlie dairy are shown in Figures 28, 29, 30, and 31, respectively. It should be mentioned that the age of the solids used in these experiments was not known because the solids were collected arbitrarily from the barn. As can be seen from Figure 28, there were a few peaks of CH_4 emissions during the measurements for the first and second batch of manure solids and very low emissions of NH_3, N_2O, and H_2S were determined with a few peaks (Figures 29, 30, and 31).

The emission rates of CH_4, and NH_3 ranged from 0 to 5.70 and from 0 to 0.31 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 11.41 and from 0 to 13.46 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 1.07 and 0.04 g/m^2/hr, respectively (Table 9), while emissions of N_2O and H_2S were 1.20 and 2.22 mg/m^2/hr, respectively.

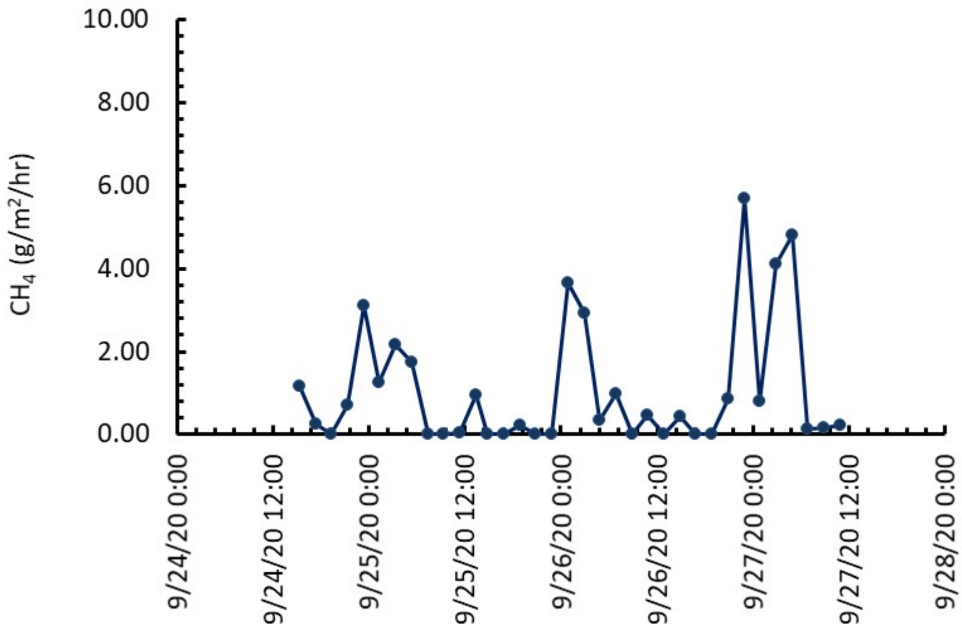

Figure 28. Emission rates of CH_4 from solids at Charlie dairy.

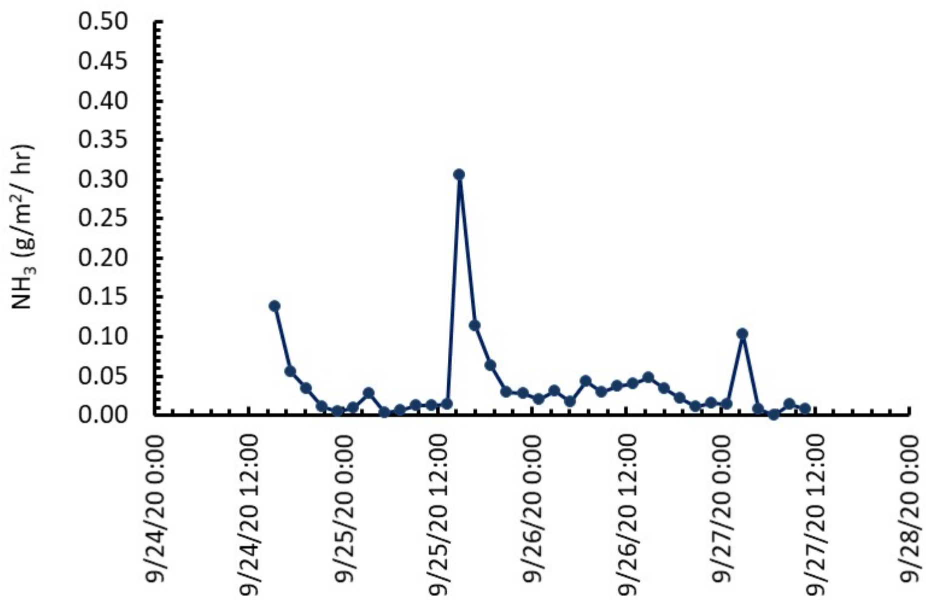

Figure 29. Emission rates of NH_3 from solids at Charlie dairy.

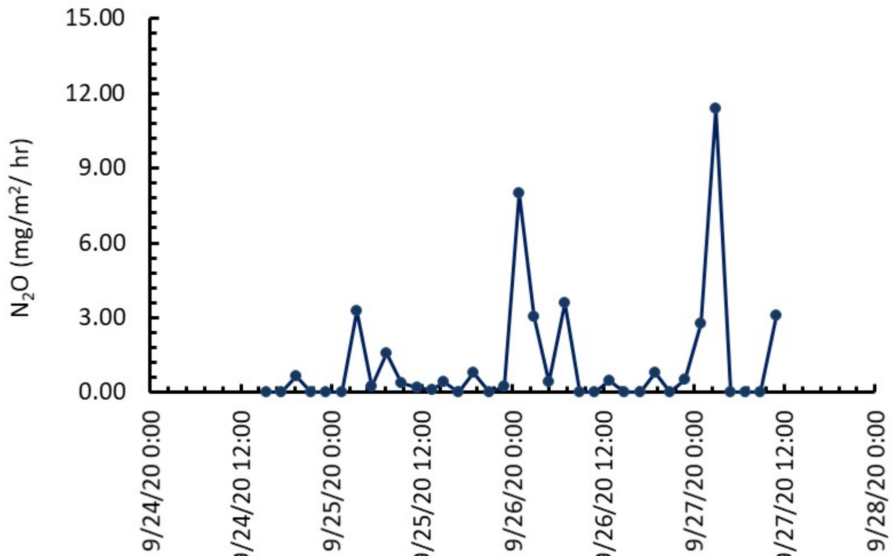

Figure 30. Emission rates of N_2O from solids at Charlie dairy.

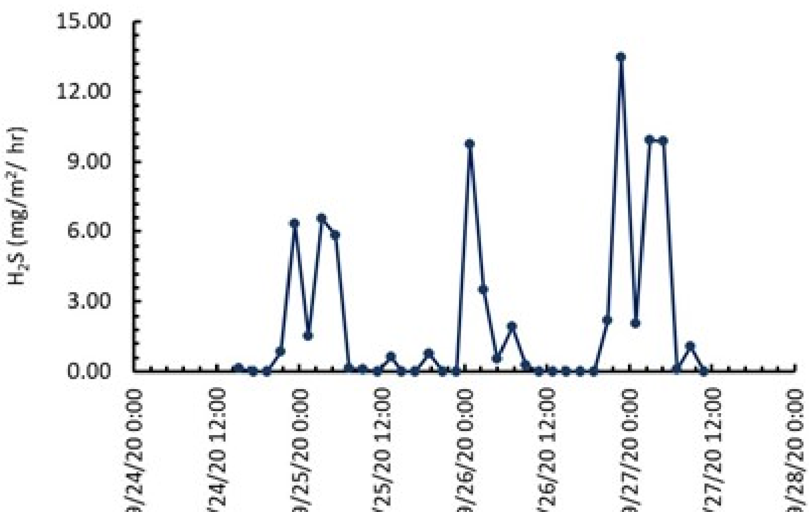

Figure 31. Emission rates of H_2S from solids at Charlie dairy.

Emissions from the lagoon on Foxtrot dairy

The emission rates of CH_4, NH_3, N_2O, and H_2S from the lagoon on Foxtrot dairy are shown in Figures 32, 33, 34, and 35, respectively. Relatively constant emission rates, with a few peaks, of CH_4 and NH_3 were found for most of the monitoring period. Some peaks of emission rates of N_2O and H_2S were determined.

The emission rates of CH_4, and NH_3 ranged from 1.43 to 31.49 and from 0.07 to 0.32 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 218.89 and from 0 to 0.32 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 7.89 and

0.15 $g/m^2/hr$, respectively (Table 9) and 16.66 and 0.06 $mg/m^2/hr$, for N_2O and H_2S, respectively. The daily emission of CH_4, NH_3, N_2O, and H_2S were 662.3, 12.6, 1.4, and 0.01 g/ animal unit/day, respectively (Table 10). Comparing the emissions rates from the lagoon and the settling basin indicated that the lagoon had relatively lower emission rates of CH_4, NH_3, and H_2S and higher emission rates of N_2O than the settling basin.

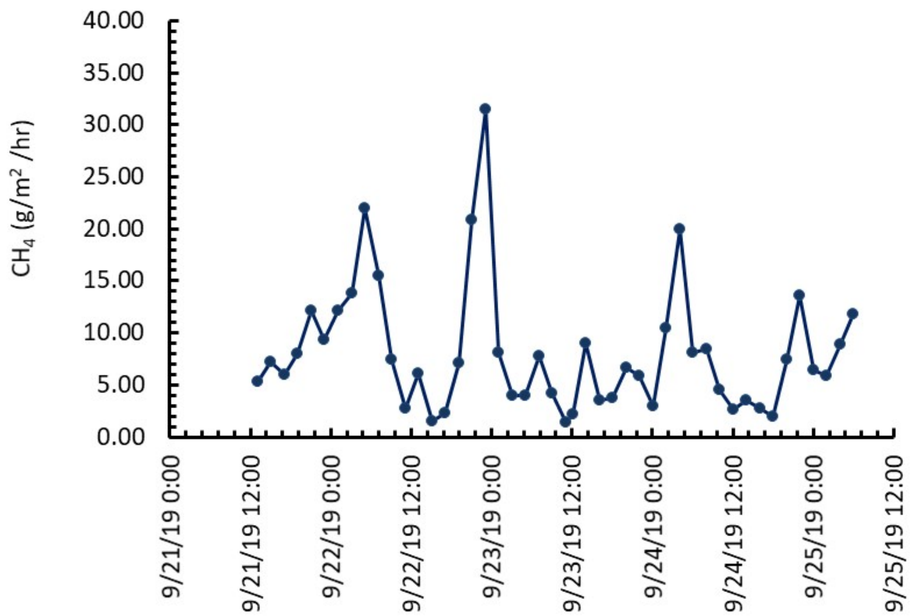

Figure 32. Emission rates of CH_4 from the lagoon at Foxtrot dairy.

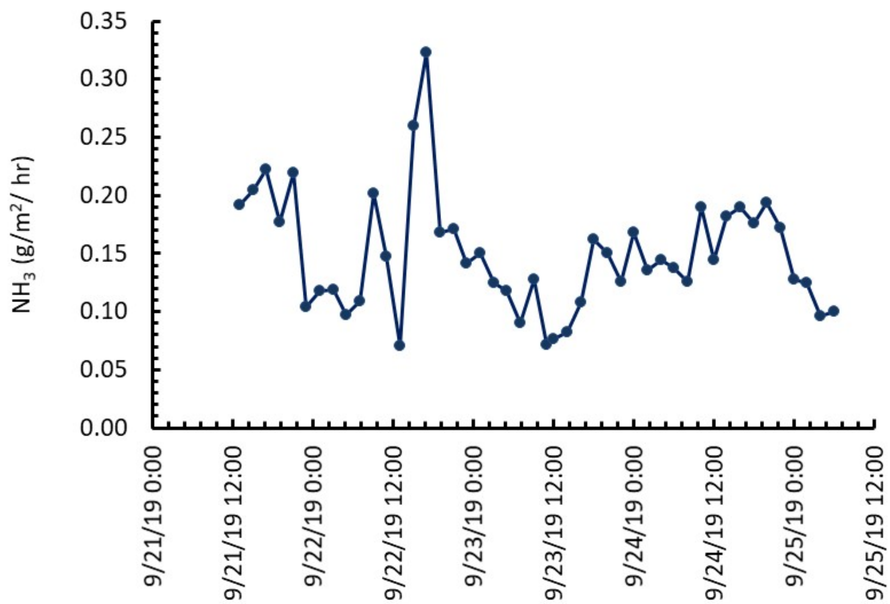

Figure 33. Emission rates of NH_3 from the lagoon at Foxtrot dairy.

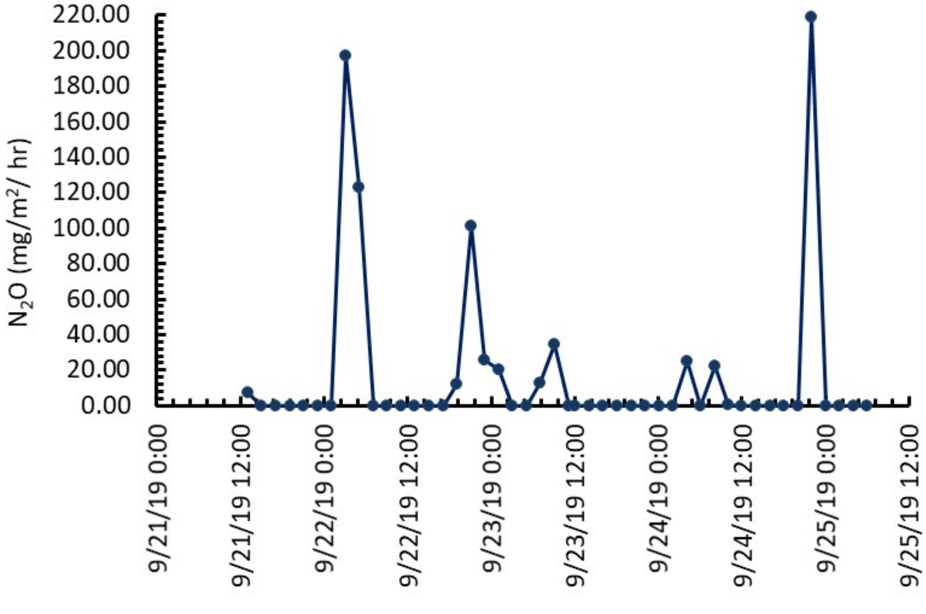

Figure 34. Emission rates of N_2O from the lagoon at Foxtrot dairy.

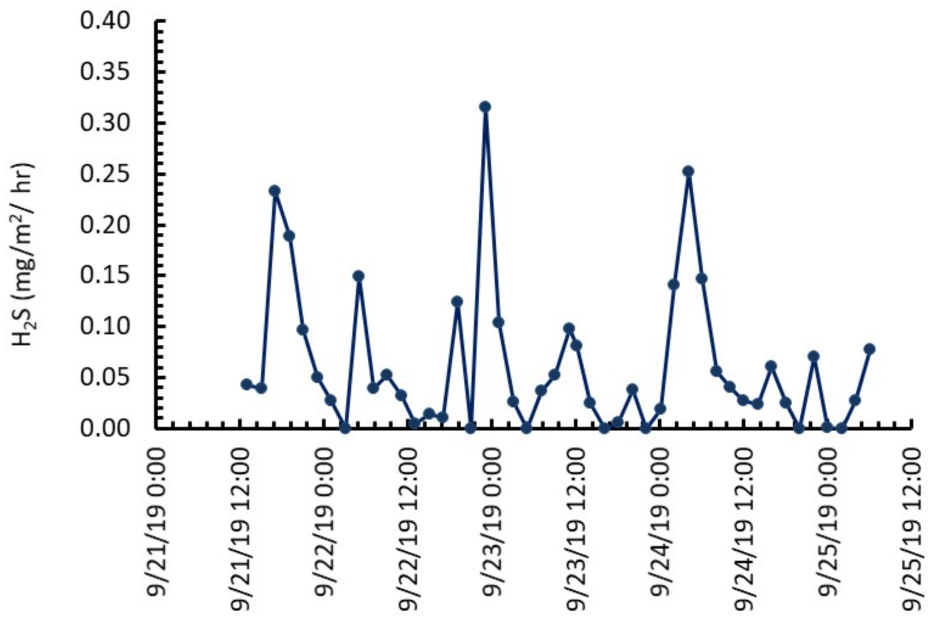

Figure 35. Emission rates of H_2S from the lagoon at Foxtrot dairy.

Emissions from the settling basin on Foxtrot dairy

The emission rates of CH_4, NH_3, N_2O, and H_2S from the settling basin at Foxtrot dairy are shown in Figures 36, 37, 38, and 39, respectively. The methane emission rate was relatively constant during the emissions monitoring period with a peak of approximately 19.94 g/m^2/hr on the second day of the monitoring period. Ammonia emissions were relatively constant during the day and night times. The emissions were higher during the day versus nighttime. The emissions of

N_2O were negligible for most of the monitoring time except for one peak of 32.97 mg/m^2/hr. For H_2S, there were a few peaks of emissions during the monitoring period.

The emission rates of CH_4, and NH_3 ranged from 9.98 to 19.94 and from 0.10 to 0.27 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 32.97, and from 0 to 0.33 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 13.82 and 0.19 g/m^2/hr, respectively (Table 9) and they were 2.74 and 0.12 mg/m^2/hr, for N_2O and H_2S, respectively. The daily emission of CH_4, NH_3, N_2O, and H_2S were 661.6, 9.1, 0.13, and 0.01 g/animal unit/day, respectively (Table 10).

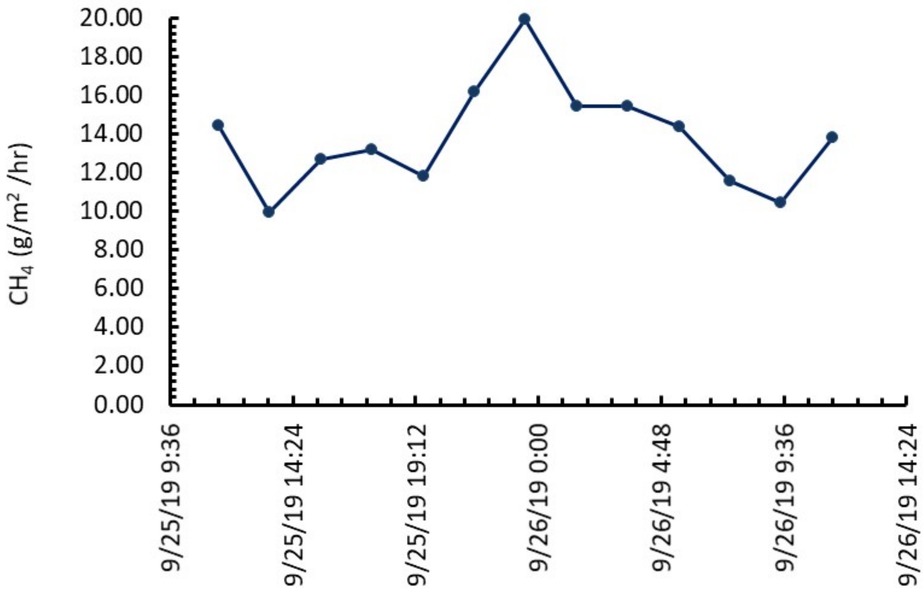

Figure 36. Emission rates of CH_4 from the settling basin at Foxtrot dairy.

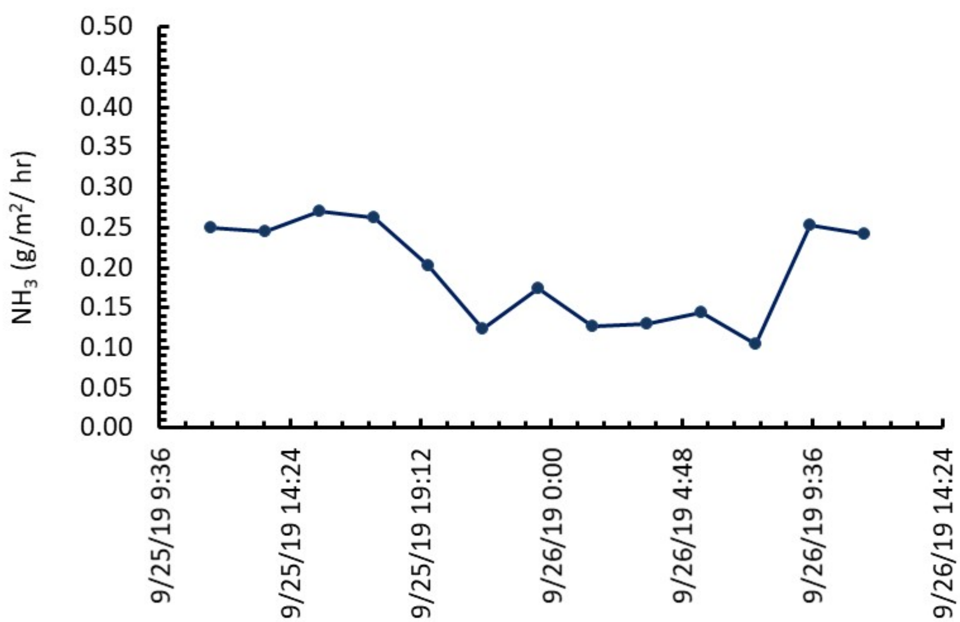

Figure 37. Emission rates of NH_3 from the settling basin at Foxtrot dairy.

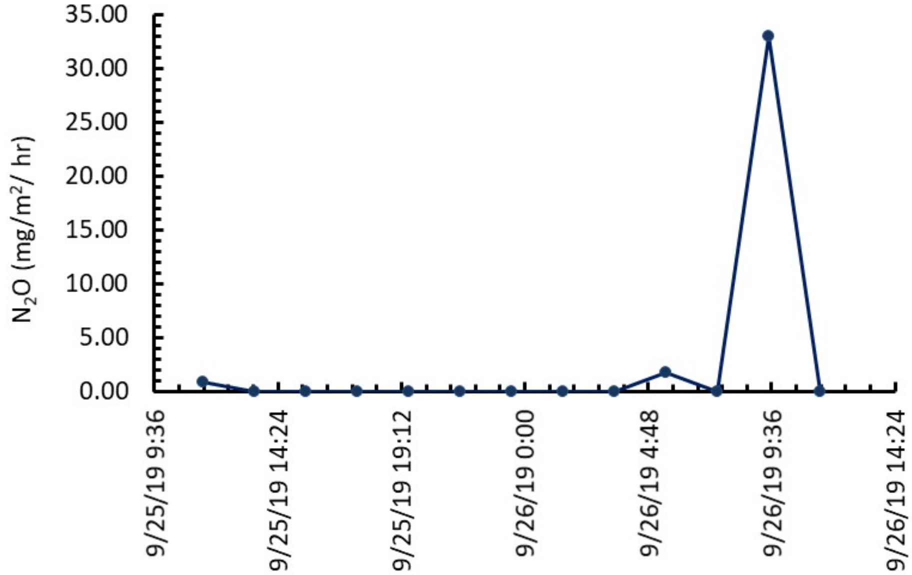

Figure 38. Emission rates of N_2O from the settling basin at Foxtrot dairy.

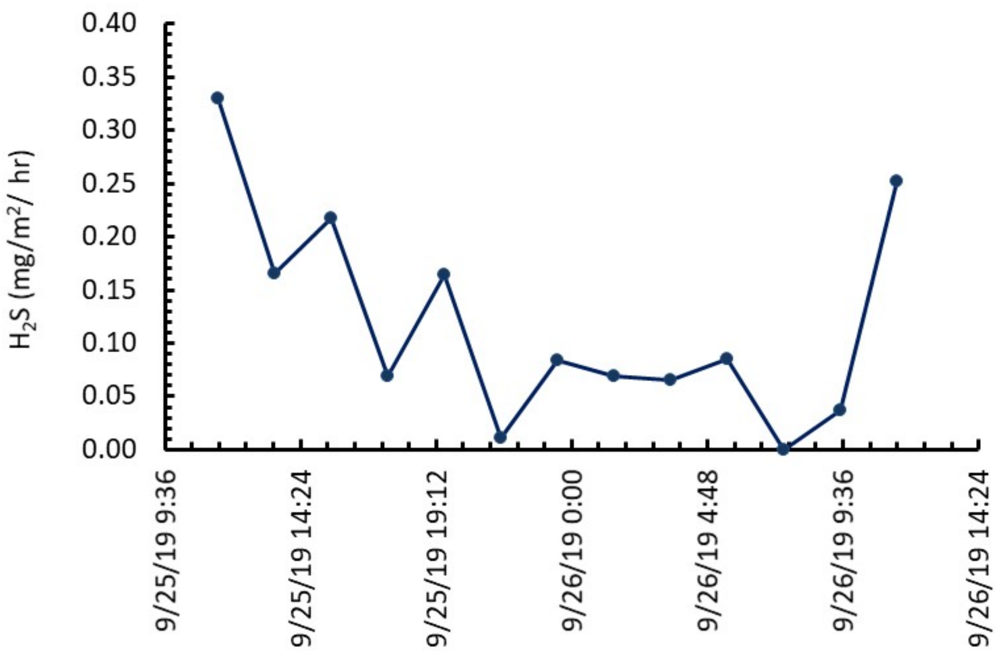

Figure 39. Emission rates of H_2S from the settling basin at Foxtrot dairy.

Emissions from solids on Foxtrot dairy

The emission rates of CH_4, NH_3, N_2O, and H_2S from solids at Foxtrot dairy are shown in Figures 40, 41, 42, and 43, respectively. As can be seen from Figure 40, the emissions of CH_4 decreased after starting the measurements, then increased reaching a peak of 30.37 CH_4 g/ton/hr. Then the emissions gradually decreased. The emissions of ammonia sharply decreased after starting the measurements reaching a relatively constant rate after approximately 14 hours (Figure 41). The emissions rates of N_2O and H_2S were low except that there were a few peaks of emissions as shown in Figures 42 and 43. The emission rates of CH_4, and NH_3 ranged from 0 to 30.37 and from 0.49 to 4.64 g/ton/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 285.63 and from 0 to 1.69 mg/ton/hr, respectively. The average emission rates of CH_4 and NH_3 were 10.41 and 1.66 g/ton/hr, respectively (Table 9) and the emissions of N_2O and H_2S were 39.05 and 0.33 mg/ton/hr, respectively.

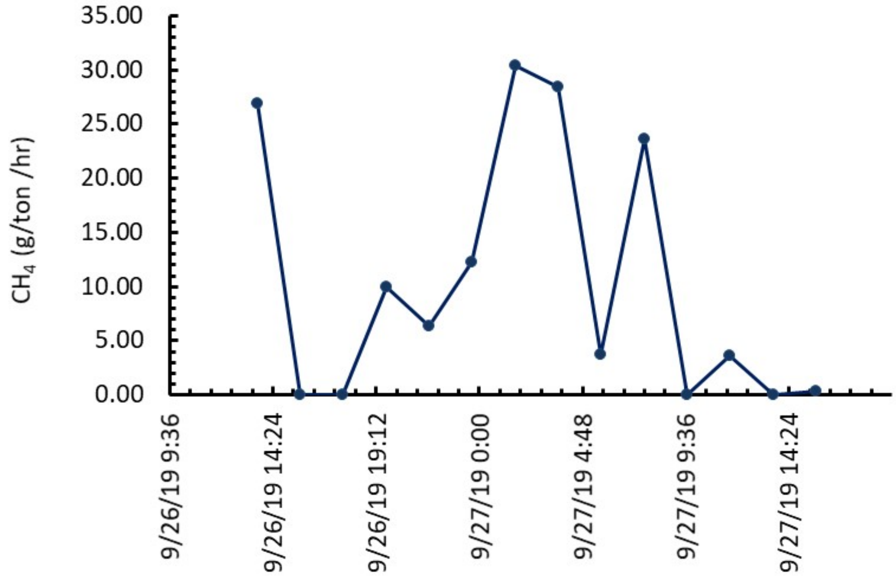

Figure 40. Emission rates of CH_4 from solids at Foxtrot dairy.

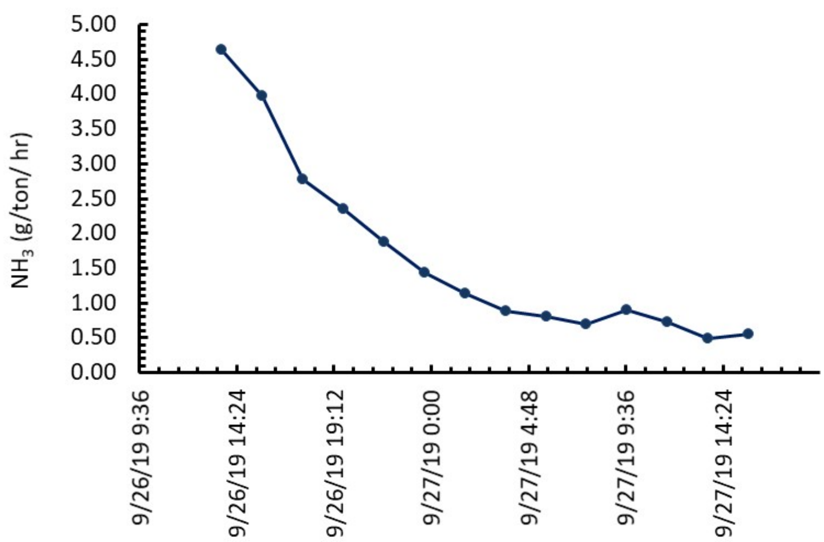

Figure 41. Emission rates of NH_3 from solids at Foxtrot dairy.

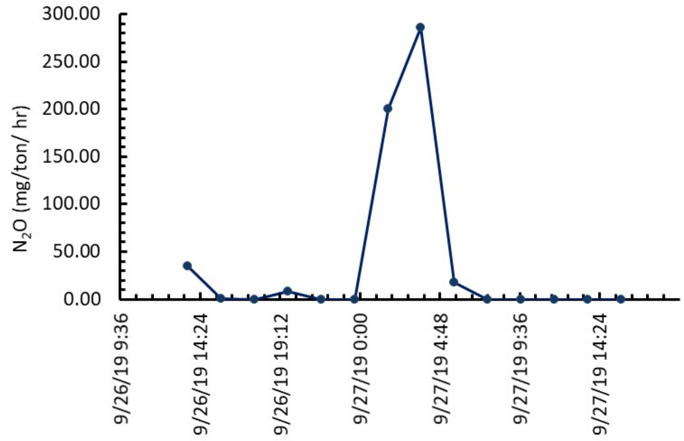

Figure 42. Emission rates of N_2O from solids at Foxtrot dairy.

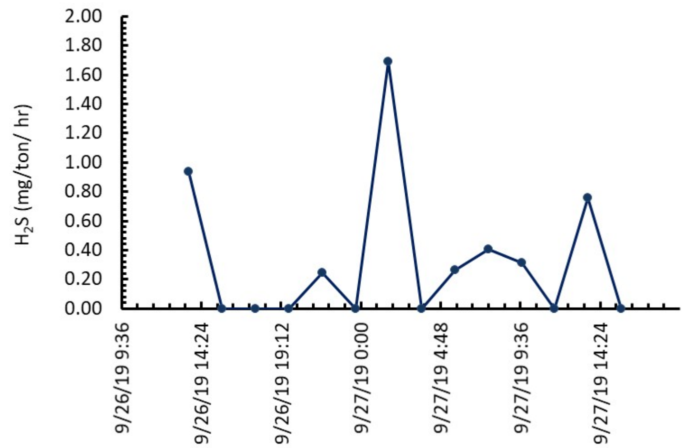

Figure 43. Emission rates of H_2S from solids at Foxtrot dairy.

Table 9. Average, minimum, and maximum emission rates of different gases from the lagoons and settling basin.

Dairy	Parameter	CH_4 (g/m^2/ hr)		NH_3 (g/m^2/ hr)		N_2O (mg/m^2/ hr)		H_2S (mg/m^2/ hr)	
		Lagoon	**Settling basin**	**Lagoon**	**Settling basin**	**Lagoon**	**Settling basin**	**Lagoon**	Settling basin
Charlie	Average	17.03	NA*	0.03	NA	0.66	NA	10.13	NA
	Minimum	0.58	NA	0.00	NA	0.00	NA	0.00	NA
	Maximum	69.69	NA	0.09	NA	10.06	NA	35.78	NA
Foxtrot	Average	7.89	13.82	0.15	0.19	16.66	2.74	0.06	0.12
	Minimum	1.43	9.98	0.07	0.10	0.00	0.00	0.00	0.00
	Maximum	31.49	19.94	0.32	0.27	218.89	32.97	0.32	0.33

*Charlie dairy does not have a settling basin

Table 10. Average emission rate (g/animal unit/day) of different gases.

Dairy	Number of animal units*	CH_4		NH_3		N_2O		H_2S	
		Lagoon	Settling basin	Lagoon	Settling basin	Lagoon	Settling basin	Lagoon	Settling basin
Charlie	3,475	1,475.1	NA**	2.6	NA	0.06	NA	0.88	NA
Foxtrot	1,502	662.3	661.6	12.6	9.1	1.40	0.13	0.01	0.01

*Animal unit=454 kg of live weight (Arndt et al., 2018). The average live weight of milking cow, dry cow, heifer, and calve was 680, 684, 407, and 118 kg.

**Charlie dairy does not have a settling basin

Emissions from manure solids

The average, minimum and maximum emission rates of CH_4, NH_3, N_2O, and H_2S from solids monitored at Charlie and Foxtrot are shown in Table 11.

Table 11. Average, minimum, and maximum emission rates of different gases from solids.

Dairy	Parameter	Average	Minimum	Maximum
Charlie	CH_4 (g/m^2/hr)	1.07	0	5.70
	NH_3 (g/m^2/hr)	0.04	0	0.31
	N_2O (mg/m^2/hr)	1.20	0	11.41
	H_2S (mg/m^2/hr)	2.22	0	13.46
Foxtrot	CH_4 (g/ton/hr)	10.41	0	30.37
	NH_3 (g/ton/ hr)	1.66	0.49	4.64
	N_2O (mg/ton/ hr)	39.05	0	285.63
	H_2S (mg/ton/ hr)	0.33	0	1.69

Modeling of Emissions

Results of the IPCC/CARB model for methane emissions

Predicted methane emissions from the lagoon at Alpha dairy

The predicted daily methane emissions from the lagoon at the Alpha dairy using the IPCC/CARB model are shown in Figure 44. Low emission rates were predicted on days with low temperatures. The predicted minimum, maximum, and average emission rates of methane were 86.0, 997.6, and 312.4 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the lagoon on the Alpha dairy are shown in Figure 45. The modeled values represented 90.9%, 65.1%, and 54.9% of the measured values for September 29th and 30th, and October 1st, respectively. The average predicted emissions value, over the three days, represented 67.8% of the average measured value during this period.

It should be mentioned that the average measured values for September 29th, September 30th, and October 1st were calculated based on the average of the measured values during the period of September 29th at 4:26 PM and September 30th at 5:00 PM, September 30th at 5:00 PM and October 1st at 5:00, and October 1st at 9:00 PM and October 2nd 3:10 PM, respectively. Moreover, since the time step in the model was one day, the reported modeled values for September 29th, September 30th, October 1st were the average predicted values for September 29th and September 30th, September 30th and October 1st, and October 1st and October 2nd, respectively.

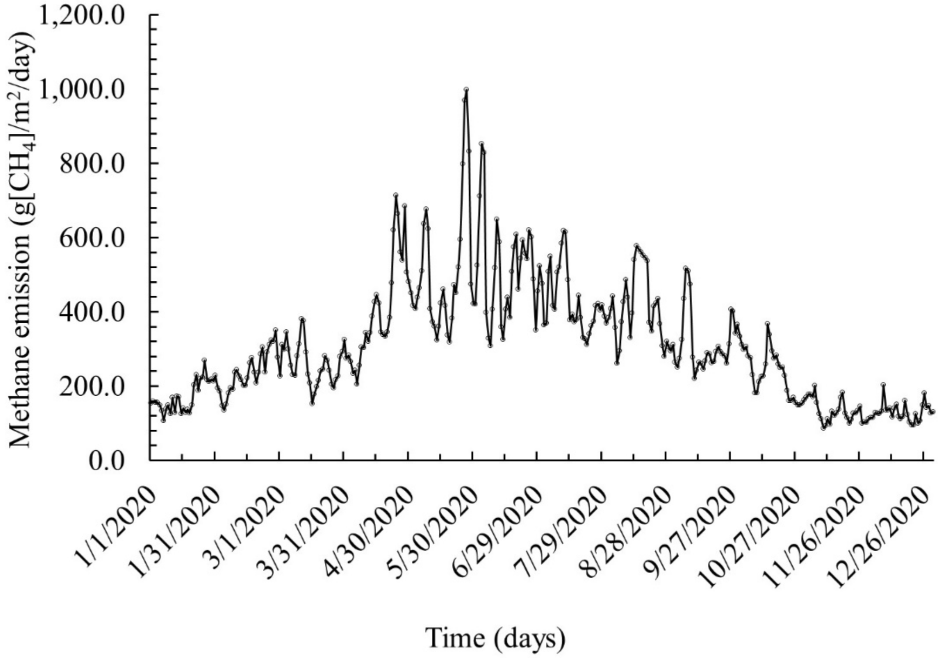

Figure 44. Predicted daily methane emissions from the lagoon at Alpha dairy.

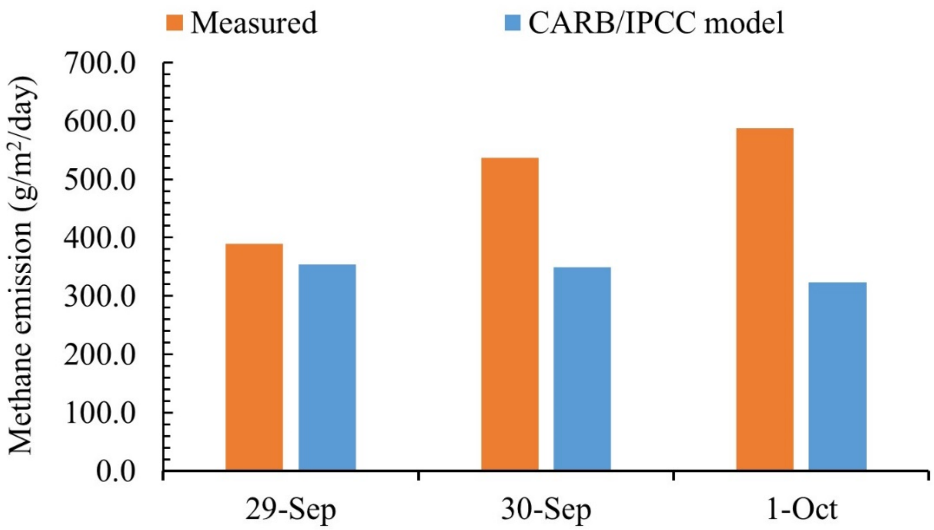

Figure 45. Measured and predicted methane emissions from the lagoon at Alpha dairy.

Predicted methane emissions from the settling basin at Alpha dairy

The predicted daily methane emissions from the settling basin at the Alpha dairy using the IPCC/CARB model are shown in Figure 46. As can be seen, low emission rates were predicted during January and in the beginning of July. This is due to low temperature in January and the assumption that the settling basin was cleaned in December and June. The minimum, maximum, and average predicted emission rates were 2.0, 903.6, and 228.4 $g/m^2/day$, respectively. Measured and modeled emission rates of CH_4 from the settling basin are shown in Figure 47. The average predicted emissions value represented 60.4% of the average measured value during this period.

Because the measurements were conducted from October 2nd at 7:20 PM until October 3rd at 5:20 PM, the modeled value reported here is the average predicted emissions for October 2nd and October 3rd.

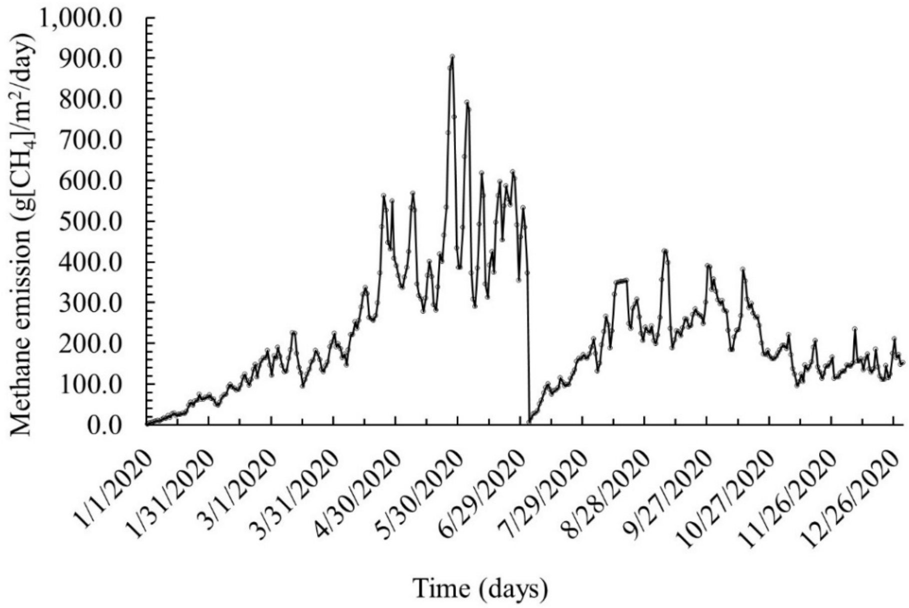

Figure 46. Predicted daily methane emissions from the settling basin at Alpha dairy.

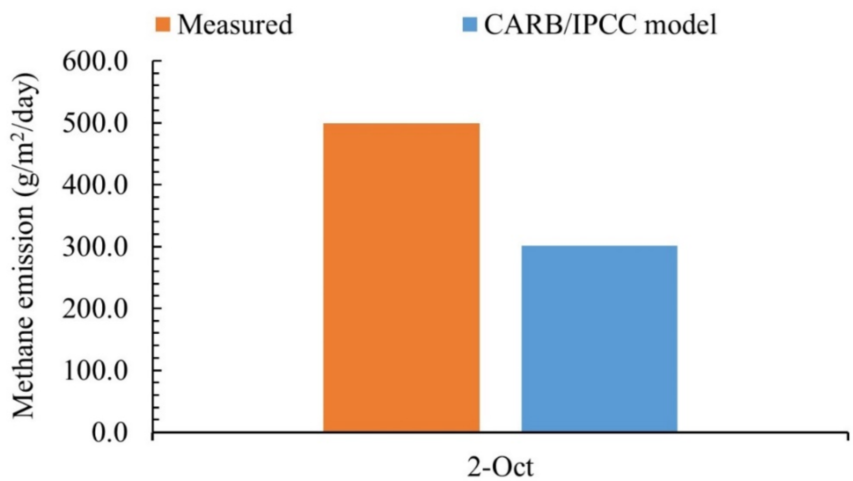

Figure 47. Predicted and measured methane emissions from the settling basin at Alpha dairy.

Predicted methane emissions from the lagoon at Bravo dairy

The predicted daily methane emissions from the lagoon at Bravo dairy using the IPCC/CARB model are shown in Figure 48. The minimum, maximum, and average emission rates were 21.8, 209.3 and 69.2 g/m^2/day, respectively. Measured and predicted emission rates of CH_4 from the lagoon at Bravo dairy are shown in Figure 49. The predicted emissions values for the settling basin represented 141.0%, 54.9%, and 57.1% of the measured values for November 20th, 22nd, and 23rd, respectively. The average predicted emissions represented 69.9% of the average measured value during this period.

The reported measured values for November 20th, 22nd, and 23rd were calculated based on the average of the measured values during the period of November 20th at 3:40 PM and November 21st at 3:40 PM, November 21st at 5:40 PM and November 22nd at 6:30 PM, and November 22nd at 8:30 PM and November 23rd at 8:50 PM, respectively. Moreover, since the time step in the model was one day, the reported modeled values for November 20th, 22nd, and 23rd were the average predicted values for November 20th and November 21st, November 21st and November 22nd, and November 22nd and November 23rd, respectively.

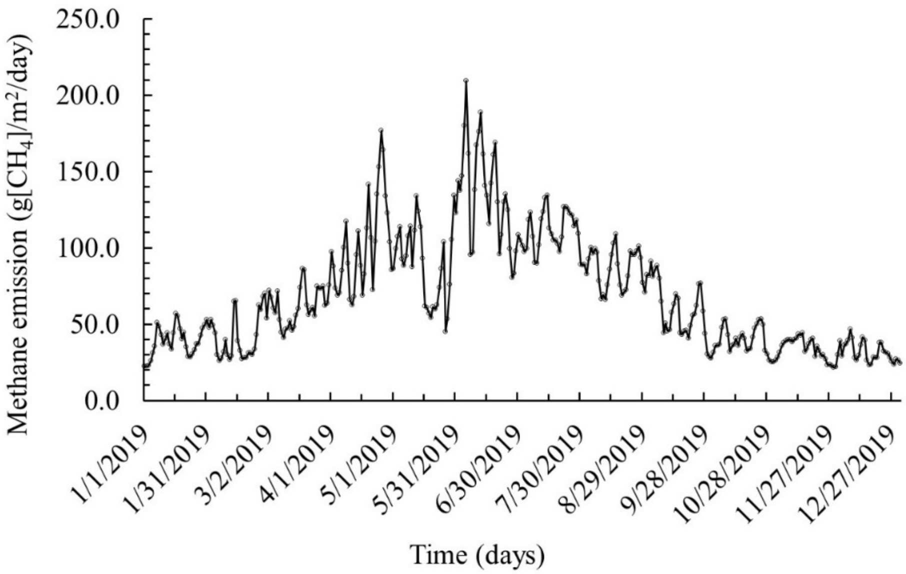

Figure 48. Predicted daily methane emissions from the lagoon at Bravo dairy.

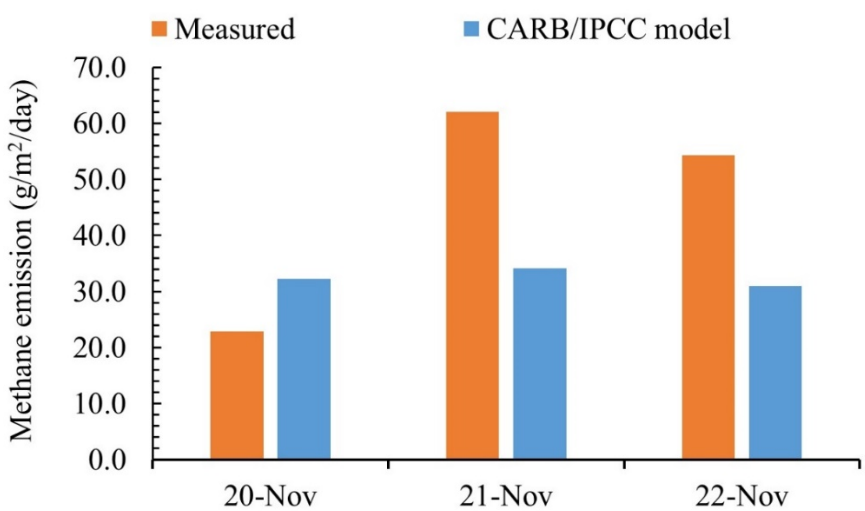

Figure 49. Measured and predicted methane emissions from the lagoon at Bravo dairy.

Predicted methane emissions from the settling basin at Bravo dairy

The predicted daily methane emissions from the settling basin at the Bravo dairy using the IPCC/CARB model are shown in Figure 50 . As can be seen, low emission rates were predicted during January and in the beginning of July. This is due to low temperature in January and the assumption that the settling basin was cleaned in December and June. The minimum, maximum, and average predicted emission rates were 2.3, 1,505.4, and 391.5 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the settling basin on the Bravo dairy are shown in Figure 51. The average predicted emissions value represented 370% of the average measured value during this period.

Because the measurements were conducted from December 16th at 3:26 PM until December 17th at 1:36 PM, the predicted value reported here is the average of predicted emissions for December 16th and 17th.

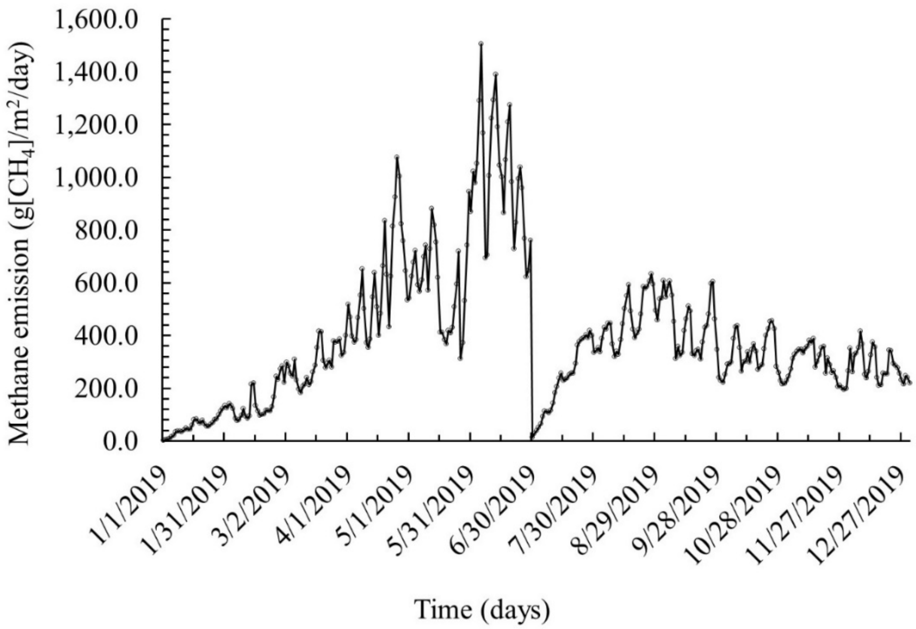

Figure 50. Predicted daily methane emission from the settling basin at Bravo dairy.

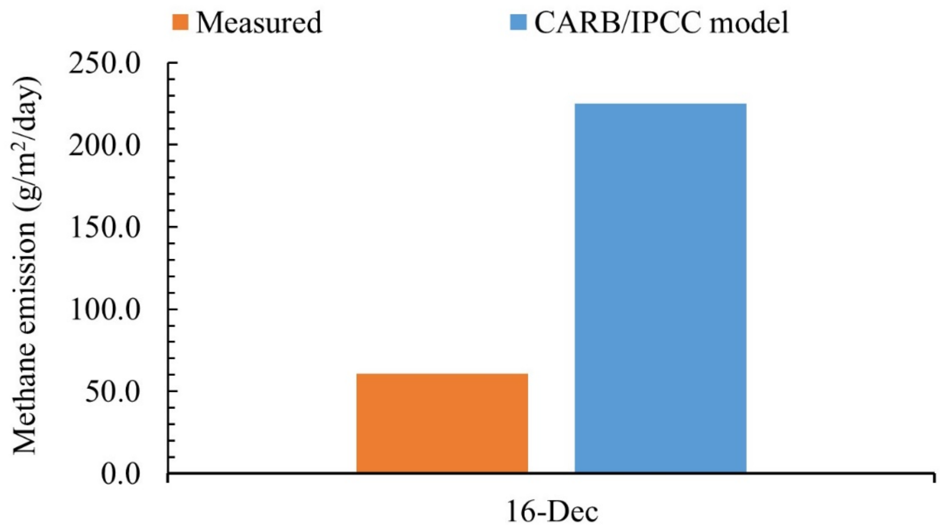

Figure 51. Measured and predicted methane emissions from the settling basin at Bravo dairy.

Predicted methane emissions from the lagoon at Charlie dairy

The predicted daily methane emissions from the lagoon at Charlie dairy using the IPCC/CARB model are shown in Figure 52. The minimum, maximum, and average emission rates were 12.1, 245.44, and 78.2 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the settling basin on the Charlie dairy are shown in Figure 53. The modeled values for the settling basin represented 45.0%, 15.1%, and 5.5% of the measured values for September 21st, 22nd, and 23rd, respectively. The average predicted emissions represented 11.6% of the average modeled value during this period. It should be mentioned that the reported values for the average measured values for September 21st, 22nd, and 23rd, were calculated based on the average of the measured values during the period of September 21st at 1:35 PM and September 22nd 1:35PM, September 22nd at 3:35 PM and September 23rd 2:30 PM, September 23rd at 4:30 PM and September 24th 4:30 PM, respectively. Moreover, since the time step in the model was one day, the reported modeled values for September 21st ,22nd , and 23rd were the average predicted values for September 21st and 22nd , September 22nd and 23rd , and September 23rd and 24th, respectively.

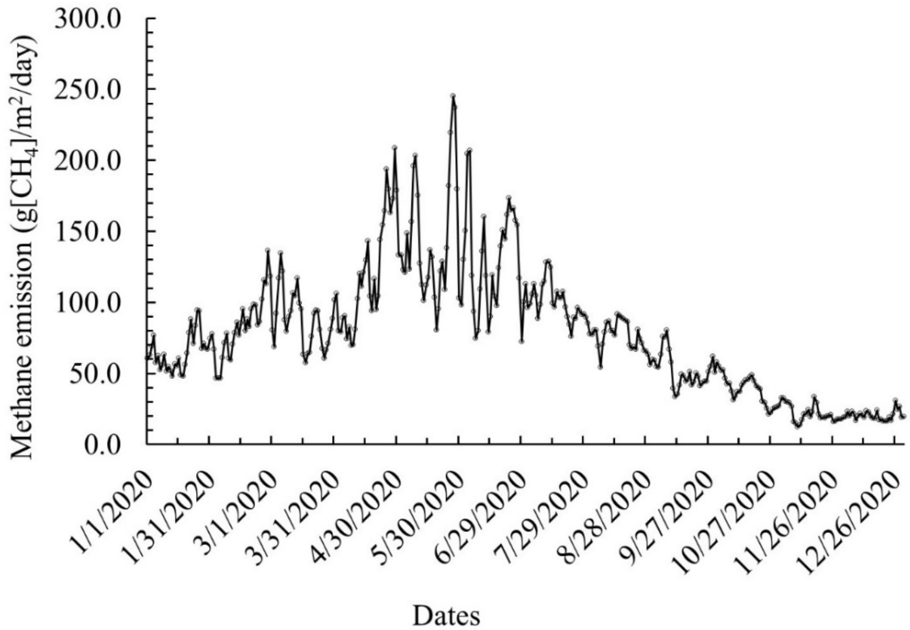

Figure 52. Predicted daily methane emission from the lagoon at Charlie dairy.

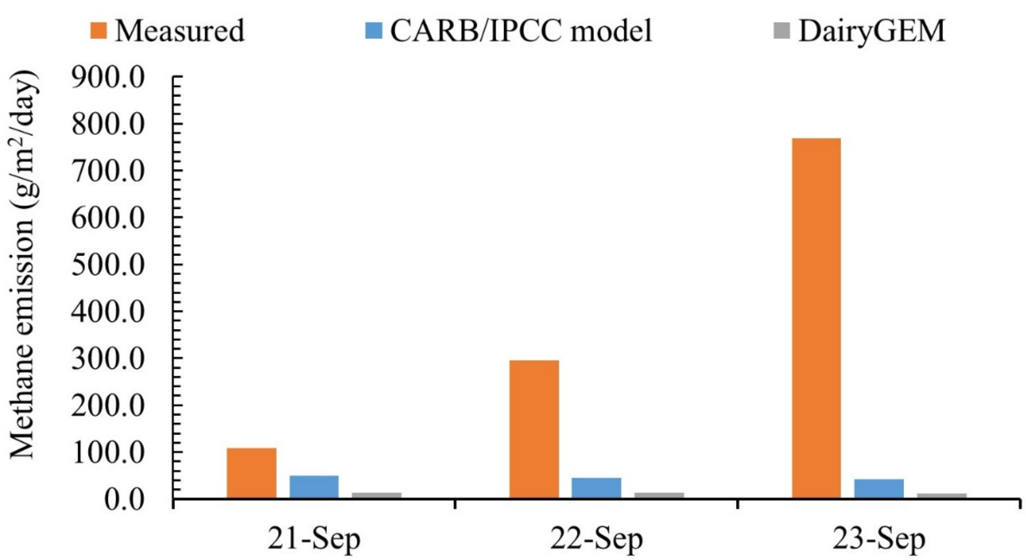

Figure 53. Measured and predicted methane emission from the lagoon at Charlie dairy.

Results of DairyGEM model for emissions from Charlie

The predicted methane emissions, using DairyGEM, from the barn and lagoon at Charlie dairy are shown in Figure 54. As can be seen high emissions were predicted for the hot weather days. Based on the predicted emissions from the barn and lagoon, the emissions from the lagoon were estimated as shown in Figure 55. The minimum, maximum, and average emission rates were 7.4, 18.9, and 12.4 g/m^2/day, respectively. The modeled values for the settling basin represented 12.2%, 4.3%, and 1.6% of the measured values for September 21st, 22nd, and 23rd, respectively. The average predicted emissions represented 3.1% of the average modeled value during this period.

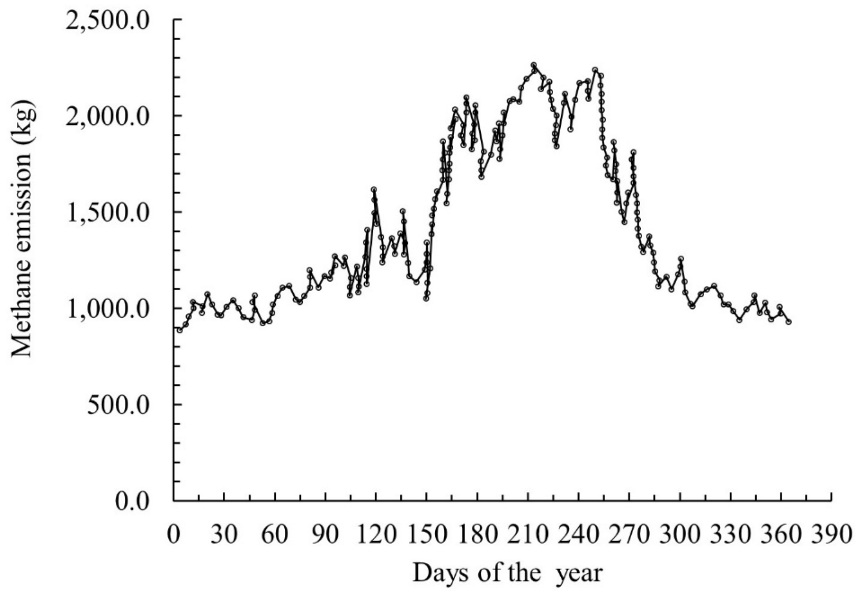

Figure 54. Predicted methane emissions, using DairyGEM, from the barn and lagoon at Charlie dairy.

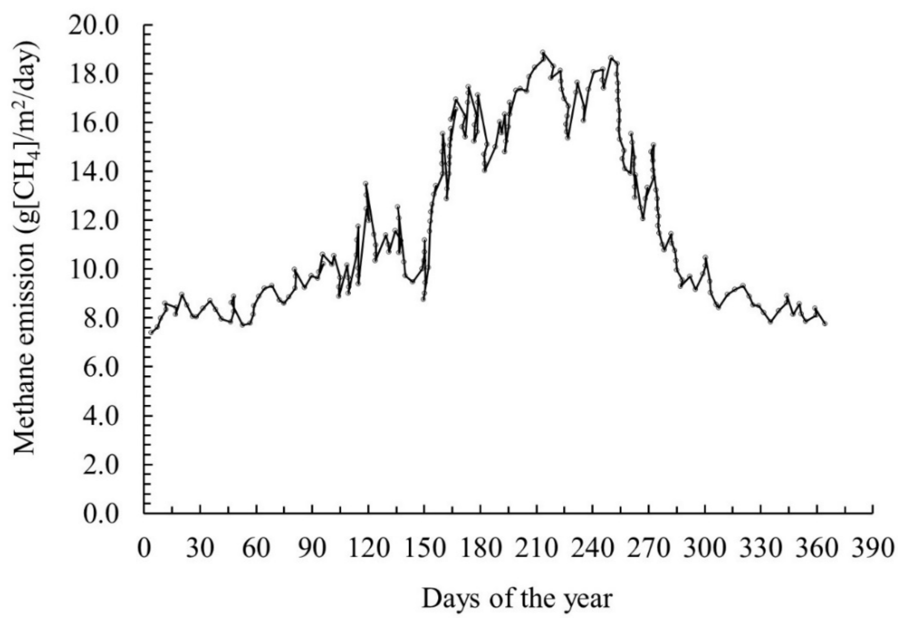

Figure 55. Predicted methane emission, using DairyGEM, from the lagoon at Charlie dairy.

Predicted methane emissions from the lagoon at Delta dairy

The predicted daily methane emissions from the lagoon at Delta dairy using the IPCC/CARB model are shown in Figure 56. The minimum, maximum, and average emission rates were 66.3, 674.6 and 226.7 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the settling basin on the Delta dairy are shown in Figure 57. The modeled values for the settling basin represented 65.1 %, 63.8%, and 63.5% of the measured values for September 14th, 15th, and 16th, respectively. The average predicted emissions represented 64.3% of the average modeled value during this period. The modeled values using the IPCC/CARB model are in the same order of magnitude for most of the modeled dairies. Lory et al. (2010) calculated greater emission of CH_4 using the IPCC methane emission factors than measured values. In their calculation, they also used different values for methane yield and VS destruction than the default values used in the IPCC model.

The reported values for the average measured values for September 14th, 15th, and 16th were calculated based on the average of the measured values during the period of September 14th at 2:35 PM and September 15th 2:35PM, September 15th at 4:35 PM and September 16th 4:00 PM, and September 16th at 6:00 PM and September 17th 6:00 PM, respectively. Moreover, since the time step in the model was one day, the reported modeled values for September 14th, 15th, and 16th were the average predicted values for September 14th and 15th, September 15th and 16th, and September 16th and 17th, respectively.

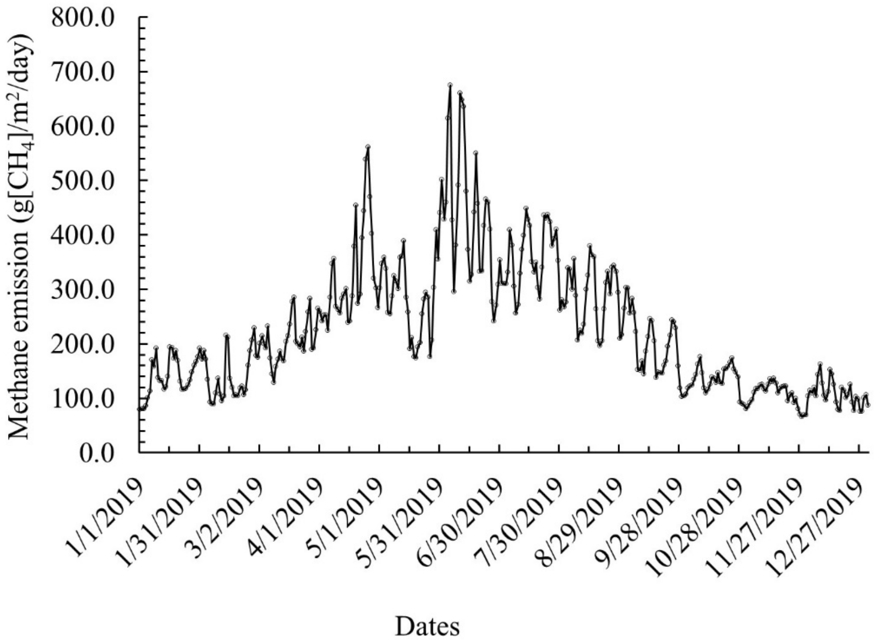

Figure 56. Predicted daily methane emission from the lagoon at Delta dairy.

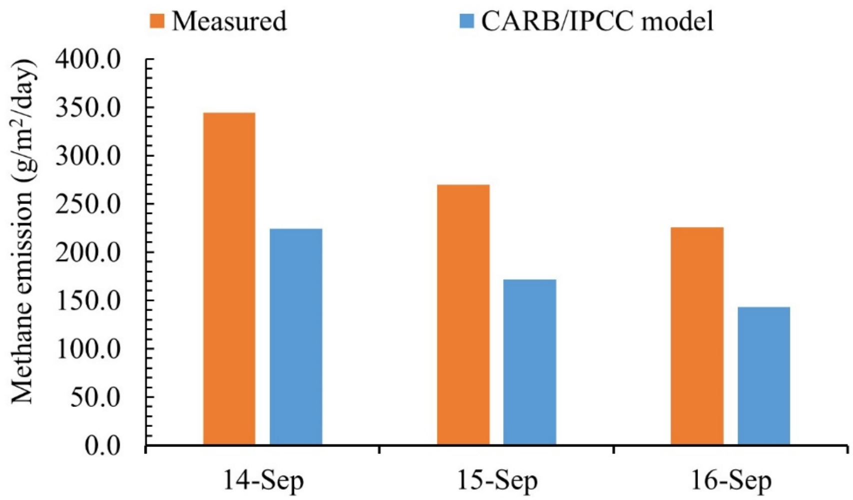

Figure 57. Measured and predicted methane emission from the lagoon at Delta dairy.

Predicted methane emissions from the settling basin at Delta dairy

The predicted daily methane emissions from the settling basin at Delta dairy using the IPCC/CARB model are shown in Figure 58. As can be seen low emission rates were predicted during January. This may be due to low temperature and the assumption that the settling basin was started in January as the farmer reported that they cleaned the settling basin once per year. The minimum, maximum, and average predicted emission rates were 0.5, 288.1, and 95.2 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the settling basin on Delta dairy are shown in Figure 59.

Since the measurements were conducted from September 18th at 12:00 PM until September 19th at 12:00 PM, the modeled value reported here is the average of values predicted for September 18th and September 19th. The modeled value for the settling basin represented 50.4% of the measured values.

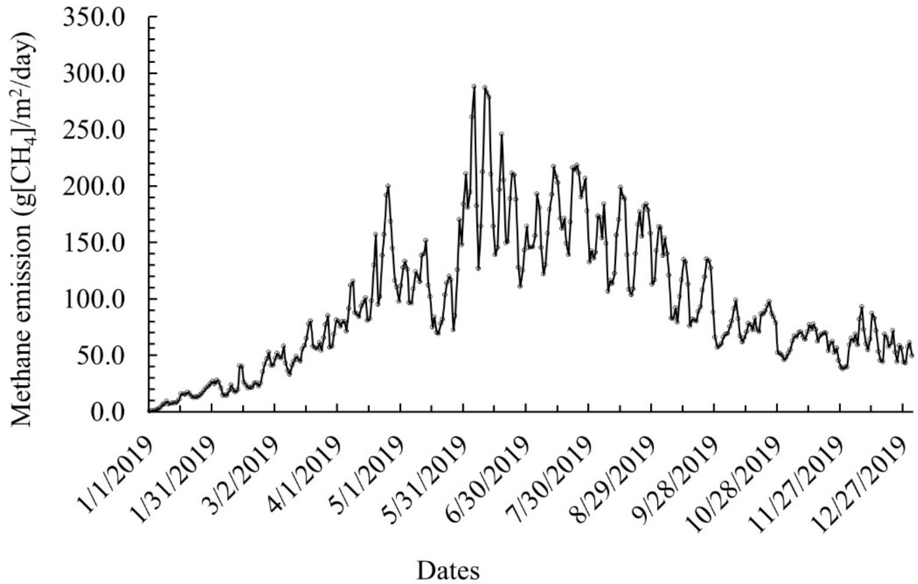

Figure 58. Predicted daily methane emission from the settling basin at Delta dairy.

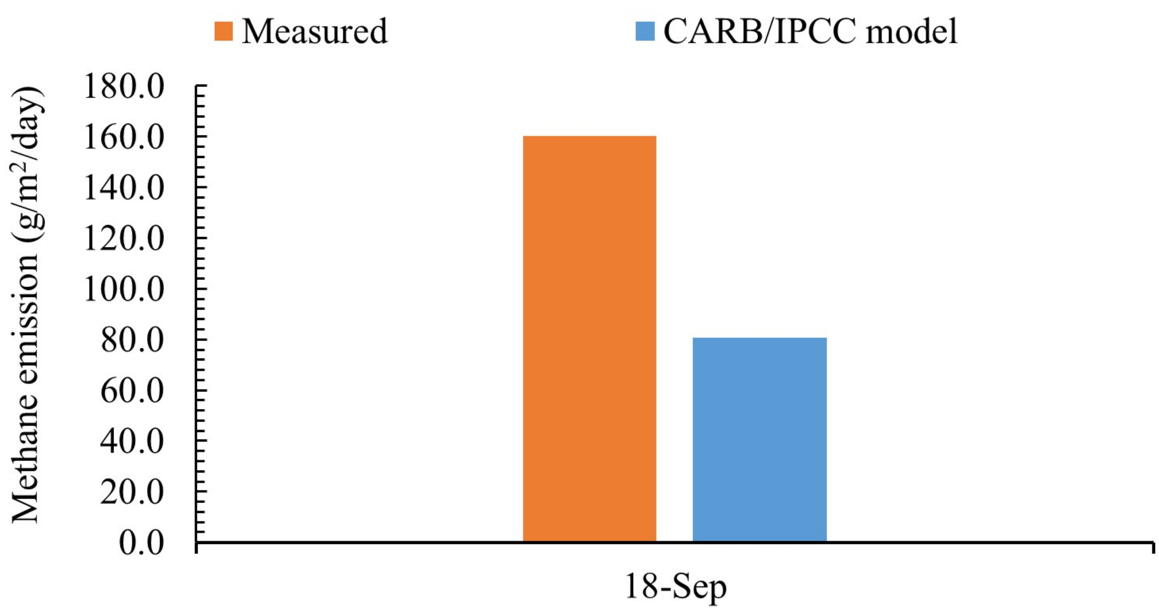

Figure 59. Measured and predicted methane emission from the settling basin at Delta dairy.

Predicted emissions from the lagoon at Echo dairy

The predicted daily methane emissions from the lagoon at Echo dairy using the IPCC/CARB model are shown in Figure 60. The minimum, maximum, and average emission rates were 11.4, 116.9, and 39.0 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the lagoon on the Echo dairy are shown in Figure 61. The modeled values for the lagoon represented 48.4%, 84.7%, 46.1% of the measured values for October 26th, 27th, and 28th, respectively. The average modeled value during this period represented 55.6% of the measured value. It should be mentioned that the reported values for the average measured values for October 26th, 27th, and 28th, were calculated based on the average of the measured values during the period of October 26th at 1:00 PM and October 27th at 13:0 PM, October 27th at 4:00 PM and October 28th at 4:00 PM, and October 28th at 5:40 PM and October 29th at 6: 10 PM, respectively. Moreover, because the time step in the model was one day, the reported modeled values for October 26th were the average predicted values for October 26th and October 27th; for October 27th was the average predicted values for October 27th and October 28th; and for October 28th was the average predicted values for October 28th and October 29th.

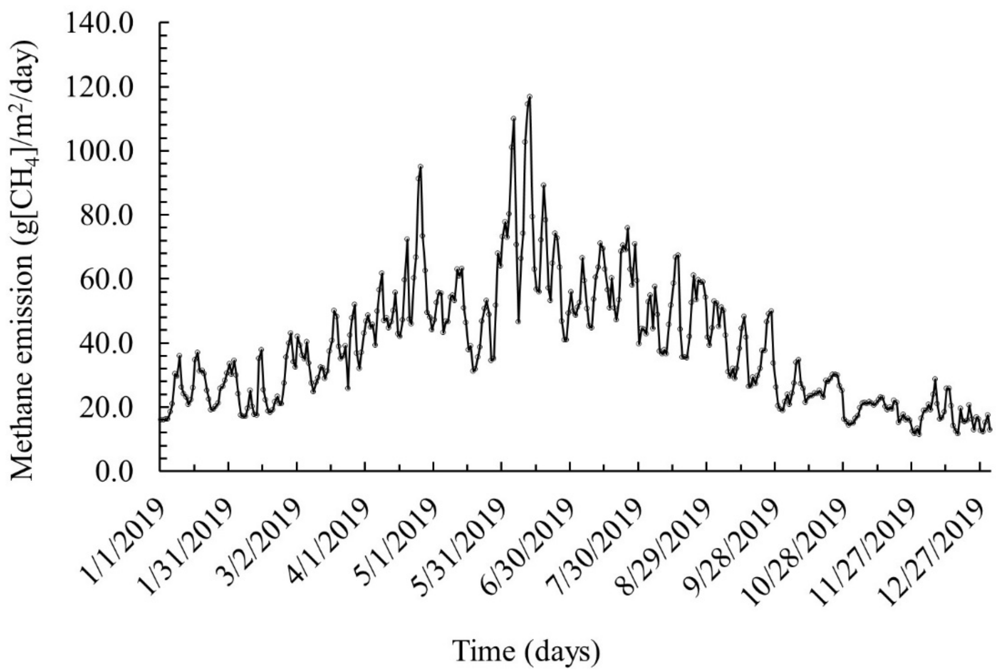

Figure 60. Predicted daily methane emission from the lagoon at Echo dairy.

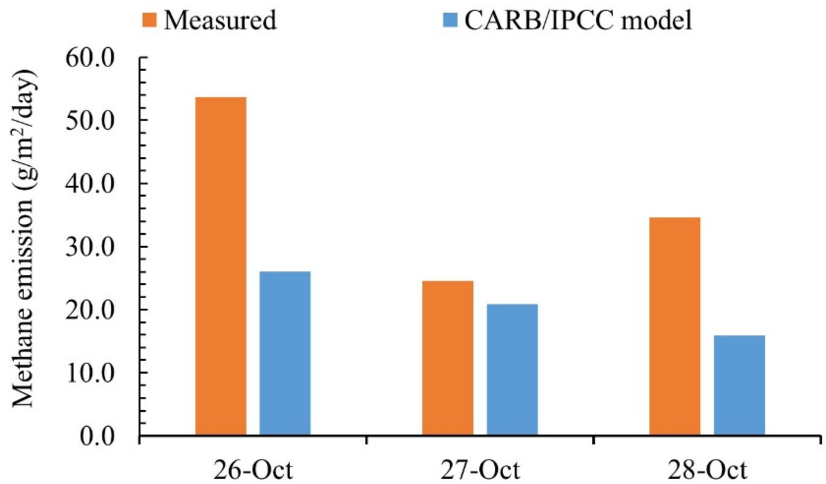

Figure 61. Measured and predicted methane emission from the lagoon at Echo dairy.

Predicted emissions from the settling basin at Echo dairy

The predicted daily methane emissions from the settling basin at Echo dairy using the IPCC/CARB model are shown in Figure 62. The maximum, and average emission rates were 168.9 and 59.1 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the settling basin at the Echo dairy are shown in Figure 63. Since the measurements were conducted from October 30th at 2:40 PM till October 31st at 2:40 PM, the modeled value reported here is the average of values predicted for October 30th and 31st. The modeled value for the settling basin represented 70.7% of the measured values. The farmer reported that he cleaned the settling basin once in February and therefore, in the model, it was assumed that the settling basin start at zero volatile organic matter.

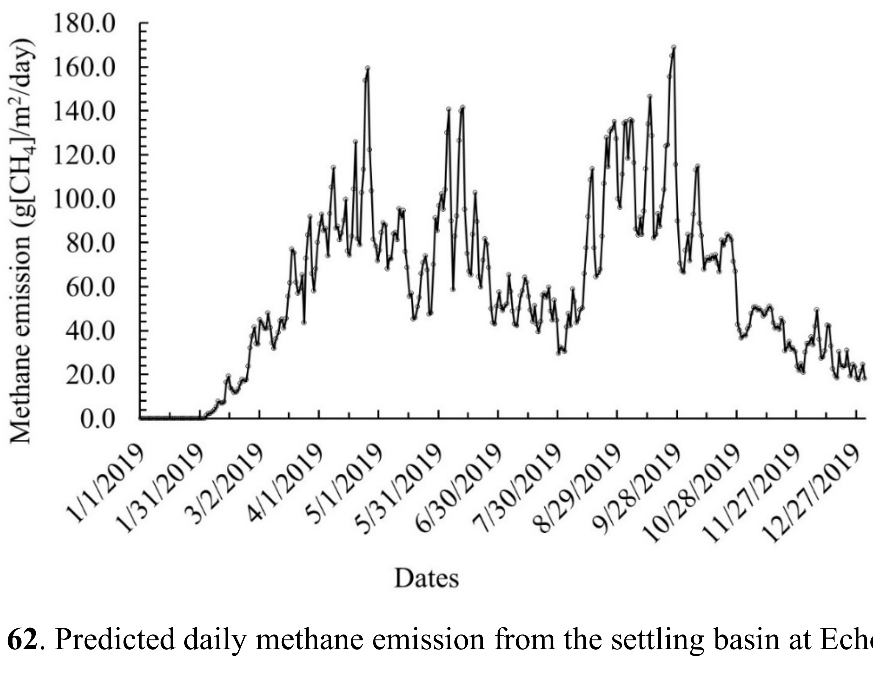

Figure 62. Predicted daily methane emission from the settling basin at Echo dairy.

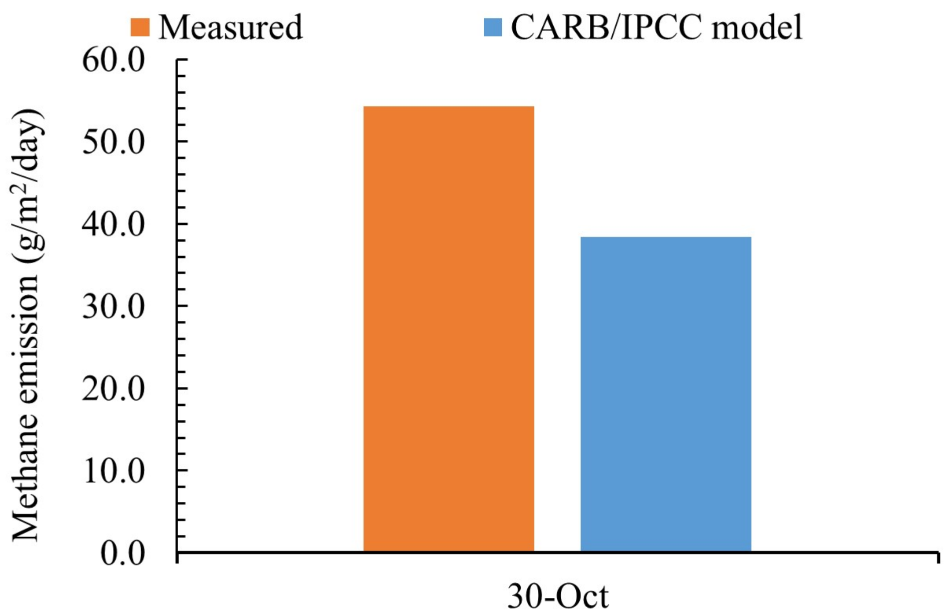

Figure 63. Measured and predicted methane emission from the settling basin at Echo dairy.

Predicted emissions from the lagoon at Foxtrot dairy

The predicted daily methane emissions from the lagoon at Foxtrot dairy using the IPCC/CARB model are shown in Figure 64. The minimum, maximum, and average emission rates were 20.3, 194.6 and 66.9 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the lagoon on the Foxtrot dairy are shown in Figure 65. The modeled values for the lagoon represented 17.9%, 25.1%, 32.6% of the measured values for September 21st, 22nd, and 23th, respectively. The average modeled methane emission rate was 25.2% of the average measured value.

The average measured values reported for September 21st, 22nd, and 23th were calculated based on the average of the measured values during the period of September 21st at 1:05 PM and September 22nd, 13:05 PM, September 22nd at 3:05 PM and September 23rd at 2:05 PM, and September 23rd at 6:05 PM and September 24th at 6:00PM, respectively. Moreover, since the time step in the model was one day, the reported modeled values for September 21st was the average predicted values for September 21st and 22nd; for September 22nd was the average predicted values for September 22nd and September 23rd; and for September 23rd was the average predicted values for September 23rd and 24th.

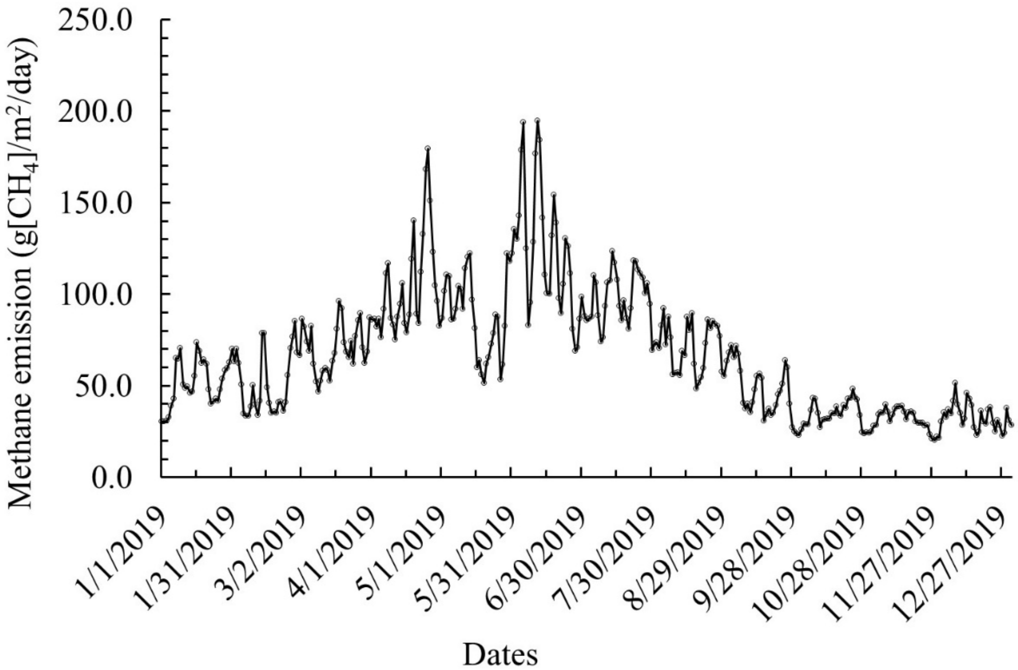

Figure 64. Predicted daily methane emission from the lagoon at Foxtrot dairy.

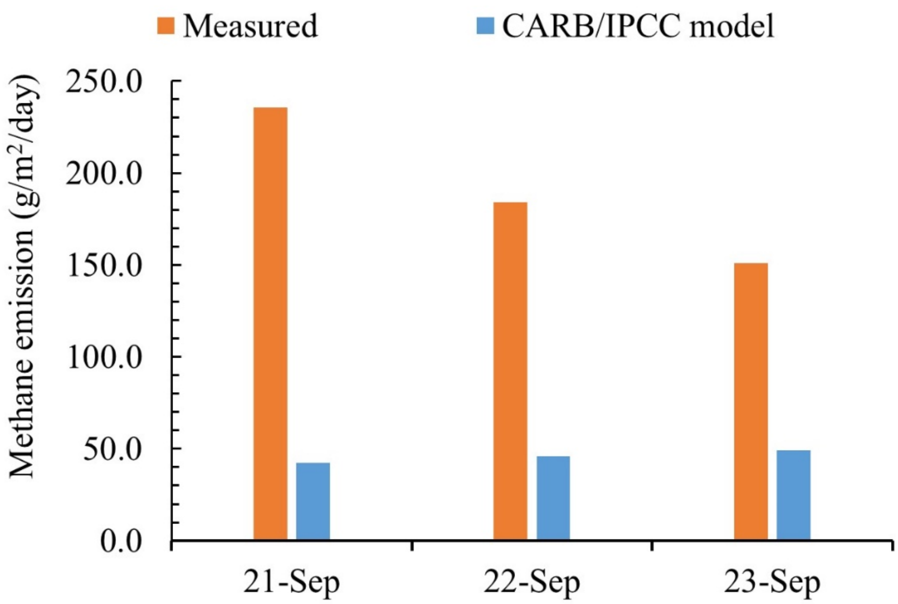

Figure 65. Measured and predicted methane emission from the lagoon at Foxtrot dairy.

Predicted emissions from the settling basin at Foxtrot dairy

The predicted daily methane emissions from the settling basin at Foxtrot dairy using the IPCC/CARB model are shown in Figure 66. As can be seen, low emissions rates were predicted in the beginning of January, May and September because the farmer reported that he cleaned the settling basin in these months. Therefore, in the model, the volatile organic matter in the settling basin was assumed to be 20% of that is available before the settling basin cleaning. This 20% was based on the reported value by the farmer. The minimum, maximum, and average emission rates were 8.8, 171.5, and 52.9 g/m^2/day, respectively. Measured and modeled emission rates of CH_4 from the settling basin on Foxtrot dairy are shown in Figure 67. Since the measurements were conducted from September 25 at 11:30 AM till September 26th at 11:30 AM, the modeled value reported here is the average of values predicted for September 25th and 26th. The modeled value for the settling basin represented 14.3% of the measured values. The low predicted emission rates might be due to the accuracy of the input values for the volatile solids removed from the settling basin and also the value of the percentage of the manure delivered to the settling basin.

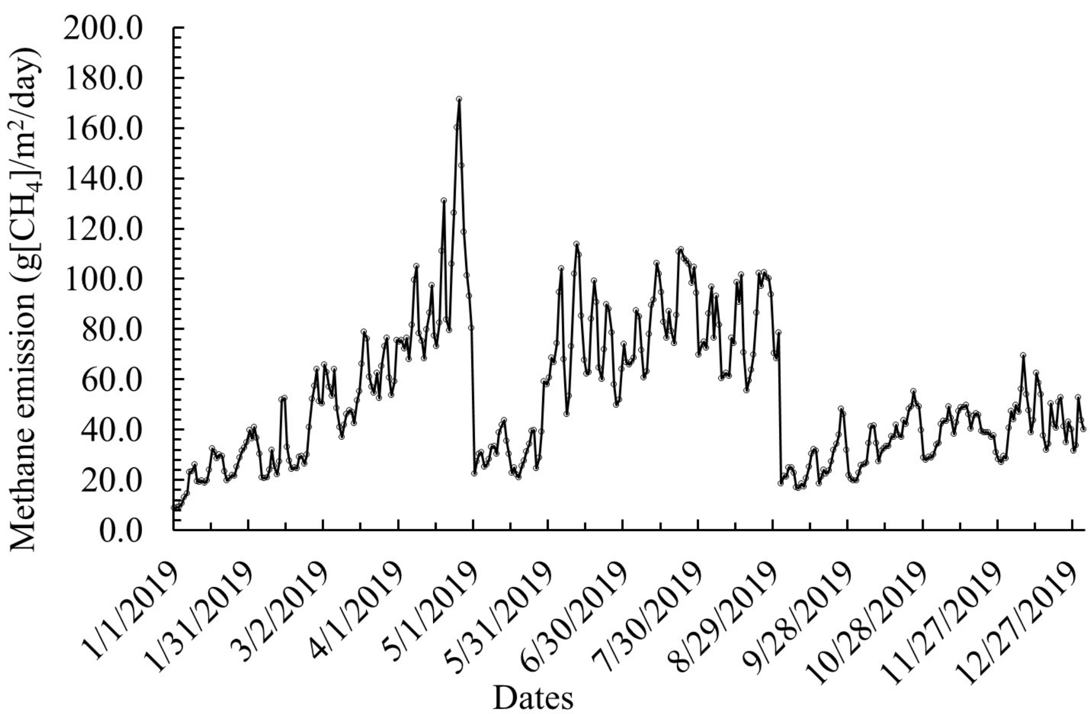

Figure 66. Predicted daily methane emission from the settling basin at Foxtrot dairy.

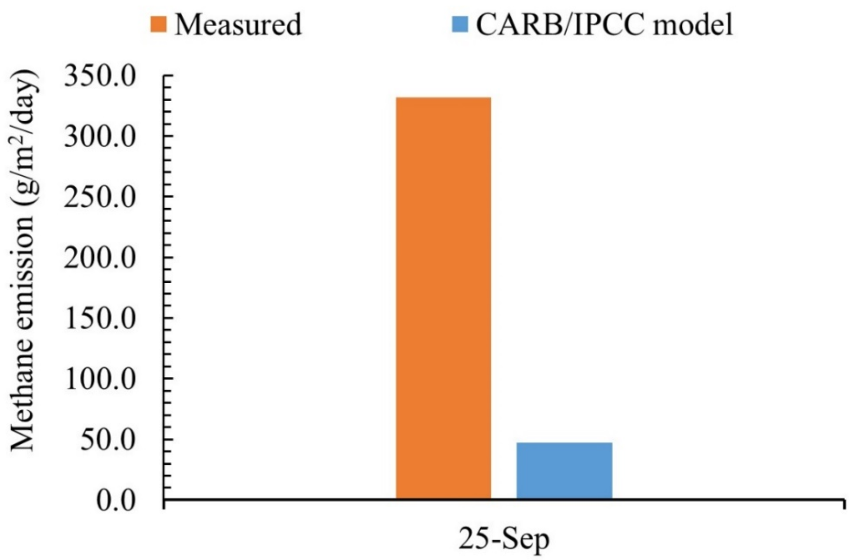

Figure 67. Measured and predicted methane emission from the settling basin at Foxtrot dairy.

Comparing emissions pre- and post-AMMP

Table 12 shows measured and corrected average methane emission rates of methane pre-AMMP and measured average methane emission rates post-AMMP from the settling basins and lagoons at the two studied dairies. It should be mentioned that the values for the emissions pre-AMMP were corrected for temperature as if they were measured at the same weather conditions that occurred during the post-AMMP measurements period. Although the lower number of animal units at Charlie dairy post-AMMP (3,475 animal units) than that pre-AMMP (3,879.5 animal units), the average measured emission of methane, per square meter of the lagoon, post-AMMP from the lagoon were higher than those pre-AMMP. The emission rates of methane were 1,054.0 and 1,475.0 g/animal unit/day, respectively for pre-AMMP and post-AMMP. This might be due to the increased amount of flushed manure delivered to the lagoon post-AMMP (from other animals not housed in the compost-bedded pack barns) or due to differences in the accumulation of volatile solids in the lagoon pre- and post-AMMP. Moreover, the differences in the emissions pre- and post-AMMP could also be attributed to the quantity and quality (VS content) of water withdrawn from the lagoon for irrigation. No information was available on the quantity and quality of the water used for irrigation pre-and post-AMMP. The farmer mentioned that the lagoon is excavated only around the corners every couple of years. However, there was no information about the exact time and amount of solid removed during each cleaning event.

For the Foxtrot dairy, the emission rates of methane from the setting basin post-AMMP were lower than those pre-AMMP. The number of animal units during the period of emission measurements post-AMMP (1,502.1 animal units) was lower than the pre-AMMP (1,797.8 animal units). The emission rates from the settling basin were 761.4 and 661.6 g/animal unit/day, respectively for pre-AMMP and post-AMMP. However, for the lagoon, they were 402.6 and 662.3 g/animal unit/day, respectively. The dairyman mentioned that solids are removed three time per year from the settling basin and no information was given on solids removal from the lagoon. It should be mentioned that the separator was fed with some of the effluent of the settling basin and the rest was delivered directly to the lagoon. The increased emissions from the lagoon, during the monitoring period, does not mean that the AMMP practices increased emissions. More long-term measurements of emissions are needed to determine the reduction of emissions by employing this AMMP practice.

The design and the operation of the mechanical separator at Foxtrot dairy should be modified. All flushed manure should first be treated with the mechanical separator prior to the delivery to the settling basin and lagoon. A processing pit may be required to process all the manure before pumping it to the separator. Modifying the system design and operation could increase the amount of solids (i.e., volatile solids) that can be averted from the settling basin and lagoon. Reducing the amount of volatile solids delivered to the settling basin and lagoon decreases the emissions of methane and other gases from them. For selected mechanical separators at California dairies, Zhang et al. (2018) found that methane production potential from screened manure was well correlated with TS and VS removal by mechanical separators. Their results showed that for a single stage separator, the VS removal ranged from 6.5% to 48.8% and the methane production potential ranged from 1.4% to 42.2%. The performance of the mechanical screen separators depended on system design (e.g., screen size and orientation), concentration of TS in flushed manure, separator operation and management (manure flow rate), and manure processing pit type and configuration.

The measured emission rates of methane in the current study are in the range reported in the literature. Grant et al. (2015) determined emissions in different seasons on two basins at a dairy in Wisconsin, and a lagoon in Indiana. The farm in Wisconsin, had a solid separator that was failing during the study. The lagoon at the dairy in Indiana received manure from a setting pit that had a weir to limit the transfer of solids to the lagoon. Concentrations of CH_4 were measured using a photoacoustic infrared absorption spectroscopy and a flame ionization gas chromatography. Emission rates were estimated using a Backward Lagrangian Stochastic model with on-site turbulence measurements. Results showed that average methane emission rates in October were 374.4 and 59.4 g/animal unit/day from the basins at the dairy in Wisconsin, and the lagoon at the dairy in Indiana. A maximum emissions rate of 9.4 and 11.04 g/m^2/hr (3,641 and 1,291 g/animal unit/day) could be measured respectively for three non-sequential days. The authors concluded that the separation of solids prior to storage reduced the emission of CH_4 per animal.

The emissions of methane from two dairies in California were estimated using three techniques during three to six days per farm in the summer of 2016 (Arndt et al., 2018). The techniques included open-path measurements with inverse dispersion modeling, vehicle measurements with tracer flux ratio method, and aircraft measurements with the closed-path method. The open-path method was used to estimate whole-facility CH_4 emissions over 13 to 14 days per farm in the winter of 2017. The emissions of CH_4 from the whole facility were similar among the three techniques. No seasonal variations in the emissions form animal housing were determined. For the first dairy, the measured emissions using the open-path technique from manure storage were 1,264 and 408 g/animal unit/day, during the summer and winter, respectively. For the second dairy, the emissions were 849 and 129 g/animal unit/day, respectively.

Methane emissions from five dry lot farms in Idaho ranged from 3.0 to 10.3 g/m^2/day; and from a freestall dairy, the emission was 12.6 g/m^2/day (Leytem el al., 2017). Based on the data presented, it was not possible to calculate the emission rates per head. Applying the Backward Lagrangian Stochastic Inverse Dispersion Technique, Leytem et al. (2012) measured the emissions from 10,000 cows in Idaho. The dairy had five ponds for storing wastewater from the freestall barns. Methane emission rates from the ponds ranged 3.6 to 54.1 g/m^2/day. The average seasonal emission rate was 0.75 kg/cow/days from the freestall and manure storages. During the summer and spring, the wastewater ponds represented 51% of the total emissions. While they represented 35% and 33% during the fall and winter, respectively.

Table 12. Measured and corrected average methane emission rates of methane pre-AMMP and measured average methane emission rates post-AMMP from the settling basins and lagoons at the two studied dairies.

Dairy		**Emission rates pre-AMMP**			**Measured emission rates post-AMMP**		
		Corrected measured emission rates (Mitloehner et al., 2019)					
		Settling basins	**Lagoons**	**Total**	**Settling basins**	**Lagoons**	**Total**
Charlie	CH_4 g/m^2/day	--	326.02		---	408.69	
	CH_4 g/animal unit/day	--	1054.0	1,054.0		1,475.0	1,475.0
Foxtrot	CH_4 g/m^2/day	456.91	137.76		331.57	189.39	
	CH_4 g/animal unit/day	761.4	402.6	1,164	661.6	662.3	1,323.9

Characteristics of manure samples

Total and volatile solids

The characteristics of manure samples collected during the emissions monitoring period are shown in Tables 13 and 14. It should be mentioned that the lagoon at Charlie dairy received manure directly from flushed feeding lanes and milking parlor. No settling basin was employed at Charlie dairy. In contrast, at Foxtrot dairy, flushed manure from the freestalls was first pumped to a settling basin where solids (especially large particles) were first removed, and the manure liquid flowed to the lagoon. As can be seen from Table 13, the pH values for the inlet of the lagoon were 7.25 and 7.13, and for the lagoon surface were 7.58 and 7.26 at Charlie and Foxtrot, respectively. The values were 9.4 and 7.85 for the solids, respectively. The TS in the lagoon inlets was 0.31% and 0.38 % at Charlie and Foxtrot, respectively. The TS of the inlet of the settling basin at Foxtrot was 0.56% that was higher than the TS in flushed manure at Charlie dairy. Although the lagoon at Charlie dairy received manure directly from feed lanes and wastewater from parlor, the TS content was relatively lower than that at Foxtrot dairy. This may be due to the greater ratio of water to flush manure to the amount of manure produced in the feed lanes at Charlie dairy. The TS contents of solids used in the emission measurements at Charlie and Foxtrot dairies were 57.26% and 12.17%, respectively. This might be due to water evaporation in the barn and the utilization of bedding materials at Charlie dairy. At Foxtrot dairy, solids were mainly fibrous materials that were larger than the opening of the mechanical separator. The TS contents in the lagoon surface were 0.18% and 0.48%, at Charlie and Foxtrot dairies, respectively. The higher TS at Charlie dairy may be due to the presence of scum layer that was present during manure sampling period. At Foxtrot dairy, the VS/TS in the selling basin and lagoon inlets were 53.62% and 39.36%, respectively. The lower VS/TS in the lagoon inlet than settling basin inlet may be due to the separation of most of fibrous materials in the settling basin and by the mechanical separator. The screened manure may contain more sand and inorganic matter than freshly flushed manure that goes to the settling basin. The VS/TS in lagoon surfaces were 30.97%, and 45.27%, at Charlie and Foxtrot dairy, respectively. The higher VS/TS at Foxtrot may be attributed to the presence of the scum layer that might contain high organic matter contents. Although some of the measured TS concentrations in the inlets of lagoon at Charlie and the setting basin at Foxtrot are typical for the flushed manure in California, others are lower than expected concentrations.

Dissolved organic carbon and nitrogen contents in liquid samples

As can be seen from Table 14, Dissolved Organic Carbon (DOC) in manure samples during the emission measurements (g/g TS) in the inlet of the lagoons at Charlie and Foxtrot dairy were similar at 0.06 g/gTS, though the separation of solids in the settling basin at Foxtrot dairy. Relatively lower DOC concentrations were determined in the lagoon surface at Foxtrot. The organic nitrogen contents in the inlet of the lagoon at Charlie dairy were higher than that at Foxtrot. Ammonium concentrations were higher in the inlet of the lagoon at Foxtrot dairy than that at Charlie dairy. This may be due to the fact that the lagoon at Charlie received freshly flushed manure and there was no settling basin. While the lagoon at Foxtrot received manure from the settling basin that could affect the mineralization of manure while manure passed through it before reaching the separator and then the lagoon. The total nitrogen contents in freshly flushed manure in the inlet of the settling basin at Foxtrot (0.11 g/g [TS]) was almost double that of the inlet of the lagoon at Charlie (0.05 g/g [TS]). This might be due to the low concentration of manure in the flushed manure at Charlie than that at Foxtrot. Generally, for both dairies, low concentrations of nitrate were determined for all samples.

Volatile fatty acids in liquid samples

The concentrations of VFAs are shown in Table 15. The concentrations of VFAs were determined as acetic acid equivalent. The total VFAs in the freshly flushed manure in the inlet of the settling basin at Foxtrot dairy (369.2 mg [acetic acid]/l) was more than the double of the concentration inlet of the lagoon at Charlie dairy (149.6 mg [acetic acid]/l). This might be due to the presence of lower amounts of manure at Charlie than that at Foxtrot dairy. The total VFAs in the lagoon inlet and separator outlet at Foxtrot dairy was 6.8, and 3.7 mg [acetic acid]/l. It should be mentioned that these samples were collected from the lagoon inlet pipe and directly from the pipe carrying screened manure after the separator. This pipe also ended up in the lagoon so the screened manure was mixed with the effluent of the settling basin. This may be the reason for the higher value of VFAs in the lagoon inlet than that in the screened manure.

Table 13. pH, and TS, and VS contents in manure samples during the emission measurements

Dairy	pH				TS (% Total)				VS (% TS)			
	SBInlet [1]	Lg Inlet[2]	Lg Sf[3]	Manure solids	SB Inlet[1]	Lg Inlet[2]	Lg Sf[3]	Manure solids	SB Inlet[1]	Lg Inlet[2]	Lg Sf[3]	Manure solids
Charlie	NA4	7.25± 0.12	7.58± 0.10	9.4± 0.08	NA	0.31± 0.07	0.18± 0.02	57.26± 4.06	NA	58.64± 5.31	30.97 ±4.87	56.11 ± 2.70
Foxtrot	7.69± 0.34	7.13± 0.08	7.26± 0.04	7.85± 0.35	0.56± 0.16	0.38± 0.04	0.48± 0.31	12.17± 1.91	53.62± 5.45	39.36± 9.88	45.27 ±9.19	87.45± 0.68

[1]SB Inlet: settling basin inlet/freshly flushed manure
[2]Lg Inlet: lagoon inlet/ freshly flushed manure at Charlie and settling basin outlet at Foxtrot
[3]Lg surface: lagoon surface water
[4] The dairy does not have a settling basin

Table 14. Dissolved Organic Carbon (DOC), and Nitrogen contents in manure samples during the emission measurements (g/g TS)

Dairy	DOC			Organic N			Ammonium N			Nitrate			Total N		
	SB Inlet	Lg Inlet	Lg Sf	S.B. Inlet	Lg Inlet	Lg Sf	SB Inlet	Lg Inlet	Lg Sf	SB Inlet	Lg Inlet	Lg Sf	SB Inlet	Lg Inlet	Lg Sf
Charlie	NA	0.06± 0.01	0.09± 0.01	NA	0.04± 0.01	0.03± 0.01	NA	0.01± 0.00	0.05± 0.01	NA	0.00± 0.00	0.01± 0.02	NA	0.05± 0.01	0.09± 0.01
Foxtrot	0.07± 0.03	0.06± 0.01	0.05± 0.00	0.03± 0.01	0.02± 0.01	0.03± 0.01	0.08± 0.02	0.07± 0.00	0.06± 0.01	0.001± 0.002	0.00±0. 00	0.00± 0.00	0.11± 0.03	0.09± 0.01	0.09± 0.02

[1]SB Inlet: settling basin inlet/freshly flushed manure

[2]Lg Inlet: lagoon inlet/ freshly flushed manure at Charlie and settling basin outlet at Foxtrot
[3]Lg surface: lagoon surface water
[4] The dairy does not have a settling basin

Table 15. VFA contents in manure samples during the emission measurements (mg [acetic acid]/l)

Dairy	**Source**	**Acetic acid**	**Propionic acid**	**Iso-butyric acid**	**Butyric acid**	**Valeric acid**	**Total VFAs**
Charlie*	Lagoon inlet	104.5±47.5	18.7±7.4	5.0±0.0	6.0±0.9	0.0±0.0	149.6±56.8
	Lagoon surface	25.5±7.4	5.0±0.0	0.0±0.0	3.3±2.6	0.0±0.0	38.3±11.3
Foxtrot	Settling basin inlet	295.5±33.5	23.4±4.1	6.4±0.7	13.6±3.9	3.4±0.2	369.2±33.3
	Lagoon inlet	5.4±2.3	0.1±0.2	0.0±0.0	0.7±0.1	0.0±0.0	6.8±2.6
	Lagoon surface	6.4±4.1	0.2±0.2	0.3±0.5	0.6±0.1	0.0±0.0	8.2±3.9
	Separator outlet	2.6±1.4	0.0±0.0	0.0±0.0	0.7±0.0	0.0±0.0	3.7±1.3

* Samples were analyzed by Dairy One laboratory, NY; other samples were analyzed at UC Davis

Manure solids collected from the compost-bedded pack barn

The composition of manure solids collected from the compost-bedded pack barn and used in the emissions measurements are shown in Table 16. Nutrients and elemental composition of manure solids (removed from compost-bedded pack barn) used in the emission measurement at Charlie dairy (values are dry basis). As can be seen, total organic carbon and total nitrogen contents were 27.42% and 2.26%, respectively. The C/N ratio was 12.85. The solids also contained macro- and micronutrients. These values lie in the ranges reported by Black et al. (2013) for manure compost collected from 47 compost-bedded pack barns in Kentucky (Table 17).

Table 16. Nutrients and elemental composition of manure solids (removed from compost-bedded pack barn) used in the emission measurement at Charlie dairy (values are dry basis).

Components and elements	**Concentration**
Total organic carbon, %	27.42±1.81
Dissolved OC, mg/kg	2016.16±263.78
Total nitrogen, %	2.28±0.17
Organic nitrogen, %	2.26±0.17
C/N	12.85±0.34
Ammonium, %	0.02±0.00
Nitrate, %	<0.0001
Urea, mg[N]/kg	251.25±46.84
Phosphorous, %	0.70±0.03
Potassium, %	3.20±0.24
Sulfur, %	0.54±0.03
Calcium, %	2.61±0.26
Magnesium, %	1.05±0.08
Sodium, %	0.79±0.06
Zinc, mg/kg	167.40±18.91
Iron, mg/kg	6386.30±501.51
Manganese, mg/kg	189.23±18.52
Copper, mg/kg	26.65±8.70
Boron, mg/kg	80.03±4.48

Table 17. Characteristics of manure compost collected from 47 compost bedded pack barns in Kentucky (Black et al., 2013).

Component	Range	Mean ± STD
Moisture, %	27.0-70.0	56.1±12.4
C, %	20.9-47.1	41.8±5.1
N, %	1.0-2.9	1.7±0.5
C: N	11.3-43.2	26.7±7.8
P, %	0.2-0.9	0.4±0.2
K, %	0.4-3.0	1.3±0.5
Ca, %	0.6-22.3	2.0±3.2
Mg, %	0.2-1.3	0.5±0.2
Zn, mg/kg	36.5-217.9	110.4±45.9
Cu, mg/kg	7.8-61.9	27.8±15.5
Mn, mg/kg	110.8-818.9	222.4±135.0
Fe, mg/kg	471.4-9,077.7	2,779.7±2,339.4

Farmers Experiences with the Alternative Manure Management Technologies

One of the questions of the dairy surveys in the present study was: What does the dairy farmer think of the alternative manure management technology?

For Charlie dairy, the farmer indicated that they had a learning curve to work with the bed-pack compost barns. He also indicated that the system worked well. The cow comfort and improvement in manure handing have been positive.

The owner of Foxtrot dairy indicated that they are very satisfied with the AMMP project. He indicated that installing the mechanical separator allowed them to separate more solids from manure and produce more high-quality compost. Prior to the installation of the concrete slab, the machines (e.g., front loader) used to transport the compost were digging deep and large holes that could be filled with water and causing problems during the compost process. After installing the slab, big improvements were achieved in the composting process. The produced compost is now applied to grazing land. Excess compost has been sold to other farms. The farmer said that the funding from CDFA for the AMMP project enabled him to continue his operation in a sustainable way.

Recommendations for future research needs

The emissions reported here were measured for a few days on lagoons, settling basin and manure solids. More research is needed to determine the emissions of methane and other gases for longer period of times during different seasons. It would allow researchers to determine the effect of weather conditions and different manure management on emissions. When two or more AMMP technologies are applied, like at Foxtrot dairy wherein pasture and mechanical separators are employed, there is a need to determine the effect of each AMMP technology independently on the emissions. Moreover, the measured emissions on the lagoons were conducted at three different locations and on one location at the settling basin. The emissions may vary from one location to another in the lagoons and settling basin. A long term, cross seasonal measurement of emissions, at different locations in the lagoons and settling basin are needed to determine the seasonal variation of emissions. These measurements could also be used to validate emission models. More research is needed to determine the seasonal variations of manure characteristics and specify the factors affect the variability in manure characteristics.

In the models, we used the values provided by the dairymen for the manure percentages that were delivered to lagoons. These percentages were based on the dairyman experiences. More research is needed to determine the exact amounts of manure delivered to manure storage facilities (i.e., lagoon, settling basin, and weeping wall). This is because the fraction of manure delivered to these facilities significantly affect the values predicted by the model. Moreover, most of the dairies do not have exact dates for cleaning the settling basin. That resulted in the model using approximate dates based on the information provided by the farmers. In addition, the IPCC/CARB model currently does not include the effect of the withdrawal of water from the lagoon for irrigation purposes. The amount of water withdrawn from lagoons for irrigation is generally not recorded by farmers. More research is needed to model the effect of water withdrawal from lagoons on the emissions. The effect of water withdrawal may be minimal for dairy farms that withdraw water from lagoon surface. It may significantly affect the emissions for the dairies that use mixers during water withdrawal.

There is also a need to determine the amounts of the accumulated volatile solids between different cleaning events, and volatile solids in the lagoons and settling basin, that may undergo anaerobic degradation and produce methane. More research is needed to determine the residence times of manure solids in the settling basins and lagoons and their effect on the emissions of different gases. The effect of the cleaning of lagoons and settling basins on volatile solids accumulation, and the emissions of different gases, needs to be determined. For all modeled sites, the fraction of manure that is delivered to storage (settling basin, lagoon, or weeping wall) was obtained from the survey where the farmers reported the values based on their experiences. Although the estimate of this fraction could be close to the real value, the amount of manure delivered to manure storages should be precisely determined. The modeled emissions from the lagoons and settling basin varies among the studied dairies. While some of the modeled emissions were comparable to the measured ones, others were not comparable. This might be due to the assumptions used for the amounts of manure delivered to the settling basin and lagoon. More accurate determination of the manure delivered to storages should be carried out.

The DairyGEM and DNDC models are good tools and easy to use with training, to predict emissions from dairy farms. However, it may not be possible to use them for every dairy farm in California because the dairies have different manure management systems, manure characteristics, weather conditions, and other parameters that are not easy to change by users to match the conditions on each dairy. For example, it is not easy for users to modify the models to include settling basins and/or different AMMP technologies implemented prior to entering lagoons, without the need for substantial modifications of the model codes. Alternatively, a new computer model could be developed for predicting the emissions from different emission source at dairies. The new model should include different sources of emissions (manure processing pits, settling basins, and lagoons) and different AMMP technologies that affect the quantity and quality of manure delivered to each manure storage facility on the dairies. The effect of amounts and characteristics of bedding materials delivered to manure storages need to be determined to improve the prediction of methane emissions by IPCC/CARB model.

Summary/conclusion

The emissions of methane, nitrous oxide, ammonia, and hydrogen sulfide were measured from the manure lagoons at two California dairies, each for at least three days. Both dairies utilized alternative manure management program (AMMP) practices. As their respective alternative manure management program (AMMP) practice, the first dairy (Charlie) employed a compost-bedded pack barn for milking cows and the second dairy (Foxtrot) used both a mechanical separator to treat flushed manure and grazed milking cows on pasture for eight months per year. At Foxtrot dairy, emissions were measured from the settling basin for one day and from solid separated from the mechanical separator for one day. The emissions from manure collected from the compost-bedded pack barn were measured for two days. Also studied was the utility of the Intergovernmental Panel on Climate Change (IPCC)/CARB, Dairy Gas Emissions Model (DairyGEM), and Manure Denitrification-Decomposition (Manure-DNDC) models, on predicting the emissions from the lagoon on the first dairy and from the settling basin and lagoon on the second dairy and another four dairies under complementary project (agreement # RD-17RD017).

The measured methane emissions from the lagoons on both dairies post-AMMP practices were relatively higher than those measured pre-AMMP practices. This might be due to several factors. First, though there was a relatively constant number of cows on the studied dairies over time between pre- and post AMMP, amounts of manure delivered to the lagoon in both dairies pre- and post- AMMP practices were not known. For Charlie dairy, cows were housed in open corrals pre-AMMP. The amount of manure deposited in the corrals might be equal to the amounts of manure deposited in the compost-bedded barns. For Foxtrot, the farmer reported that, pre-AMMP, cows were grazed for half of the time during summer. He also reported that post-AMMP the grazing time increased to eight months per year. Knowing the amount of manure delivered to the lagoon on Charlie dairy and the setting basin and lagoon on Foxtrot dairy, would have been helpful to determine the factor affecting the emissions. The amount of manure delivered to manure storages needs to be determined pre- and post-AMMP. Secondly, the dynamics of the microbial activity and yields and rates of methane production in lagoons and settling basins depends on flow rates and characteristics of manure, and cleaning of the lagoon. The information and data collected in this study for both dairies was not enough to compare the microbial activity pre- and post-AMMP. Thirdly, the quantity and quality (i.e., VS contents and biodegradability) of manure withdrawn from the lagoon at both dairies was not well known, when lagoon water was used for irrigation. Removing small amounts of lagoon water and VS with high biodegradability during irrigation, may increase the emissions from lagoons because more volatile solids can undergo microbial conversion into methane. Fourthly, at Foxtrot dairy, the mechanical separator was not properly applied. Ideally, flushed manure is delivered to a processing pit wherein manure is mixed and then pumped to the separator. The separated manure (i.e., liquid fraction) is then delivered directly to the lagoon or to a settling basin and then to a lagoon. However, at Foxtrot, flushed manure was delivered to the settling basin first and then an unknown part of it was fed to the mechanical separator. Liquid manure after the separator was delivered to the lagoon. Moreover, since not all manure was treated by the separator, the lagoon received manure without passing over the mechanical separator. This operational and management issue needs to be modified to increase the effectiveness of the system in reducing the emissions from the lagoon.

The emissions from the settling basin at Foxtrot dairy post- versus pre-AMMP was lower. This might be due to the increased grazing time or the removal of more solids during the cleaning of settling basin post-AMMP versus pre-AMMP. However, the summation of emissions from both the settling basin and lagoon post- versus pre AMMP was higher.

Although there were higher methane emissions post-AMMP application, that does not suggest that these practices are not effective. The studied AMMP practices in this project should reduce the emissions from the lagoon because these practices divert significant amounts of volatile solids from the settling basin and lagoons, that would otherwise undergo biological conversion into methane. The design and the operation of the mechanical separator, at Foxtrot dairy, should be modified. All flushed manure should first be treated with the mechanical separator prior to the delivery to the settling basin and lagoon. A processing pit may be required to process all the manure before pumping it to the separator. Modifying the system design and operation could increase the removal of volatile solids delivered to the settling basin and lagoon, which can result in decreasing the emissions of methane and other gases from them.

The DairyGEM and Manure-DNDC models need a major model modification to be applicable for multiple stages in manure storage (i.e. settling basin and lagoon as separate emission sources) and manure processing using different AMMP technologies. Therefore, the IPCC/CARB model was used to predict the emissions from the lagoons and settling basins. The agreement between predicted- and measured emissions of methane using the IPCC/CARB varies substantially among the studied dairies depending on the applied AMMP practices and other farm practices, such as the amount of manure organic matter that is delivered to the settling basins and lagoons. More accurate determinations of the amounts and characteristics of manure, delivered and retained to the settling basins and lagoons, are needed to improve the prediction accuracy of methane using the IPCC/CARB model. The effect of biodegradability and degradation kinetics of manure delivered to the settling basin and then to the lagoons, needs to be included in the IPCC/CARB model. Moreover, there is a need to determine the amount and characteristics of bedding materials that are delivered to manure storage.

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Appendix

Dairy Farm Questionnaire: Post-AMMP

1. What is number of lactating, and dry cows; heifers, and calves?
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2. Please describe the operational details of the AMMP technology? What is your evaluation of the technology?
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3. What is the operational time of the AMMP technology (hour per day)?
   ………………………………………………………………………………………
4. What is the electricity consumption by the AMMP technology (kWh/day)?
   ………………………………………………………………………………………….
5. What is the average milk yield, protein and fat content?
   …………………………………………………………………..……………………..
6. Describe barns and corrals? What are dimensions of each (barn and corrals)?
   ………………………………………………………………………………………
   …………………………………………………………………………………………
   ……………………………………………………………………………….
7. What do you feed your various animal types? Can you provide your rations?
   ………………………………………………………………………………………
   …………………………………………………………………………………………
   ……………………………………………………………………………….
8. Do you use crude protein and energy supplements in the feed? At what rate?
   ………………………………………………………………………………………
9. Do you use sulfur feeding adjustment? If so, at what rate?
   ……………………………………………………………………………………..
10. What is the approximate amount of manure entering the lagoon versus staying in corrals?
    ……………………………………………………………………………………..
11. How often do you flush the freestall?

……………………………………………………………………………………..

12. What is the type of bedding material used and often do you re-apply bedding to cows?
    ……………………………………………………………………………………..

13. What do you use for manure flushing (fresh water, or lagoon water)? What is the amount of water used?

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14. What are the dimensions (capacity) of lagoon and settling basin?

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15. How long is the storage time of manure in lagoon?

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16. How frequent do you remove manure (including cleaning) from the lagoon and settling basin? What is the fraction of manure removed every time?

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17. How are manure solids handled and processed?

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18. What is the diesel consumption in the management of manure solids (gal/day)?

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19. Do you export manure from farm? In what form?

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