Final Report

October 8, 2021

Benchmarking of Post-AMMP Dairy Emissions and Prediction of Related Long-term Airshed Effects

Principal Investigator:
Frank Mitloehner
Department of Animal Science
2151 Meyer Hall
University of California, Davis
One Shields Avenue
Davis, CA 95616

Co-Principal Investigator:
Mike Kleeman
Department of Civil and Environmental Engineering
University of California
Davis, CA 95616

Prepared for:

State of California Air Resources Board
Research Division
PO Box 2815
Sacramento CA 95812

Disclaimer

The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgments

We would like to express our profound gratitude for the support that we received from many organizations and individuals, particularly the California Air Resources Board and the managers and workers of the dairies studied.

The data collection and analysis described in this report were partially conducted by graduate students, postdoctoral scholars, and research scientists with guidance from their faculty mentors. In several cases, these students and postdocs are the lead authors of individual chapters that will be submitted for publication in peer-reviewed journals. The student, postdoctoral scholar, specialist, and research scientist team consisted of the following individuals:

Ali Akherati, PhD, Postdoctoral Scholar, Civil and Environmental Engineering Department, UC Davis

Jia Jang, PhD, Postdoctoral Scholar, Civil and Environmental Engineering Department, UC Davis

Sharissa Kathleen Anderson, Jr Specialists, Animal Science Department, UC Davis

Hamed El Mashad, PhD, Staff Research Associate, Biological and Agricultural Engineering Department, UC Davis

Matthew L Klein, PhD student, Animal Science Department, UC Davis

Shule Liu, Postdoctoral Scholar, Animal Science Department, UC Davis

Yuee Pan, Staff Research Associate, Animal Science Department, UC Davis

Yongjing Zhao, PhD, Project Scientist, Air Quality Research Center, UC Davis

Table of Contents

List of Figures

List of Tables

Abstract

California is the national leader of milk production and also a considerable emitter of greenhouse gases (GHG). The methane emissions from the dairy sector in California was estimated, in 2013, to be 17.69 million metric tons of carbon dioxide equivalent ($MMTCO_2e$). Methane emissions from dairy manure and enteric fermentation represented nearly half of all CH_4 emissions in California (39.30 $MMTCO_2e$), with dairy manure accounting for 25% (9.88 $MMTCO_2e$), and enteric fermentation accounting for 20% (7.81 $MMTCO_2e$). The majority of dairy farms in California utilize manure lagoons, in which organic matter in manure undergoes a biochemical degradation process that creates CH_4. Anaerobic digesters, which mitigate CH_4 emissions and produce bioenergy in the form of biogas, have been installed on 1.3% of dairy farms in the state, 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 CH_4 emissions on California dairies. These technologies need to be evaluated with respect to reducing the emission of different gases. There is a need to understand and quantify the emissions of CH_4 and other gases on dairies that have installed AMMP practices and to compare those Post- versus Pre-emission measurements that were also conducted by our lab (funded by California Department of Food and Agriculture (CDFA)). The present project aimed at addressing the research needs established by CARB and other agencies to evaluate the effectiveness of AMMP practices on the emissions of GHG and other criteria pollutants and their effect of airshed wide ozone and $PM_{2.5}$ emissions. A companion grant to the present application, funded by CDFA, provided the basis for pre-AMMP installation gas emission monitoring on six commercial dairies, while the present study focused on the monitoring of the emissions at four dairies after installation of AMMP practices. Finally, a third complementary project was funded by CARB (agreement # 18ISD025 35C10), monitoring the emissions measured at two dairies Post application of AMMP practices. The specific objectives of the present study were:

1. Conduct emissions measurements on four selected dairies Post application of AMMP practices.
2. Apply regional chemical transport models to determine the effect of AMMP emissions on ozone and $PM_{2.5}$ concentrations in the San Joaquin Valley (SJV) in the coming years.
3. Analyze, report, and disseminate project results and findings. Recommendations will be formulated for dairy manure management practices, future research, and potential policy considerations.

In the present project, the emissions of methane (CH_4), ammonia (NH_3), nitros oxide (N_2O), and hydrogen sulfide (H_2S) were measured on four dairies that employed AMMP practices. The first dairy (study name Alpha) used a mechanical separator. The second dairy (study name Bravo) used a vacuum truck for scraping of manure. The vacuum manure was then dewatered using a screw press. The third dairy (study name Delta) used a vacuum truck for manure scraping for 120 days per year. The scraped manure was then sun dried on a cement pad. The fourth dairy (study name Echo) employed a weeping wall.

Surprisingly, the measured CH_4 emissions from the lagoons at Alpha, Delta, and Echo Post-AMMP practices were relatively higher than those measured Pre-AMMP practices. The emissions from the lagoon at Bravo Post-AMMP were (non-significantly) lower than that Pre-AMMP. However, these results of these short-term measurements do not suggest that the studied AMMP practices were not effective. The studied AMMP practices were theoretically expected to reduce emissions from manure lagoons, as they divert significant amounts of volatile solids that have undergone microbial conversion to produce CH_4 in settling basins and lagoons. The higher methane emissions determined Post-AMMP may be due to: 1) unknown amounts of manure delivered to the lagoon in dairies Pre- and Post- AMMP practices; 2) the change of the lagoon microbial dynamics based on flow rates and characteristics of manure that may change from one year to another, 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 was used for irrigation. The differences in the emissions could also be due to the improper execution of the AMMP. At Alpha dairy, the mechanical separator was not operated everyday (though it was operated every day during the monitoring period) due to the high energy consumption of the system. At Echo dairy, a weeping wall with one cell was installed and the settling basin was used during drying and emptying of the weeping wall. At least one more cell should be installed so that the two cells could be employed alternately and no manure would need to be stored in the settling basin. Moreover, more research is needed for a long term monitoring of the emissions and to determine the best operation and management procedures for applying the AMMP practices.

Modeling efforts that predicted the effects of AMMPs on air quality in the future San Joaquin Valley were configured in a way that acknowledged the uncertainty in the emissions associated with AMMPs based on different technologies. Limiting cases were designed to compare how a Perfect AMMP that achieved 100% control of all emissions from dairy waste and how a widespread Biogas Digester scenario would change air quality in the SJV. The specific control technology used in the Perfect AMMP is not specified. Both limiting scenarios were evaluated in a future Business as Usual (BAU) atmosphere and a future Low Carbon Energy atmosphere. Two future scenarios were considered to fully explore the possible future chemical regimes that determine how efficiently pollutants such as ozone (O_3) and airborne particulate matter with diameter smaller than 2.5 µm ($PM_{2.5}$) form from precursor emissions. The results show that dairy waste emissions make small contributions to future O_3 mixing ratios (<0.6 ppb) and secondary $PM_{2.5}$ concentrations (<0.2 $\mu g\ m^{-3}$). Primary dust emissions from dairy freestall barns and adjacent drylot corrals may present an opportunity for future air quality improvements if AMMPs employ technologies to reduce dust emissions.

Complementary modeling studies were also conducted to evaluate changes to air quality under a scenario of widespread implementation of dairy digesters to produce biogas that is then burned to generate electricity on the farm. This scenario represents the CH_4 mitigation strategy with the greatest potential for negative impact on air quality in the SJV due to the NOx and PM emissions that would be released by the biogas combustion process. Even in this limiting biogas scenario, changes to ambient O_3 and $PM_{2.5}$ concentrations were minor in both the BAU atmosphere and the Low Carbon Energy atmosphere. Other biogas uses such as upgrading for transportation fuel or upgrading to pipeline-quality biomethane would have even lower impact on ambient air quality.

The results of the modeling study suggest that all of the GHG mitigation strategies under consideration for dairy waste will have minor impacts on O_3 and $PM_{2.5}$ concentrations in the future San Joaquin Valley. The optimal control strategy for dairy waste can therefore be selected based on other considerations such as GHG reduction effectiveness, cost, ease of implementation, and secondary environmental impacts.

Executive Summary

The dairy industry represents California's largest agricultural commodity generating approximately $6.3 billion dollars out of a total $50 billion in agricultural production in 2019. However, methane (CH_4) emissions from dairy manure account for 25% of the 118 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) that was the total CH_4 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 CH_4 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 CH_4 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 the present project were to; (1) conduct emission measurements for selected dairy Post-AMMP installation practices; (2) apply regional chemical transport models to determine the effect of AMMP emissions on airshed wide ozone and $PM_{2.5}$ emissions in the coming years; and (3) analyze, report, and disseminate project results and findings to regulatory agencies, and stakeholders.

In the present project, the emissions of methane (CH_4), ammonia (NH_3), nitros oxide (N_2O), and hydrogen sulfide (H_2S) were measured on four dairies that employed AMMP practices. The first dairy (study name Alpha) used a mechanical separator. The second dairy (study name Bravo) used a vacuum truck for scraping of manure. The vacuumed manure was then dewatered using a screw press. The third dairy (study name Delta) used a vacuum truck for manure scraping for 120 days per year. The scraped manure was then sun dried on a cement pad. The fourth dairy (study name Echo) employed a weeping wall. The separation and then sun drying of manure solids may reduce the emissions that could be produced if the solids would have been stored in lagoons.

The average emissions rates were determined as follows:

Table 1. Average emission rates of CH_4, NH_3, and N_2O from lagoons and settling basins on the surveyed dairies

Dairy	Emissions from lagoon			Emissions from settling basin		
	CH_4 (g/m^2/hr)	NH_3 (g/m^2/hr)	N_2O (mg/m^2/hr)	CH_4 (g/m^2/hr)	NH_3 (g/m^2/hr)	N_2O (mg/m^2/hr)
Alpha	20.74	0.16	23.67	20.80	0.15	40.15
Bravo	1.78	0.02	1.56	2.53	0.02	1.13
Delta	11.09	0.27	3.95	6.67	0.18	0.12
Echo	1.70	0.11	2.35	2.26	0.01	1.17

Surprisingly, the measured CH_4 emissions from the lagoons at Alpha, Delta, and Echo Post-AMMP practices were relatively higher than those measured pre-AMMP practices. The emissions from the lagoon at Bravo Post-AMMP were (non-significantly) lower than that Pre-AMMP. These results do not suggest that AMMP practices were not effective. The studied AMMP practices were expected to reduce emissions from manure lagoons, as they divert significant amounts of volatile solids that would have undergone microbial conversion to produce CH_4 in settling basins and lagoons. The higher CH_4 emissions 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; 3) the unknown quantity and quality (i.e., organic matter contents) of manure withdrawn from the lagoon when lagoon water is used for irrigation; and 4) the improper design and operation of the AMMP practices in Alpha and Echo facilities. At Alpha dairy, the mechanical separator was not operated everyday (though it was operated every day during the monitoring period) due to the high energy consumption by the system. At Echo dairy, a weeping wall with one cell was installed and the settling basin was used during drying and emptying of the weeping wall. At least one more cell should be installed so that the two cells could be employed alternately and no manure could be treated by the settling basin. 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 lagoons. A comprehensive dairy emissions model is needed to compare different dairies operated under different management procedures and employed different AMMP practices. Although there are available models such as the Dairy Gas Emissions Model (DairyGEM) (https://www.ars.usda.gov/) and Manure-DNDC (https://www.dndc.sr.unh.edu/), they need modification before they can be used to predict the emissions from California Dairies.

Modeling efforts that predicted the effects of AMMPs on air quality in the future San Joaquin Valley were configured in a way that acknowledged the uncertainty in the emissions associated with AMMPs. Limiting cases were designed to compare how a Perfect AMMP that achieved

100% control of all emissions from dairy waste and how a widespread Biogas Digester scenario would change air quality in the SJV. The specific control technology used in the Perfect AMMP is not specified, but it was assumed to control all Volatile Organic Compounds (VOC), NH_3, and PM emissions from dairy waste.

Both the Perfect AMMP and the Biogas Digester scenarios were evaluated in a future Business as Usual (BAU) atmosphere and a future Low Carbon Energy atmosphere. Two future background atmospheres were considered to fully explore the possible future chemical regimes that determine how efficiently pollutants such as ozone (O_3) and airborne particulate matter with diameter smaller than 2.5 µm ($PM_{2.5}$) form from precursor emissions. Simulations were conducted across a ten-year window to fully consider the year-to-year variability associated with the El Nino Southern Oscillation (ENSO). All future conditions were downscaled from a global climate model (GCM) under the Representative Concentration Pathway (RCP) 8.5. Future baseline emissions were projected from present-day emissions inventories prepared by CARB using the energy economic model CA-TIMES coupled with the criteria pollutant emissions model CA-REMARQUE.

The results of the modeling exercises show that dairy waste emissions make small contributions to future O_3 mixing ratios (<0.6 ppb) and secondary $PM_{2.5}$ concentrations (<0.2 $\mu g\ m^{-3}$). Primary dust emissions from dairy freestall barns and adjacent drylot corrals may present an opportunity for future air quality improvements if AMMPs employ technologies to reduce dust emissions.

Complimentary modeling studies were also conducted to evaluate changes to air quality under a scenario of widespread implementation of dairy digesters to produce biogas that is then burned to generate electricity on the farm. This scenario represents the methane mitigation strategy with the greatest potential for negative impact on air quality in the SJV due to the NOx and PM emissions that would be released by the biogas combustion process. Even in this limiting biogas scenario, changes to ambient O_3 and $PM_{2.5}$ concentrations were minor in both the BAU atmosphere and the Low Carbon Energy atmosphere. The model results indicated that the chemical regime of the summer atmosphere changed from VOC-limited under the BAU scenario to NOx-limited under the low carbon energy scenario. Additional NOx emissions from biogas combustion therefore lowered O_3 in the BAU scenario but increased O_3 mixing ratios in the low carbon energy scenario. Despite these interesting chemistry dynamics, changes to ambient O_3 and $PM_{2.5}$ concentrations were minor under the biogas scenario in both the BAU atmosphere and the Low Carbon Energy atmosphere.

The overall results of the modeling study suggest that all of the GHG mitigation strategies under consideration for dairy waste will have minor impacts on O_3 and $PM_{2.5}$ concentrations in the future San Joaquin Valley. The optimal control strategy for dairy waste can therefore be selected based on other considerations such as GHG reduction effectiveness, cost, ease of implementation, and secondary environmental impacts.

1 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) required 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 $50 billion generated from all agricultural production in the state (CDFA, 2019). There were 1,331 dairies in California in 2017, with an average of 1,304 cows per dairy (CDFA, 2018). According to CARB (2015), the CH_4 emissions from California was estimated to be 39.30 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) in 2013. Methane emissions from dairy manure and enteric fermentation represented nearly half of all CH_4 emissions in California, with dairy manure accounting for 25% (9.88 $MMTCO_2e$), and enteric fermentation accounting for 20% (7.81 $MMTCO_2e$). 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 CH_4. 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 AMMP practices on the reduction of CH_4 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 # 18ISD025 35C10) to measure the GHG emissions from six dairies Pre- and Post-AMMP practices. They included: screen mechanical separators; vacuum truck for scarping manure then employs a screw press for manure dewatering and sun drying of manure solids; vacuum truck and sun drying on concrete pad, and weeping wall.

The objectives of this project were to:

1) Conduct emissions measurements for four select dairies after application of AMMP (i.e. Post installation AMMP). This process allows for the quantification of the effectiveness of changes in manure management practices from Pre- to Post-AMMP installation by comparing the results of the two companion projects. This specific objective was to be achieved through identification and recommendation of the best measurement practices for farm-scale dairy manure emissions monitoring. A protocol for measurement of both GHGs

(CH_4 and N_2O) and other pollutants (NH_3, H_2S) is an important task for the methodology development. Measurements of emissions were conducted on four dairies that adopted AMMP practices to establish a solid understanding of Post-AMMP emissions benchmark data. The emissions data Pre- and Post-AMMP were compared. The Pre-AMMP emission data was collected through a project funded by the CDFA.

2) Apply regional chemical transport models to determine the effect of AMMP emissions on ozone and PM2.5 concentrations. Present-day AMMP scenarios will estimate emissions from candidate AMMP dairies under one of several AMMP treatments. 2050 AMMP scenarios predict emissions from dairies outside of viable digester clusters under the various AMMP treatments in order to examine interactions between digester clusters (i.e. where they make economic sense) and different AMMP practices (where digesters are not practical).

3) Analyze, report, and disseminate project results and findings. Data from the monitoring and modeling parts of the study was synthesized to benchmark the Post-project emissions from the selected study dairies and to predict airshed wide effects until 2050.

The CDFA funded Pre-AMMP project and the present CARB Post-AMMP and the companion project (agreement # 18ISD025 35C10) are the first to investigate the impacts of the AMMP practices on GHGs and other pollutants emissions.

1.1 Literature Review

The study monitors the emissions on four dairies that were named Alpha, Bravo, Delta, and Echo. These four dairies had freestall barns and flushed manure was delivered to setting basins and then lagoons. These dairies implemented different AMMP technologies:

- 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 120 days per year. 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 solids were allowed to dry for some time before emptying the weeping wall using a front loader. Because the weeping wall had only one cell, when it was full, the flushed manure was delivered to the settling basin and then to the lagoon.

The findings of a literature review of such technologies are discussed below.

1.1.1 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 CH_4 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, two-stage sloped dual-screen separator, and rotary drum separator systems. 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 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 2 shows the solids removal efficiency of several screen separators for dairy manure as reported in the literature.

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.

*: Total Solids

**: Reduction of volatile solids.

As shown in Table 3, a literature review focusing on both flush manure and solid separation treatments showed a reduction of 15 – 40% in CH_4 potential from manure after some solids are removed. Screens and presses were used for solid separation in these studies.

Table 3. Relative CH_4 production potential from solids-separated vs untreated manure.

Separation method	Relative CH_4 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 et al. (2015)
Screw Press	63%	~50%	Amon et al. (2006)

Hills (1985) investigated and compared the CH_4 production potential of untreated and filtered dairy manure (with 10 mesh screens), 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 CH_4 production potential of the manure after filtration. Rico (2007) reported on the CH_4 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 CH_4 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 CH_4 production potential than the unscreened manure. Witarsa et al. (2015) investigated CH_4 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 production 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. Amon et al. (2006) measured GHG (CH_4 and N_2O) 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 CH_4 production 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 CH_4 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 CH_4 production potential reduction. As can be seen, the reduction in CH_4 production pential depnds on the type and configuration of the AMMP system. For example, while a single-stage sloped screen separator could achieve a CH_4 production potential reduction of 28.9 – 42.2%, a single-stage sloped dual-screen separator achieved 38.2 – 57.2%. These values are lower that the values (69.0 – 83.4%) determined for a weeping wall system.

Table 4. Solid removal efficiencies and CH_4 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

1.1.2 Weeping walls

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 requirements, minimum equipment requirements, and lower repair and maintenance costs (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 operations as 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 manure 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) described weeping walls as an increasingly popular technology 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. 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 – 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 CH_4 production potential, the authors estimated the reduction of CH_4 production potential of 75% – 81%.

Williams et al. (2020) recommended a 65% solids retention default with a CH_4 conversion factor (MCF) of 0.22 for weeping wall systems in the quantification methodology. The proposed MCF was calculated based on the average filling times of 43, 49, and 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 CH_4 emissions by 46%.

1.1.3 Manure vaccuming and scraping

Vaccum trucking and mechanical scraping are two systems that remove manure from barns without using water for flushing. Although these system can divert manure from the lagoon and reduce the emissions from lagoons, the emissions from the barns may be higher than the flushing systems. Results of Ross et al. (2021) showed that the NH_3 emissions from scraping were greater than flushing treatments. This was due to the fact that scraping may leave a film of manure that could be a source of NH_3 emissions.

2 Methods

2.1 Measurements

2.1.1 Selection of the studied sites

GHG emissions were measured on four dairies. The names, locations, and types of AMMP technologies employed on each dairy are shown in Table 5.

Table 5. 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
Delta	Turlock	Partial scrape with windrow drying
Echo	Gustine	Weeping wall

2.1.2 Description of manure management on the studied dairies

2.1.2.1 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 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 1 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.

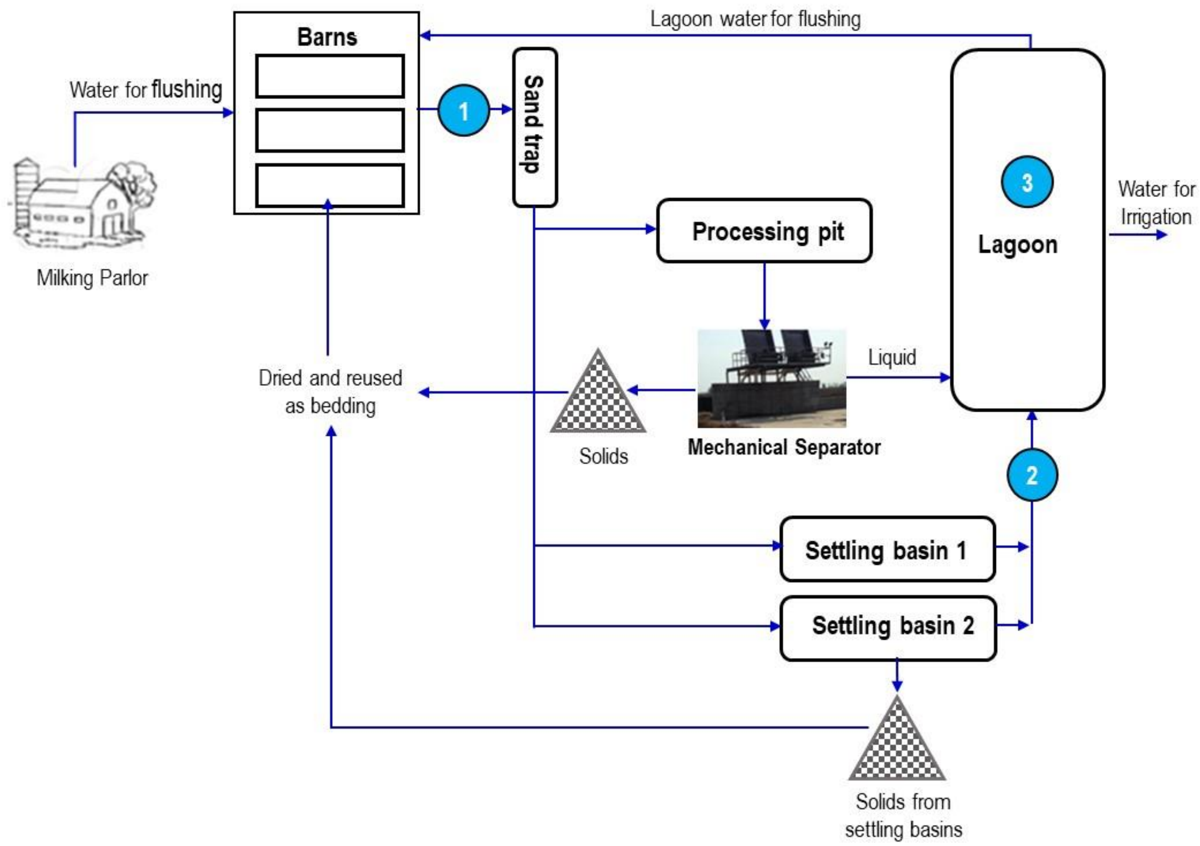


Figure 1. Single-line flow diagram for the manure management system on Alpha dairy.

2.1.2.2 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 49 and 150 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 180 and 607 ft (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 2 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

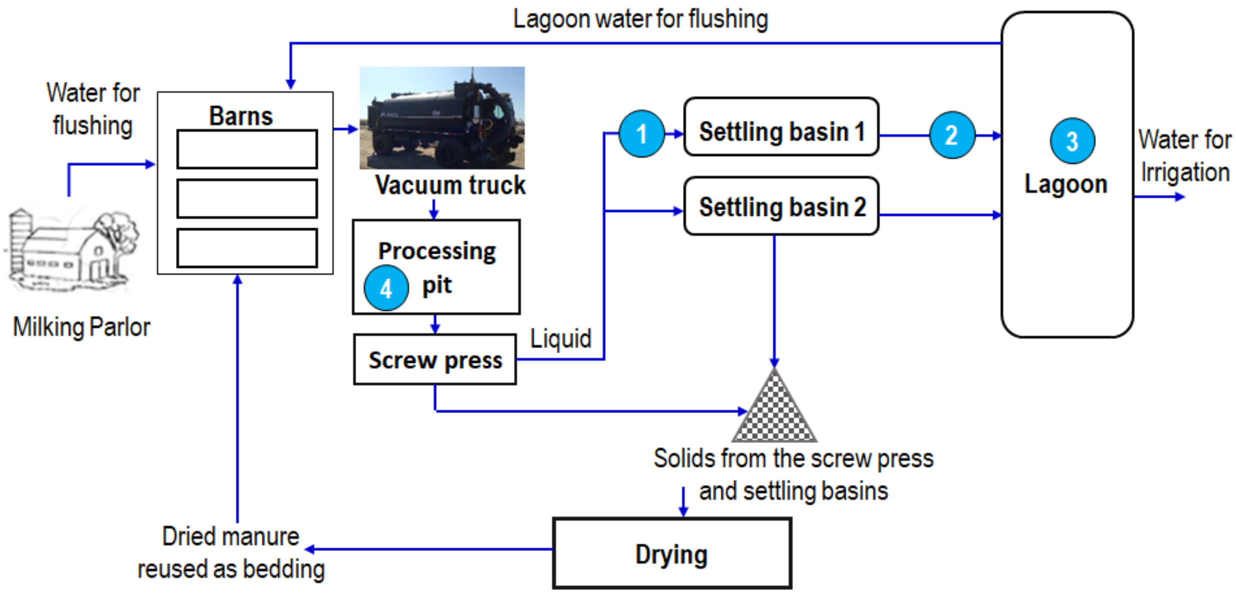


Figure 2. Single-line flow diagram for the manure management system on Bravo dairy.

2.1.2.3 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 and 145ft (338 and 44 m) respectively, and the second one was 1,110 x 150 ft (338 x 46 m). 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 and 140 ft (309 and 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, and 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 3 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, 3, and 4.

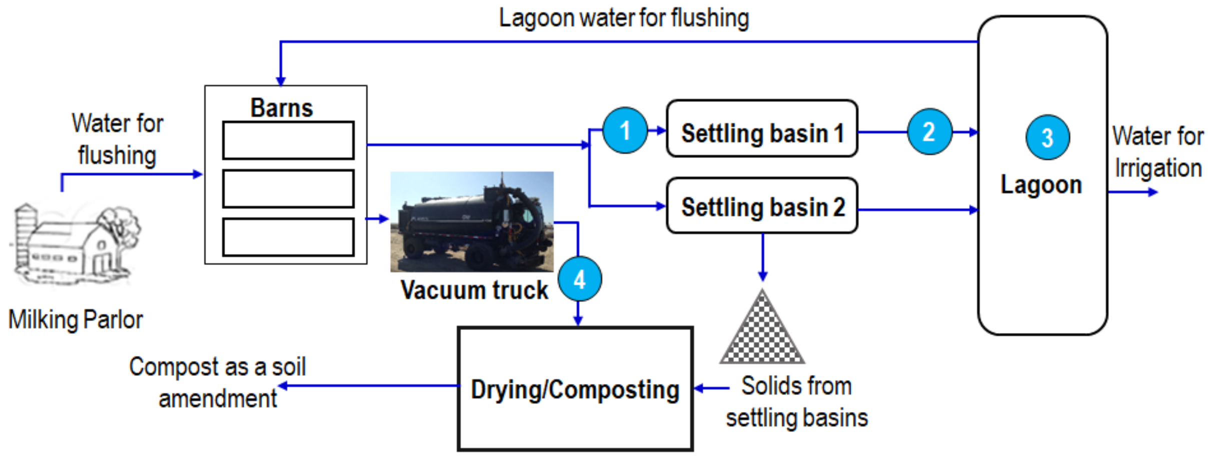


Figure 3. Single-line flow diagram for the manure management system on Delta dairy.

2.1.2.4 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. During the monitoring period at the farm, the weeping wall started to be filled on October 3, 2019. The operation time for filling and emptying the weeping wall are shown in Figure 4.

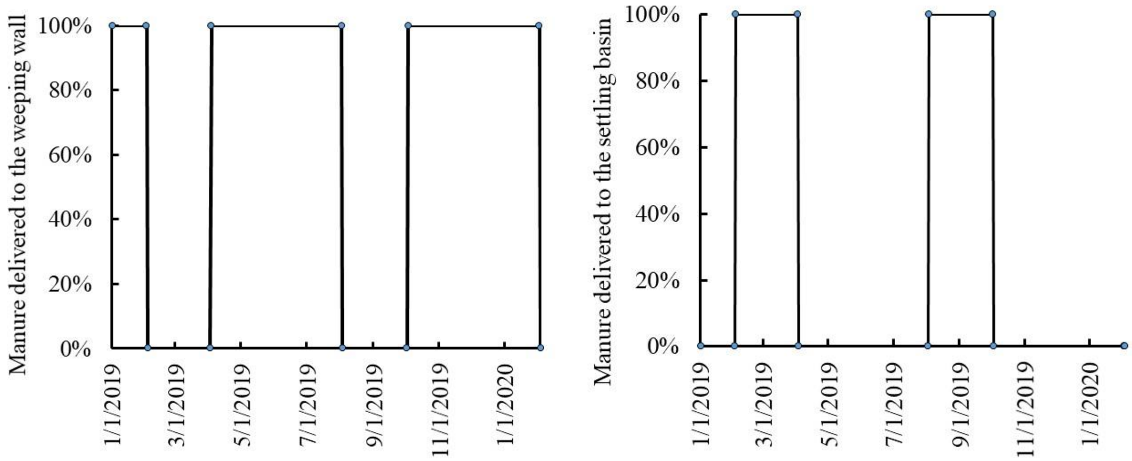


Figure 4. Percentage of manure delivered the weeping wall and settling basin at Echo.

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 compost 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 5 shows a single-line flow diagram for the manure management system on Echo dairy. Samples were collected at points 1, 2, and 3.

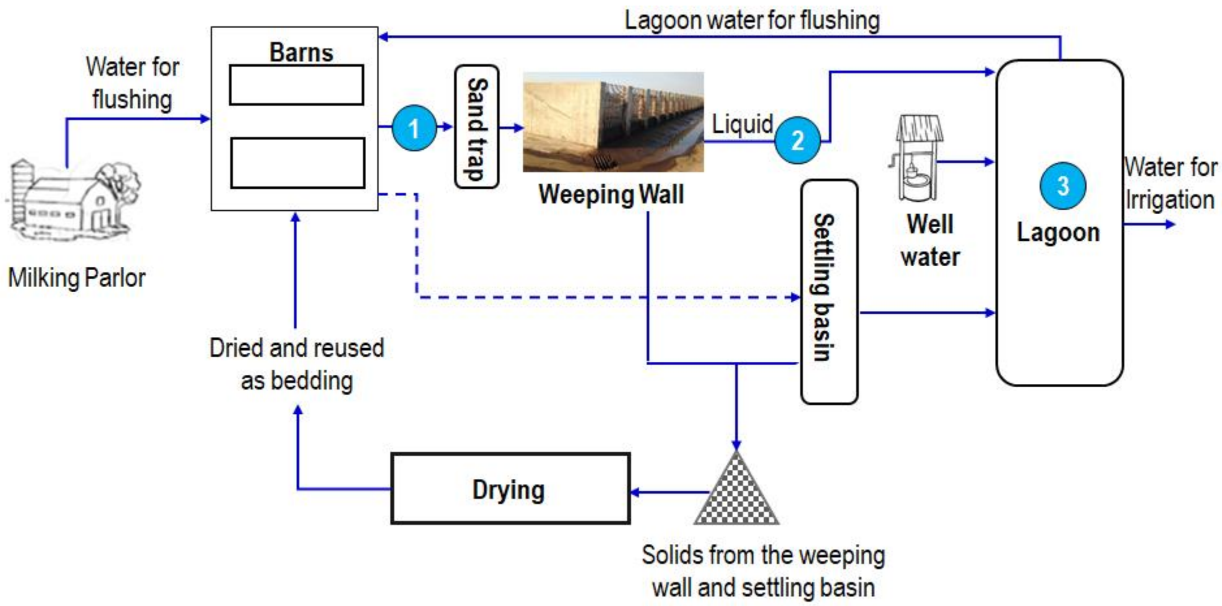


Figure 5. Single-line flow diagram for the manure management system on Echo dairy.

2.1.3 Measurement techniques

2.1.3.1 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 required to measure and record the emissions. 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 6. 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 6A shows the MAQ Lab and electricity generator. Mitloehner et al. (2018, unpublished data) conducted on farm measurements of the emissions of GHG and NH_3 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, the MAQ Lab was parked on a location that was close to the lagoon and settling basin.

Figure 6. (A) The Mobile Air Quality Laboratory (MAQ Lab) and engine-generator set; (B) different analyzers and supporting equipment onboard of the MAQ Lab.

2.1.3.2 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 7.

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.

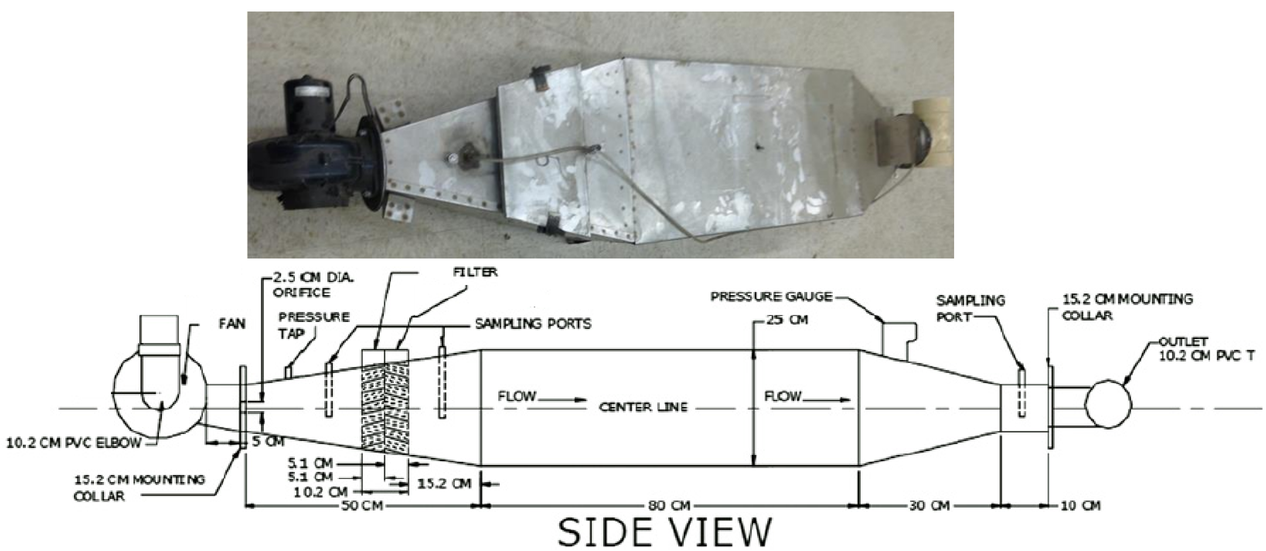


Figure 7. Main parts and dimensions of the wind tunnel (adapted from Kumar et al., 2011).

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 managers helped the research team 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. Figure 8 to Figure 14 show the wind tunnel during the emission measurements of lagoons and settling basins on the dairies that were monitored in this study.

2.1.3.3 Calculation of emission flux

The emission flux rate was calculated using the equation:

$$E = Q \times (C_{out} - C_{in}) / A \qquad \text{eq (1)}$$

Where:

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

C_{out} = 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 locations 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 6 shows monitored sources and schedule of emissions measurements on the studied dairies. The sites were ordered in this Table based on the dates of the measurements.

Table 6. 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
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
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

2.1.4 Emissions measurement description

2.1.4.1 Alpha dairy

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 8A 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 remove the scum layer on its surface using an excavator (Figure 8B and C). Figure 8D 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 9A. 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 9B) prior putting the wind tunnel over the solids (Figure 9C). The weight of manure solids used for measuring the emissions using the wind tunnel varies among the studied dairies due to the variation in the bulk density that depends on the moisture content of the solids available on each dairy. 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.

A B C D

Figure 8. (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.

A B C

Figure 9. (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.

2.1.4.2 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 10A 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 10B). Figure 10C 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 11A. 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 11B) prior putting the wind tunnel over the solids (Figure 11C). 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 10. (A) 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 11. (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 Bravo dairy.

2.1.4.3 Delta dairy

The emissions from the lagoon, settling basin, and vacuumed manure were measured. The wind tunnel was floated on the lagoon surface and emissions were measured at three different locations. The emission measurements were conducted for one day at each location. Figure 12A 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 13A) 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 13B) prior putting the wind tunnel over the manure (Figure 13C). 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 12. (A) The wind tunnel on the lagoon; and (B) the wind tunnel on the settling basin at the Delta dairy.

A B C D

Figure 13. (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.

2.1.4.4 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 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 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 14B). Figure 14C 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 15A). Then the surface of manure was leveled off using a shovel (Figure 15B). Finally, the wind tunnel was placed on the manure surface as shown in Figure 15C. The emissions from the weeping wall were measured for two days.

Figure 14. (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.

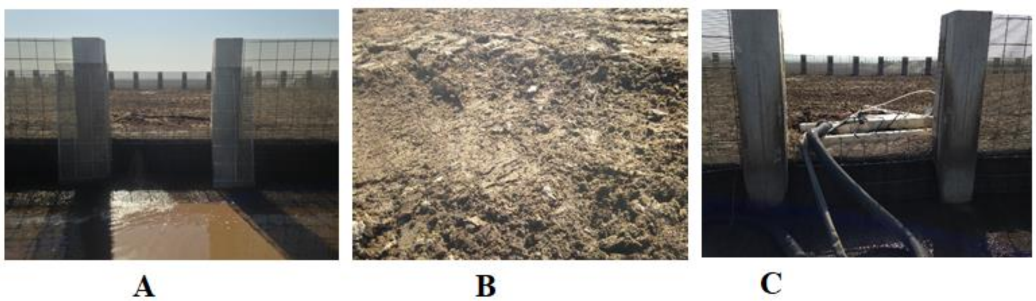


Figure 15. (A) two screens were removed from the weeping wall side; (B) leveling manure surface inside the weeping wall; and (C) the wind tunnel on the manure surface inside the weeping wall at the Echo dairy.

2.1.5 Manure sampling

During the emissions measurements, flushed manure samples were collected for three days from the manure flushed from feed lanes. These samples were analyzed for some characteristics that could be necessary to compare different sources of emissions at the same dairy and among all the studied dairies. The characteristics are also important for future modeling studies. 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 (lagoon inlet). 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 that were used in the emissions measurements. 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. 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 Delta, Bravo, and Echo dairies, 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). Due to the limited access to UC Davis laboratory during the COVID-19 pandemic, manure samples from Alpha 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.

Manure samples from all the four studied dairies were analyzed for NH_4^+, TKN, DOC, OC, and TC by Ward Laboratory (https://www.wardlab.com/).

2.1.6 Dairy 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 was to get more information about the AMMP practices that were employed by each of the studies dairies; and to obtain the respective dairyman's opinion of the AMMP practices. The research team obtained answers for the questionnaire questions from Delta and Echo dairies and Alpha and Bravo dairy managers did not responded to the request. Therefore, some information was obtained from CARB activity data for the respective dairies. A copy of the questionnaire survey questions is added to the appendix.

2.1.7 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 average of the measured Pre-AMMP values were corrected for the average temperature during the Post-AMMP measurements. The correction for temperature was conducted as follows (Petersen et al., 2016):

$$\ln(k_2/k_1) = -\left(\frac{E_a}{R}\right)\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad \text{eq (2)}$$

Where k_1 is the measured Pre-AMMP CH_4 emission rates ($CH_4/m^2/hr$), k_2 is the corrected CH_4 emission rates ($CH_4/m^2/hr$), E_a is activation energy (81 J/mol (Elsgaard et al. (2016)), R is the universal gas constant (8.314 J/K/mol), 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).

2.1.8 Statistical analysis

Quantile vs quantile plots (QQP) were used to determine the normal distribution of data. Qqplot function in Matlab was used to perform QQP. Analysis of Variance (ANOVA) was used to determine the significance of difference of the emissions Pre- and Post-AMMP. The data for Pre-AMMP was collected from a previous project funded by the CDFA. The function (anova1) in MATLAB was used to perform the test.

2.2 Modeling

2.2.1 Baseline future emissions inventories

Atmosphere chemistry is "non-linear" meaning that changes to emissions can sometimes increase or decrease ambient concentrations of chemical species depending on the atmospheric chemical regime. The current project established two baseline scenarios to evaluate the potential changes to atmospheric concentrations that may yield different behavior(s) due to different chemical regimes.

The two baseline scenarios created for the year 2050 included a Business-as-Usual (BAU) scenario and an 80% GHG reduction (GHG-Step) scenario (here-after referred to as the Low Carbon Energy scenario) (Zapata, Yang et al. 2018, Zapata, Yang et al. 2018). Both the BAU and Low-Carbon Energy state-wide emission scenarios were constructed using the energy-economic optimization model, CA-TIMES, that calculates the multi-sector energy portfolio that meets projected energy supply and demand at the lowest cost, while also satisfying scenario-specific GHG emissions constraints (Zapata, Yang et al. 2018). Corresponding criteria pollutant emissions for each scenario were then spatially allocated at 4 km resolution to support air quality analysis across California.

CA-REMARQUE uses algorithms that account for local information about activity levels and technology mixes to estimate emissions of criteria pollutants (or their precursors) that are consistent with the future GHG scenarios. The following economic sectors were separately treated using these tailored algorithms: (i) on-road, (ii) rail and off-road, (iii) marine and aviation, (iv) residential and commercial, (v) electricity generation, and (vi) biorefineries. CA-REMARQUE accounts for the adoption of new technologies in each sector, including electrification, bio-fuels, and hydrogen. Criteria pollutant emissions did not decrease uniformly across all sectors of the economy. Emissions of certain criteria pollutants (or their precursors) increased in some sectors as part of the overall optimization within each of the scenarios (Zapata, Yang et al. 2018). This produced non-uniform changes to criteria pollutant emissions close to large population centers, which has implications for exposure to air pollution for those populations. As a further complication, changing fuels and technology also modified the composition of reactive organic gas (ROG) emissions and the size and composition of particulate matter emissions. This is most apparent through a comparison of emissions reductions for different size fractions of primary particulate matter. Primary $PM_{2.5}$ emissions decrease by 3.6% in the GHG-Step scenario versus the BAU scenario while corresponding primary $PM_{0.1}$ emissions decrease by a factor of 36%. Ultrafine particles ($PM_{0.1}$) are an emerging pollutant of concern expected to impact public health in future scenarios.

2.2.2 Future AMMP scenarios

The initial chapters of the current report show that the AMMPs considered in the current study were implemented in a non-standard manner and therefore did not produce statistically significant decreases in GHG emissions. Detailed VOCs needed to predict changes in O_3 and $PM_{2.5}$ concentrations were not measured, but it seems likely that the implementation approach adopted in the current study likewise had a minor impact on these emissions. However, previous studies have determined that reducing the amount of solids entering the dairy lagoon (the primary strategy used by all correctly-implemented AMMPs) can reduce emissions of VOCs (see for example (Parker 2008)). Two limiting scenarios were therefore explored to gain insights into the potential for future AMMPs to improve air quality in the SJV.

2.2.2.1 Limiting scenario 1: Perfect AMMP

The first limiting emissions scenario assumes universal adoption of an AMMP that achieves 100% control of all VOC, NH_3, and PM emissions from dairy waste. In reality, PM emissions from dairy farms are chiefly composed of dust generated by dairy cattle walking around unpaved surfaces. It is unlikely that these dust emissions would be controlled in real-world AMMP implementations. The perfect AMMP scenario quantifies the upper bound of the air quality improvements that could be achieved through the adoption of AMMPs in central California.

2.2.2.2 Limiting scenario 2: widespread biogas digesters (100% adoption)

AMMPs were conceived at a time before best practices for dairy biogas production had been identified and widely adopted. Biogas production using covered lagoon technology has advanced significantly in recent years. Multiple commercial companies have evolved business models that install and operate covered lagoons for biogas production on dairy farms yielding financial benefits for farm owners. These innovations have significantly lowered or eliminated the barriers to biogas production that motivated AMMPs. It therefore seems reasonable to consider the air quality implications of widespread biogas production in the current project to provide a comparison to the perfect AMMP scenario.

The second AMMP scenario analyzed in the current project focuses on widespread adoption of biogas digesters. The resulting biogas can be burned at the production facility for electricity generation (displacing some amount of baseline electricity generation), upgraded to transportation fuel (displacing some amount of baseline transportation fuel consumption), or upgraded to pipeline quality gas (displacing some amount of fossil natural gas consumption). On-site electricity generation has the greatest potential impact on air quality in central California since this pathway places new sources of NOx and PM directly into the San Joaquin Valley. Upgrading gas for use in vehicles and / or pipeline delivery to natural gas consumers will not change end-use NOx emissions, and changes to emissions from fuel production will generally happen outside the study region. The second AMMP scenario therefore focuses on biogas production coupled with on-site electricity generation.

Biogas production is feasible on farms of almost any size, but commercial production for electricity generation is currently only economically feasible for large dairies. Advances in future technology combined with regulatory pressure to reduce GHG emissions from farms of all sizes will almost certainly lower this threshold in the future. The second AMMP scenario analyzed in the current study is designed for a limiting analysis that assumes all farms adopt covered lagoon digesters with on-site electricity generation.

Biogas production at dairy facilities was assumed to eliminate emissions of dairy waste VOCs but otherwise leave emissions of NH_3 and PM from dairy waste unchanged. Biogas electricity production at dairy facilities generates new emissions of NOx and PM from the engines operating on biogas. Engine technology used for electricity generation was assumed to meet Tier 4 standards for diesel engines of 0.4 g NOx/kW /hr, and 0.02 g PM/kW /hr (https://nepis.epa.gov/Exe/ZyPDF.cgi? Dockey=P100OA05.pdf). It should be noted that these levels are slightly lower than the currently permitted levels for biogas-fired engines in the SJV. The current calculations account for continued tightening of future standards and/or the incorporation of safety factors by engine manufacturers to avoid emissions violations. It was assumed that digesters would process 100% of the generated dairy waste, and that biogas production potential was proportional to the amount of dairy waste VOC emissions in the emissions inventory produced by CARB. Records describing dairy waste emissions were copied and updated to remove waste emissions and add NOx and PM emissions from dairy biogas combustion. The placement of the biogas combustion emissions assumes that the biogas production facilities would be located close to existing dairy barns so that existing spatial surrogates for dairy VOC emissions can also act to locate emissions from engines operating on dairy biogas. Summary of emissions scenarios evaluated are showon in Table 7.

Table 7. Summary of Emissions Scenarios Evaluated

Business as Usual + Perfect AMMP	Low Carbon + Perfect AMMP
Business as Usual + Biogas Electricity	Low Carbon + Biogas Electricity

Table 8 summarizes the emissions associated with dairy waste in California under the Baseline (BAU or Low Carbon Energy) atmophere, the Perfect AMMP Scenario, and the Biogas Digester Scenario. Baseline emissions are estimated as the 2010 dairy waste emissions coded with EIC=620-618-0262-0101 multiplied by a factor of 1.5 to represent increased demand in response to population growth by the year 2050. The emissions of all particles and gases are eliminated under the Perfect AMMP scenario as a limiting case study. Emissions are modified in the Biogas Digester scenario to account for removal of VOC emissions from the dairy waste and the addition of engine exhaust produced from burning the biogas.

Table 8. Daily Emissions Totals Associated with Dairy Waste Under Different Scenarios

Species	Baseline	Perfect AMMP	Biogas Digester for Electricity Generation
Gas-Phase Species (kmol/day)			
CO	0	0	1,790
NO_x	0	0	111
CH4	22,443	0*	1,173
ALK1	3,425	0	114
ALK2	0	0	16
ALK3	325	0	6
ALK4	171	0	1
ETHENE	0	0	6
OLE1	0	0	11
OLE2	0	0	2
ACETYLENE	0	0	3
HCHO	0	0	7
ACET	177	0	0
ETOH	198	0	0
NH3	9,140	0	9,140
Particle-phase Species (kg/day)			
EC	0	0	1
OC	1,205	0	1,219
CL^-	29	0	33
SO_4^{2-}	23	0	53
NO_3^-	47	0	48
OTHER	2,596	0	2610
METL	404	0	405
Mn	3	0	3
Fe	96	0	96

* Limiting scenario assumption. Note that CH_4 reacts slowly, and so this assumption has no impact on air quality in the SJV.

2.2.3 Chemical transport model

Simulations for the years 2000-2011were carried out across California using the source-oriented UCD/CIT regional air quality model. The UCD/CIT airshed model is a reactive 3-D chemical transport model (CTM) that predicts the evolution of gas and particle phase pollutants in the atmosphere in the presence of emissions, transport, deposition, chemical reaction, and phase change as represented by Eq. (3)

$$\frac{\partial C_i}{\partial t} + \nabla \cdot uC_i = \nabla K \nabla C_i + E_i - S_i + R_i^{gas}(C) + R_i^{part}(C) + R_i^{phase}(C) \qquad \text{eq (3)}$$

where C_i is the concentration of gas or particle phase species i at a particular location as a function of time t, u is the wind vector, K is the turbulent eddy diffusivity, E_i is the emissions rate, S_i is the loss rate, R_i^{gas} is the change in concentration due to gas-phase reactions, R_i^{part} is the change in concentration due to particle-phase reactions and $R_i^{phase}$is the change in concentration due to phase change (Held, Ying et al. 2005). Loss rates include both dry and wet deposition. Phase change for inorganic species occurs using a kinetic treatment for gas-particle conversion (Hu, Zhang et al. 2008) driven towards the point of thermodynamic equilibrium (Nenes, Pilinis et al. 1998). Phase change for organic species is also treated as a kinetic process with vapor pressures of semi-volatile organics calculated using the 2-product model (Carlton, Bhave et al. 2010).

The basic capabilities of the UCD/CIT model are similar to the CMAQ model maintained by the US EPA, but the UCD/CIT model has several source apportionment features and higher particle size resolution, which makes it attractive for the current project. The UCD/CIT model explicitly tracks the mass and the number concentration of particles in 15 discrete size bins spanning the range from 10nm through 10 µm, with tracer species used to quantify source contributions to the primary particle mass in each bin. A moving sectional bin approach is used (Kleeman, Cass et al. 1997) so that particle number and mass can be explicitly conserved with particle diameter acting as the dependent variable.

The emissions of particle source tracers are empirically set to be 1% of the total mass of primary particles emitted from each source category, so they do not significantly change the particle radius and the dry deposition rates. For a given source, the simulated concentration of artificial tracer directly correlates with the amount of PM mass emitted from that source in that size bin. The corresponding number concentration attributed to that source can be calculated using Eq. (4)

$$num_i = \frac{tracer_{\ i} \times 100}{\frac{\pi}{6} Dp^3 \rho} \qquad \text{eq (4)}$$

where $tracer_i$ represents the artificial tracer mass in size bin i, Dp is the core particle diameter, and ρ is the core particle density. Core particle properties are calculated by removing any condensed species to better represent the properties of the particles when they were emitted. More details describing the source apportionment technique in UCD/CIT model are provided in previous studies (Ying, Fraser et al. 2007, Ying, Lu et al. 2008, Ying, Lu et al. 2008, Hu, Zhang et al. 2015, Yu, Venecek et al. 2018).

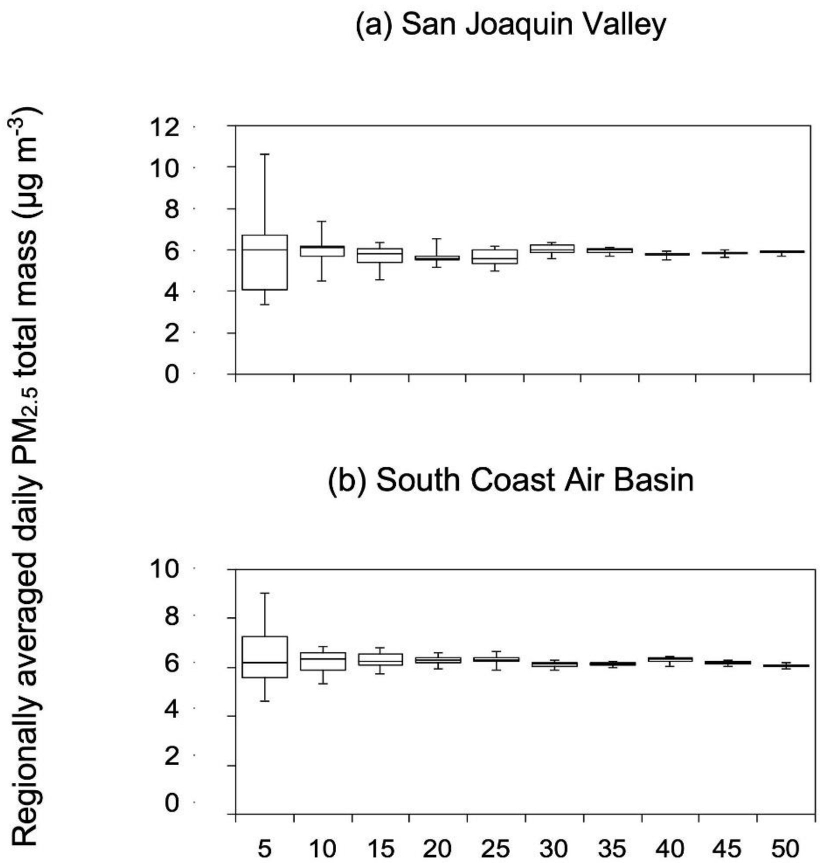
A total of 50 particle-phase chemical species are included in each size bin. Gas-phase concentrations of oxides of nitrogen (NOx), volatile organic compounds (VOCs), oxidants, ozone, and semi-volatile reaction products were predicted using the SAPRC-11 chemical mechanism (Carter and Heo 2013).

2.2.4 Meteorology model

Hourly meteorology inputs to drive the regional chemical transport model at 24-km and 4-km resolution 2045-2054 were simulated using the Weather Research and Forecasting (WRF) v3.4 model (www.wrf-model.org). WRF model vertical resolution was 31 vertical layers from the ground level to the top pressure of 100 hPa. Initial and boundary conditions for meteorological simulations were be taken from the Community Climate System Model (CCSM) using the Representative Concentration Pathway (RCP) 8.5 Scenario. The Yonsei University (YSU) boundary layer vertical diffusion scheme (Hong, Noh et al. 2006) and Pleim-Xiu land surface scheme (Xiu and Pleim 2001) were adopted in this study. Four-dimensional data assimilation was applied to anchor the model predictions to observed meteorological patterns.

2.2.5 Long-term simulation strategy

The El Nino Southern Oscillation (ENSO) strongly affects meteorology and air quality in California. ENSO cycles typically last seven years, making it necessary to simulate multi-year time periods when analyzing future air quality. The computational burden of this task can be reduced by selecting a subset of episodes across the ~decadal time period in order to build an accurate estimate of the long-term average concentrations in the presence of inter-annual climate variability. The uncertainty attributable to climate variability decreases as the number of sample points (simulation episodes) increases. For the present study, an entire decade of air quality could be simulated for every future energy portfolio, but in practice the long-term $PM_{2.5}$ and O_3 concentrations can be determined with the required accuracy by simulating a smaller number of representative episodes randomly selected across the target decade. **Figure 16** illustrates how the uncertainty in the predicted $PM_{2.5}$ concentrations decrease based on the number of randomly distributed days are simulated. In the present study, 224 simulated days divided into 32 episodes of 7-day duration will be used to resolve the population-weighted $PM_{2.5}$ concentration to ±0.5 $\mu g/m^3$.



Number of simulated episodes.

Figure 16. Uncertainty range in 2050 for $PM_{2.5}$ predictions in the (a) San Joaquin Valley and (b) South Coast Air Basin as a function of the number of episodes simulated. Each "episode" consisted of a 3 day spin-up period followed by a 14-day simulation period.

3 Results and discussion

3.1 Emissions measurements

3.1.1 Alpha dairy – lagoon

The emission rates of methane (CH_4), ammonia (NH_3), nitrous oxide (N_2O), and hydrogen sulfide (H_2S) from the lagoon on Alpha dairy are shown in Figure 17, Figure 18, Figure 19, and Figure 20, respectively. As can be seen, a few peaks of CH_4 emissions were determined. The emission rates of NH_3 were relatively constant with two peaks during the monitoring period. The emissions of N_2O and H_2S were negligible for several hours on each day during the monitoring period with a few peaks of the emissions of both gases.

The emission rates of CH_4, and NH_3 ranged from 3.24 to 55.61 and from 0.07 to 0.26 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 142.69, and from 0 to 85.49 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 20.74 and 0.16 g/m^2/hr, respectively and the emission rates of N_2O and H_2S were 23.67 and 23.84 mg/m^2/hr, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 1,298.2, 9.9, 1.5, and 1.5 g/ animal unit/day, respectively (Table 10).

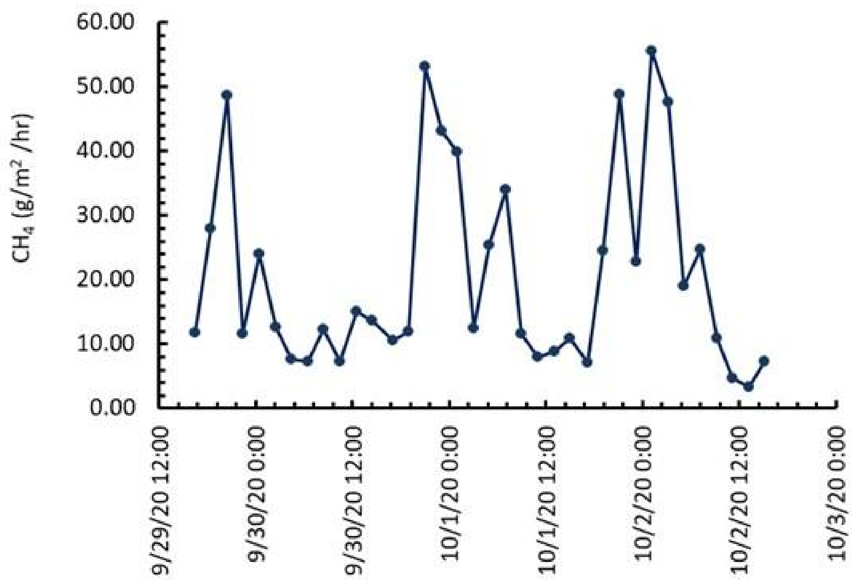


Figure 17. Emission rates of CH_4 from the lagoon at Alpha dairy.

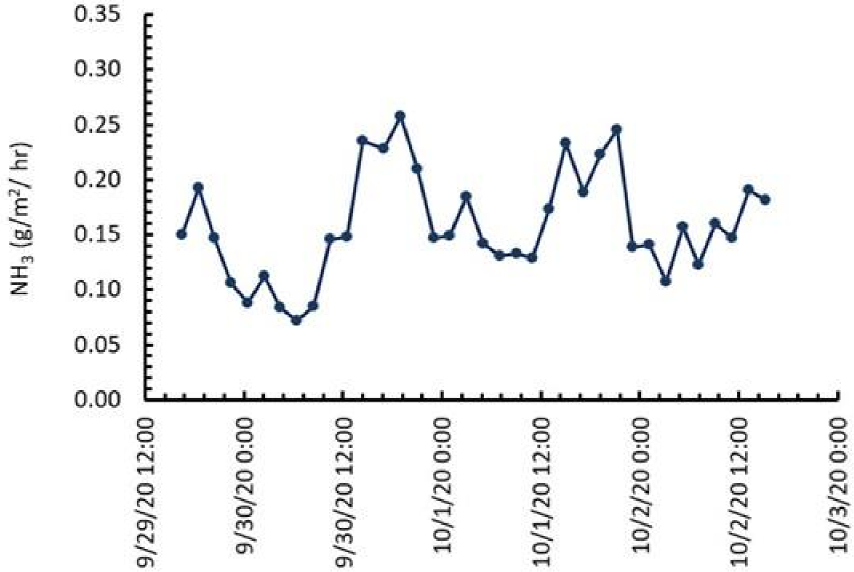


Figure 18. Emission rates of NH_3 from the lagoon at Alpha dairy.

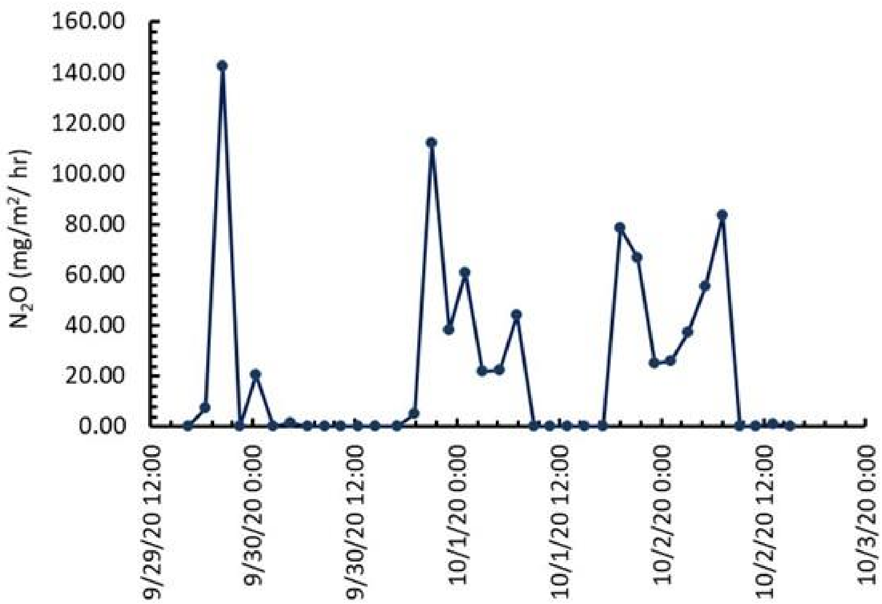


Figure 19. Emission rates of N_2O from the lagoon at Alpha dairy.

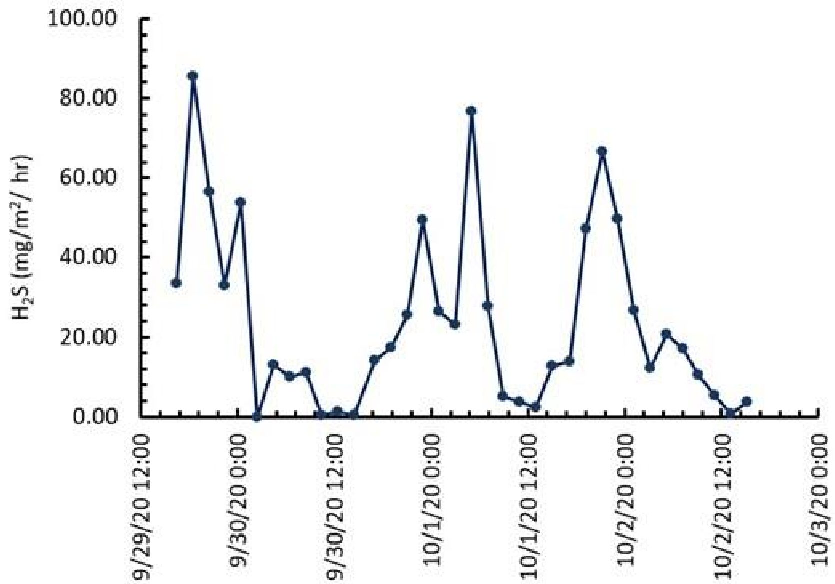


Figure 20. Emission rates of H_2S from the lagoon at Alpha dairy.

3.1.2 Alpha dairy – settling basin

The emission rates of CH_4, NH_3, N_2O, and H_2S from the settling basin at Alpha dairy are shown in Figure 21, Figure 22, Figure 23, and Figure 24, respectively. A peak of CH_4 emission rate of approximately 108 g/m^2/hr was determined after a few hours of the wind tunnel deployment in the settling basin. Then the emissions gradually reduced with another peak of approximately 40 g/m^2/hr after 12 hours of the wind tunnel deployment. Then, the emission decreased gradually reaching negligible rates. Ammonia emissions were relatively constant during the monitoring period with a light increase towards the end of the monitoring period. The emissions of N_2O and H_2S had the same trend as that of CH_4 emissions during the monitoring period but with different values for the peaks of the emissions.

The emission rates of CH_4, and NH_3 ranged from 1.47 to 108.03 and from 0.09 to 0.26 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 241.19, and from 0 to 81.93 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 20.80 and 0.15 g/m^2/hr, respectively and they were 40.15 and 18.50 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). Comparing the emissions rates from the lagoon and the settling basin indicated that they both had almost similar emissions of CH_4, and NH_3. While the lagoon had relatively lower emission rates of N_2O but higher H_2S emission rates than the settling basin. The daily emission of CH_4, NH_3, N_2O, and H_2S were 618.0, 4.6, 1.2, and 0.6 g/animal unit/day, respectively (Table 10).

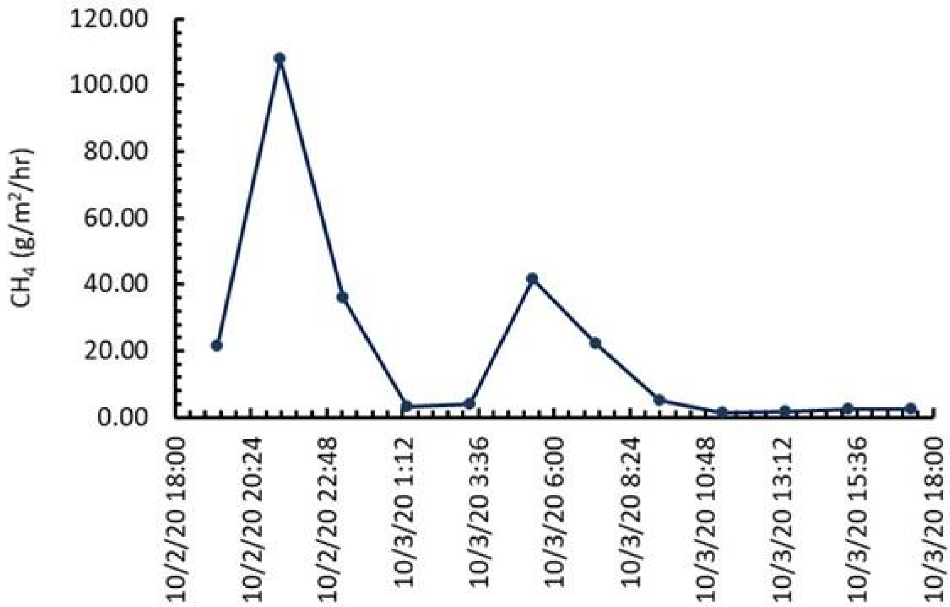


Figure 21. Emission rates of CH_4 from the settling basin at Alpha dairy.

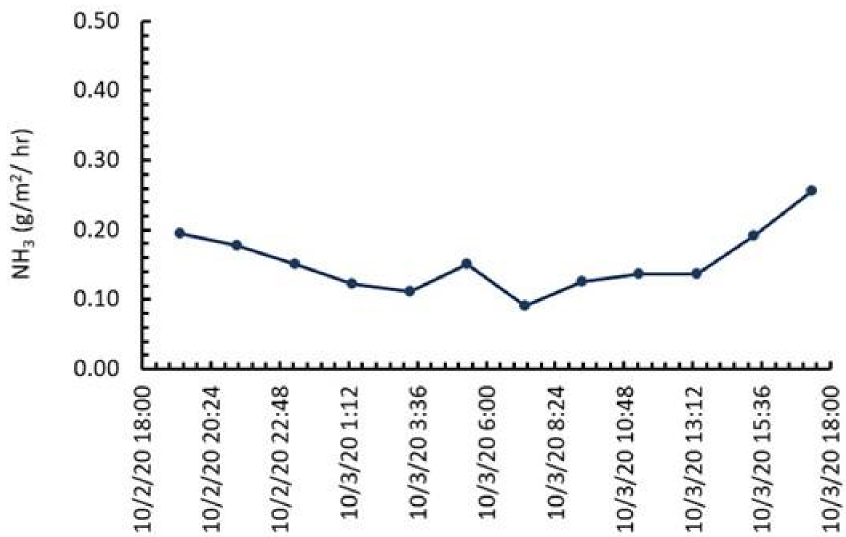


Figure 22. Emission rates of NH_3 from the settling basin at Alpha dairy.

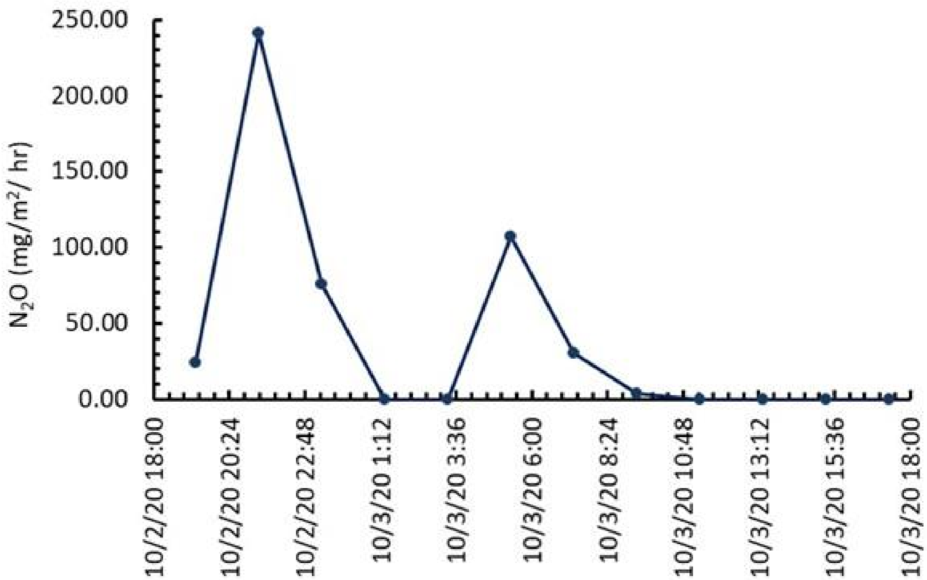


Figure 23. Emission rates of N_2O from the settling basin at Alpha dairy.

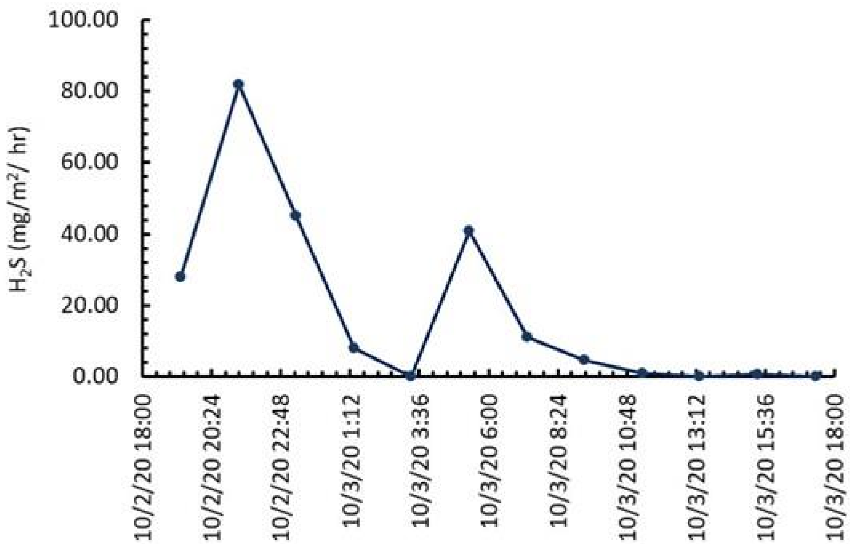


Figure 24. Emission rates of H_2S from the settling basin at Alpha dairy.

3.1.3 Alpha dairy – manure solids

The emission rates of CH_4, NH_3, N_2O, and H_2S from manure solids at Alpha dairy are shown in Figure 25, Figure 26, Figure 27, and Figure 28, respectively. The solids used in this experiments were freshly collected from the mechanical separator. As can be seen from Figure 25, there were two peaks of CH_4 emissions of approximately 709 and 1104 g/ton/hr during the measurements. The emissions of NH_3 started at rate of 9.4 g/ton/hr, then gradually decreased. Similar to CH_4 emissions, two peaks of N_2O emissions of approximately 1046 and 1246 mg/ton/hr were also determined. The emissions of H_2S were relatively constant for a few hours after the experiment started. Then they declined to be negligible after approximate 7 hours of the experiment start. A peak of H_2S emissions of approximately 1104 mg/ton/hr appeared after approximately 10 hours from the experiment start.

The emission rates of CH_4, and NH_3 ranged from 0 to 1104.09 and from 0.73 to 9.40 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 1246.34 and from 0 to 1104.75 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 319.41 and 2.78 g/m^2/hr, respectively (Table 11), while emissions of N_2O and H_2S were 395.80 and 231.03 mg/m^2/hr, respectively.

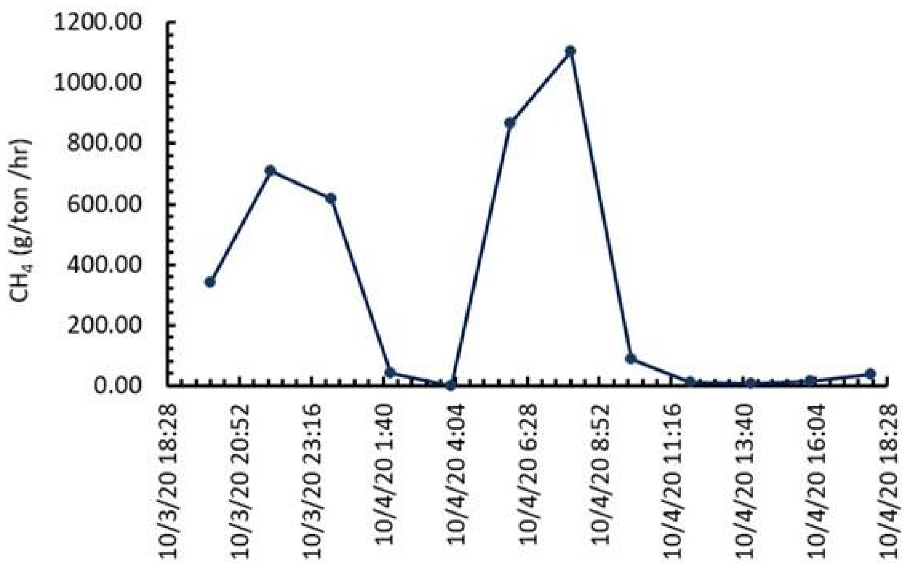


Figure 25. Emission rates of CH_4 from solids at Alpha dairy.

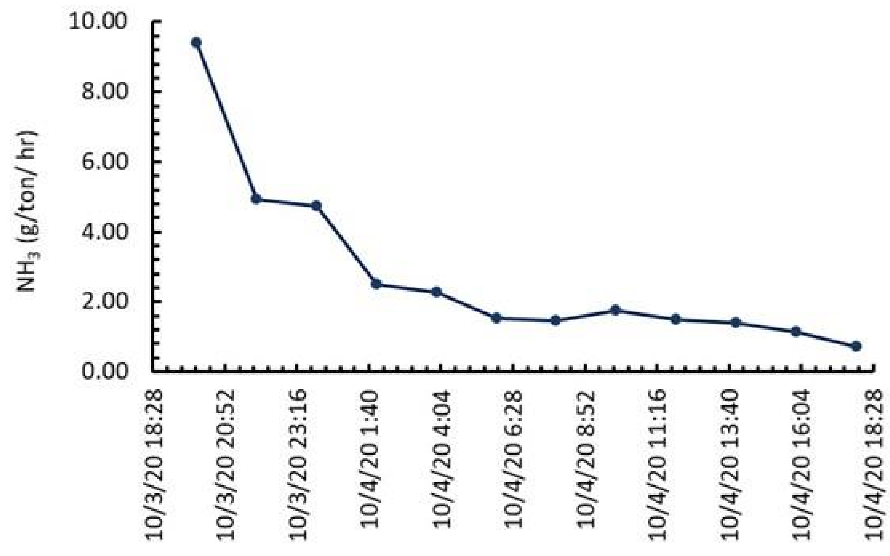


Figure 26. Emission rates of NH_3 from solids at Alpha dairy.

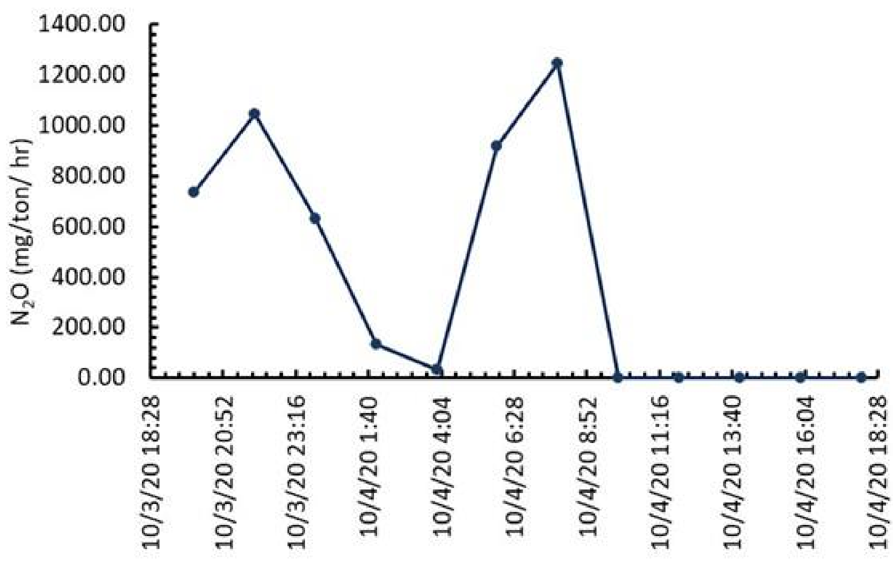


Figure 27. Emission rates of N_2O from solids at Alpha dairy.

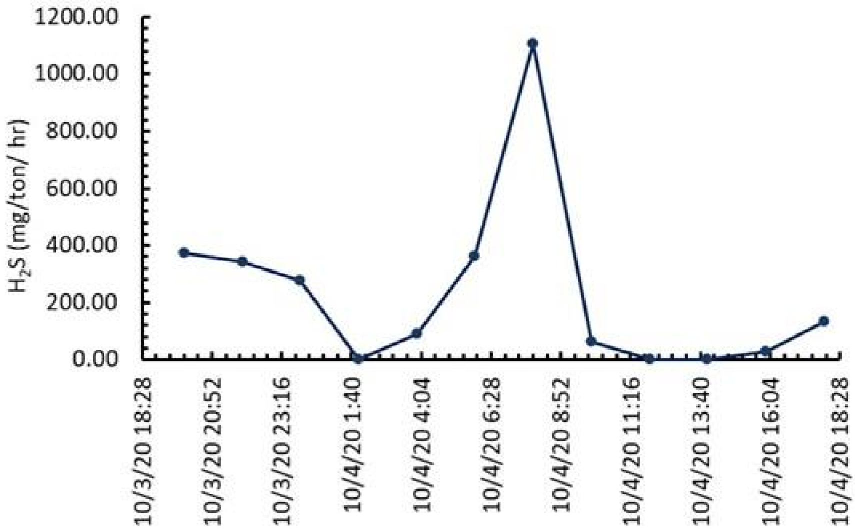


Figure 28. Emission rates of H_2S from solids at Alpha dairy.

3.1.4 Bravo dairy – lagoon

The emission rates of CH_4, NH_3, N_2O, and H_2S from the lagoon on Bravo dairy are shown in Figure 29, Figure 30, Figure 31, and Figure 32, respectively. Relatively constant emission rates, with a few peaks, of CH_4 and NH_3 were found for most of the monitoring period. A few peaks of emission rates of N_2O were also determined. Several peaks of the emissions of H_2S were also determined during the monitoring period.

The emission rates of CH_4, and NH_3 ranged from 0.22 to 12.85 and from 0.01 to 0.06 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 16.34 and from 0 to 0.08 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 1.78 and 0.02 g/m^2/hr, respectively and 1.56 and 0.02 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 333.42, 3.78, 0.29, and 0.00 g/animal unit/day, respectively (Table 10).

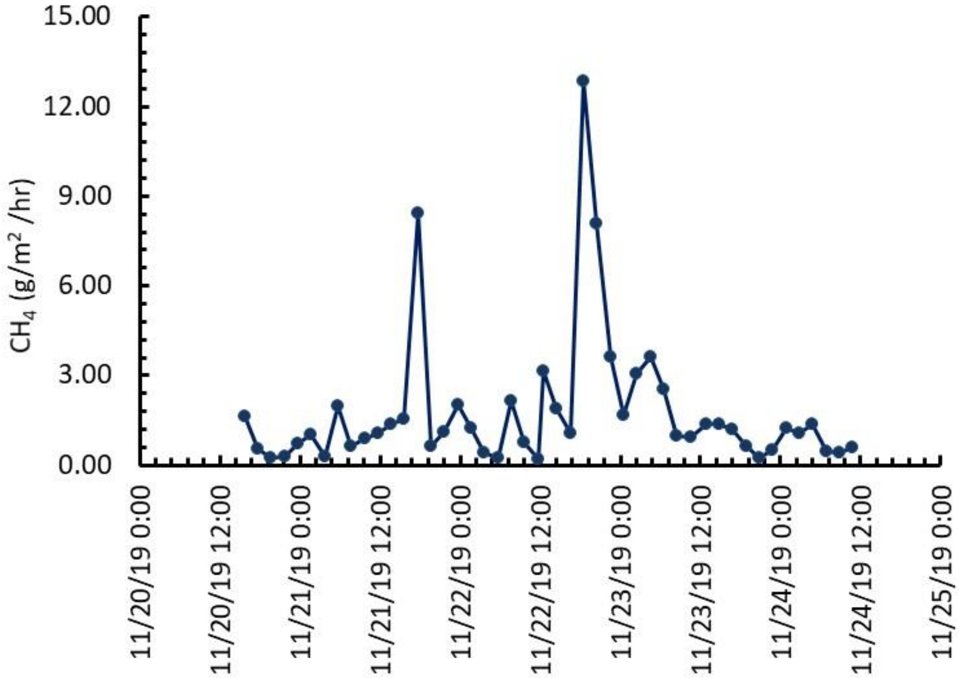


Figure 29. Emission rates of CH_4 from the lagoon at Bravo dairy.

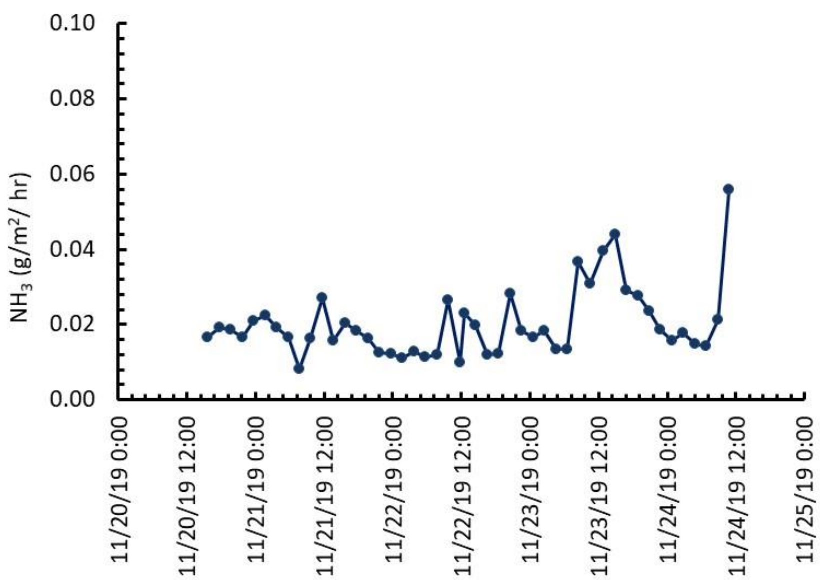


Figure 30. Emission rates of NH_3 from the lagoon at Bravo dairy.

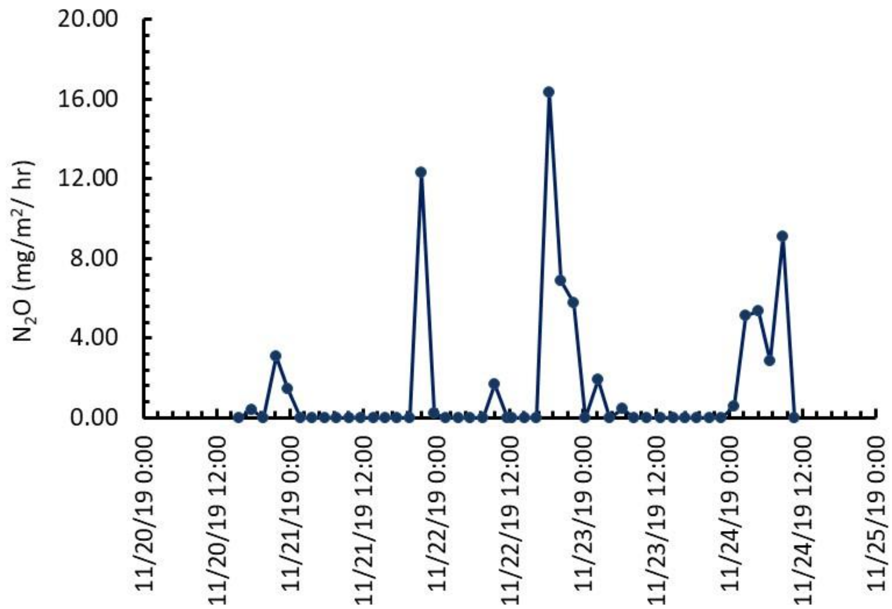


Figure 31. Emission rates of N_2O from the lagoon at Bravo dairy.

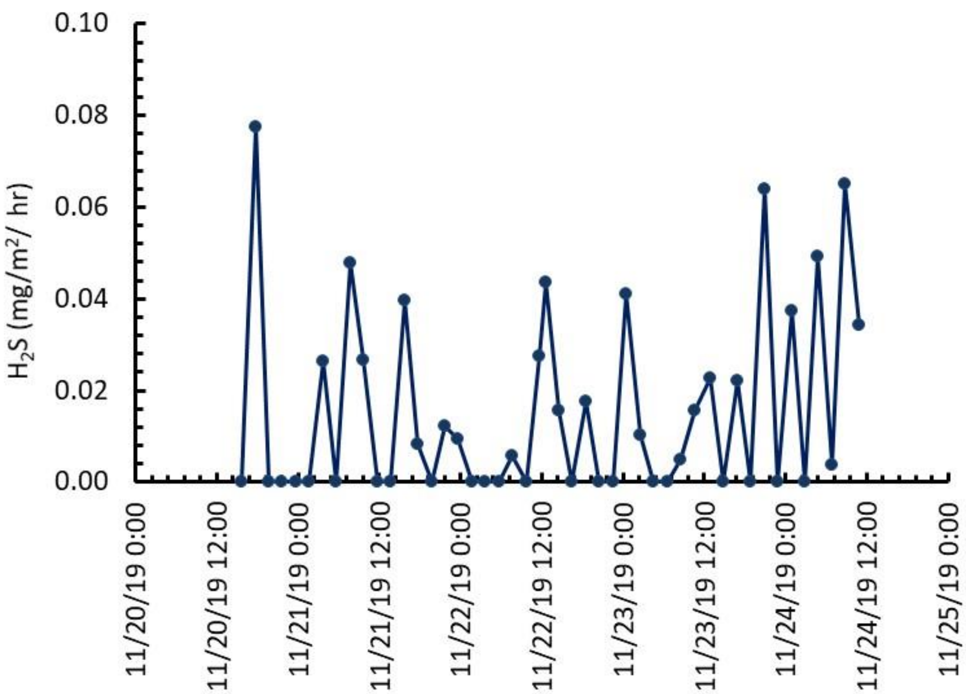


Figure 32. Emission rates of H_2S from the lagoon at Bravo dairy.

3.1.5 Bravo dairy – settling basin

The emission rates of CH_4, NH_3, N_2O, and H_2S from the settling basin at Bravo dairy are shown in Figure 33, Figure 34, Figure 35, and Figure 36, respectively. The CH_4 emission rate was relatively constant during the emissions monitoring period with a peak of approximately 6.2 g/m^2/hr. Ammonia emissions started at relatively high rate of 0.07 g/m^2/hr then sharply reduced to a rate of approximately 0.02 g/m^2/hr that was kept for about 12 hours. Then, the emission rates increased to a rate of approximately 0.03 g/m^2/hr. The emissions of N_2O and H_2S were negligible for most of the monitoring time except with a few peaks that occasionally determined during the monitoring period.

The emission rates of CH_4, and NH_3 ranged from 0.95 to 6.22 and from 0.01 to 0.07 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 5.78, and from 0 to 0.07 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 2.53 and 0.02 g/m^2/hr, respectively and they were 1.13 and 0.02 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 32.75, 0.32, 0.01, and 0.00 g/animal unit/day, respectively (Table 10). Comparing the emissions rates from the lagoon and the settling basin indicated that both sources had similar emissions of NH_3, and H_2S. The settling basin has higher emissions of CH_4 than the lagoon and the vice versa for N_2O.

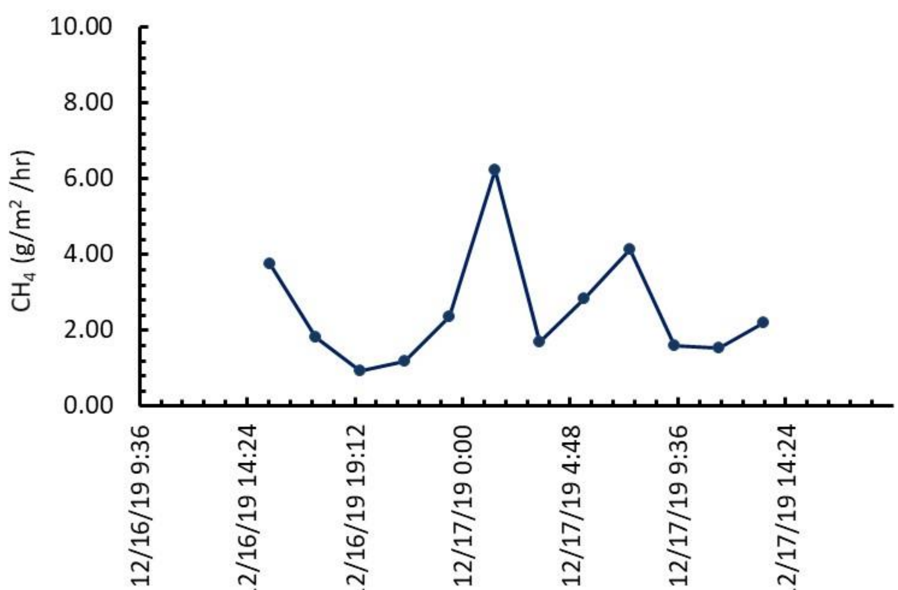


Figure 33. Emission rates of CH_4 from the settling basin at Bravo dairy.

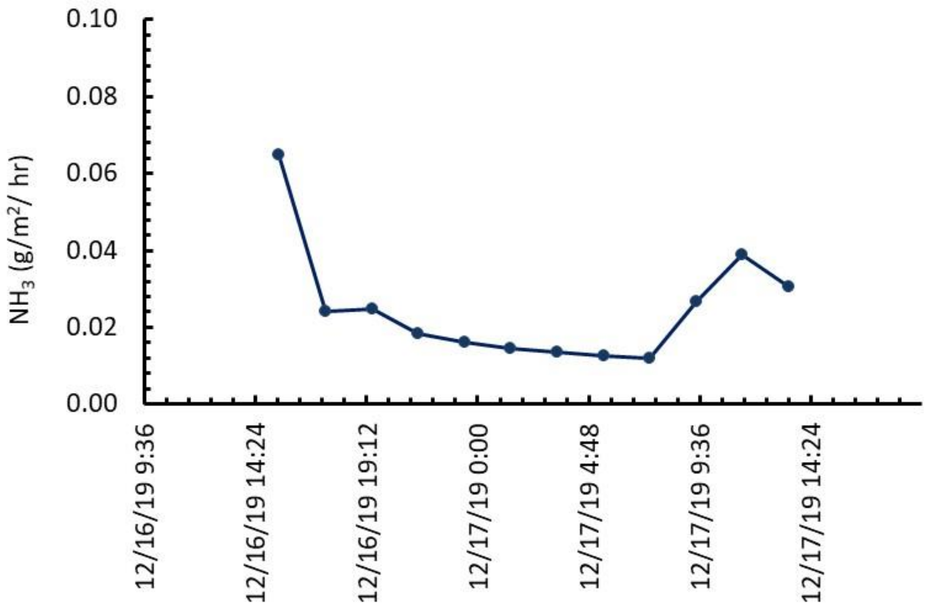


Figure 34. Emission rates of NH_3 from the settling basin at Bravo dairy.

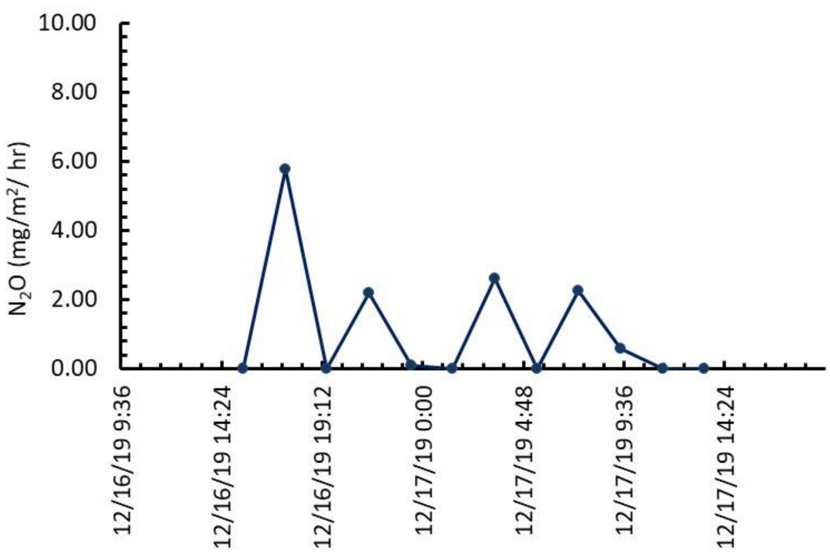


Figure 35. Emission rates of N_2O from the settling basin at Bravo dairy.

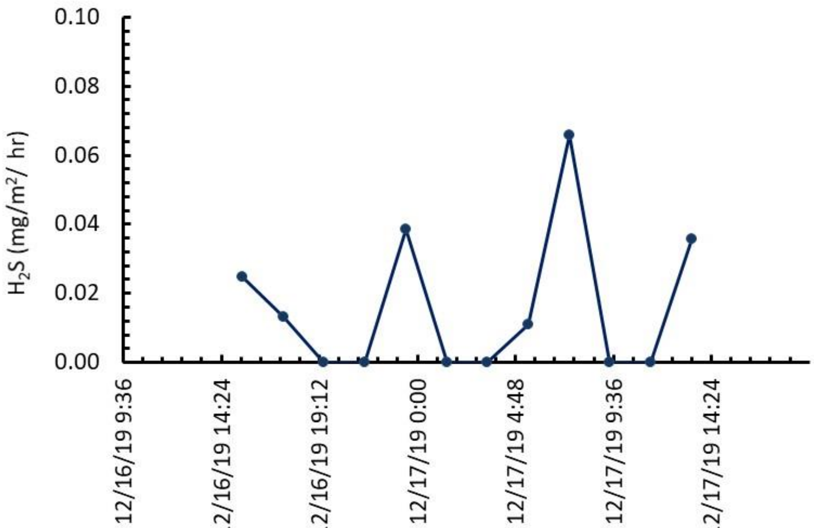


Figure 36. Emission rates of H_2S from the settling basin at Bravo dairy.

3.1.6 Bravo dairy – solids

The emission rates of CH_4, NH_3, N_2O, and H_2S from solids at Bravo dairy are shown in Figure 37, Figure 38, Figure 39, and Figure 40, respectively. As can be seen from Figure 37, a few peaks of the emissions of CH_4 were determined. The emissions of NH_3 sharply decreased after starting the measurements reaching a relatively constant rate after a few hours from the start of the experiment (Figure 38). Three peaks were also determined for the emission rates of N_2O. While, there was no emissions of H_2S for the first 10 hours of the experiments, then two peaks of emissions were determined (Figure 39 and Figure 40). The emission rates of CH_4, and NH_3 ranged from 0 to 42.07 and from 0.29 to 4.46 g/ton/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 49.23 and from 0 to 1.35 mg/ton/hr, respectively. The average emission rates of CH_4 and NH_3 were 15.71 and 1.12 g/ton/hr, respectively (Table 11) and the emissions of N_2O and H_2S were 14.31 and 0.23 mg/ton/hr, respectively.

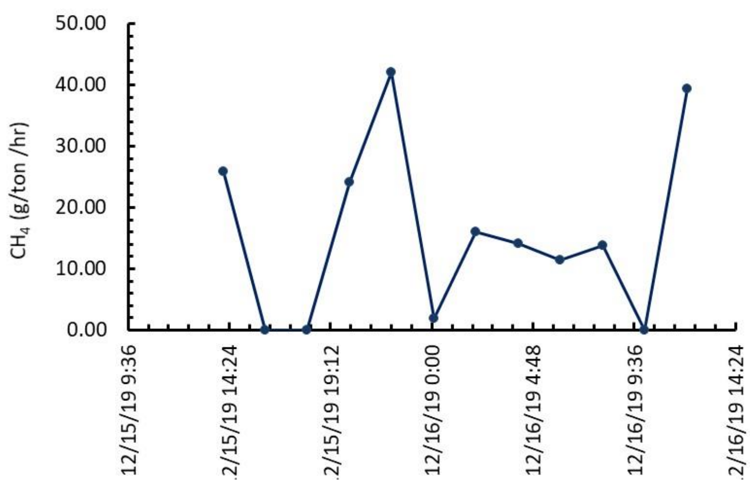


Figure 37. Emission rates of CH_4 from solids at Bravo dairy.

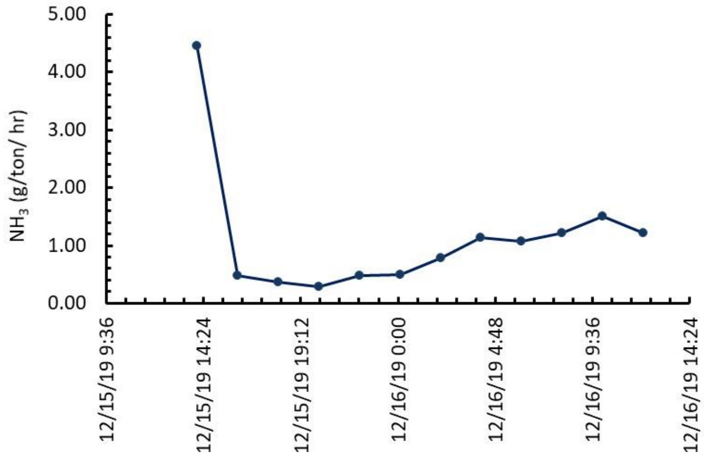


Figure 38. Emission rates of NH_3 from solids at Bravo dairy.

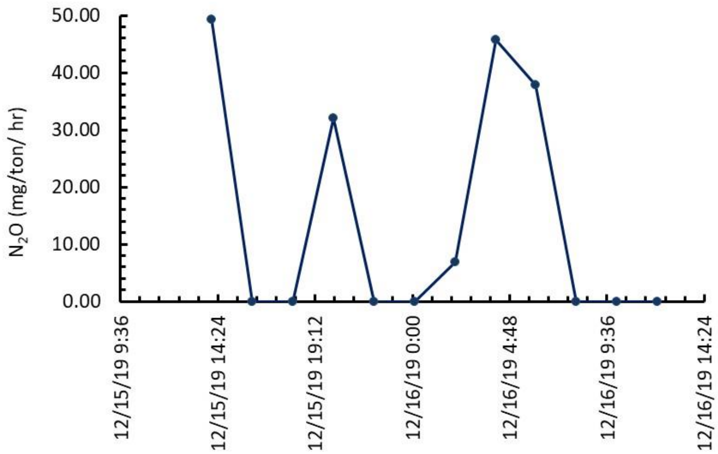


Figure 39. Emission rates of N_2O from solids at Bravo dairy.

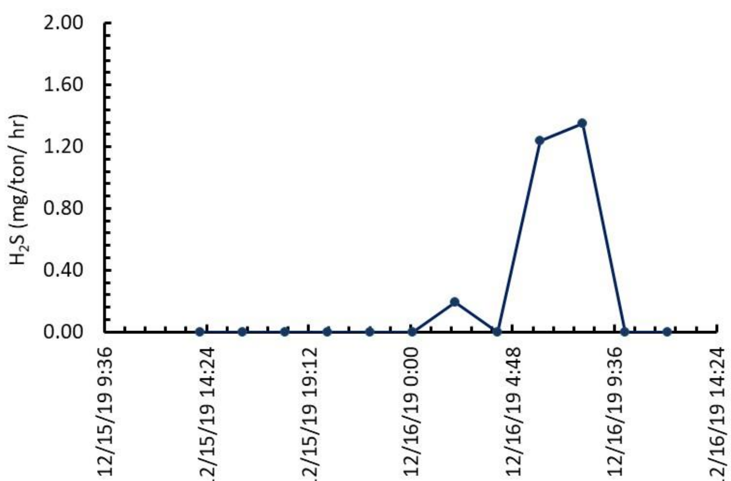


Figure 40. Emission rates of H_2S from solids at Bravo dairy.

3.1.7 Delta dairy – lagoon

The emission rates of CH_4, NH_3, N_2O, and H_2S from the lagoon on Delta dairy are shown in Figure 41, Figure 42, Figure 43, and Figure 44, respectively. The emissions of CH_4 were relatively high in the first day of the monitoring period. Then relatively constant emission rates with a few peaks were determined. The emissions rates of NH_3 were relatively constant were determined for most of the monitoring period with a few peaks. There was a one peak of the N_2O emission rates. Then low or negligible emission rates were determined. The emissions of H_2S were negligible for most of the monitoring period with a few peaks that were occasionally appeared.

The emission rates of CH_4, and NH_3 ranged from 2.88 to 32.09 and from 0.14 to 0.43 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 92.47 and from 0 to 0.15 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 11.09 and 0.27 g/m^2/hr, respectively and 3.95 and 0.01 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 744.31, 17.87, 0.27, and 0.00 g/ animal unit/day, respectively (Table 10).

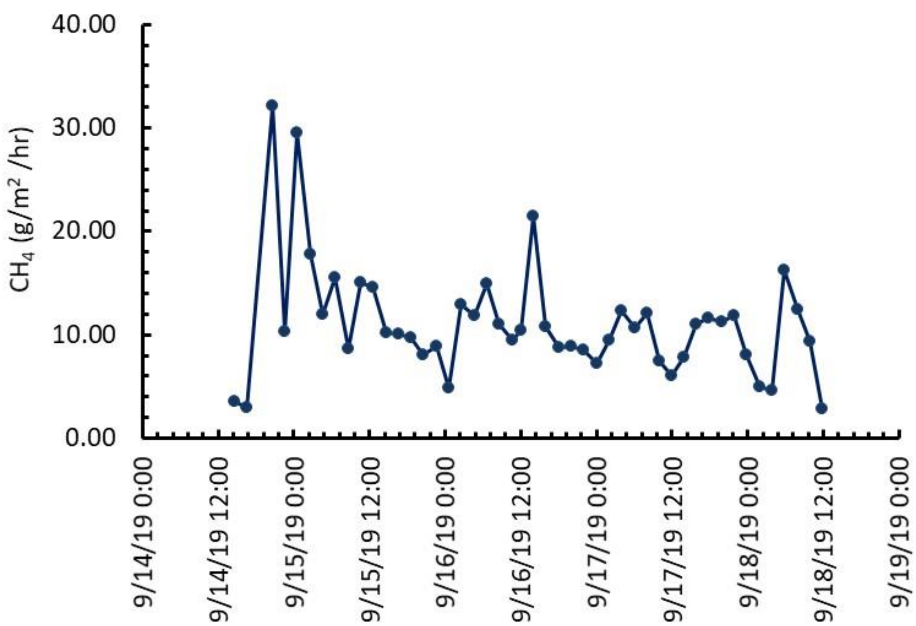


Figure 41. Emission rates of CH_4 from the lagoon at Delta dairy.

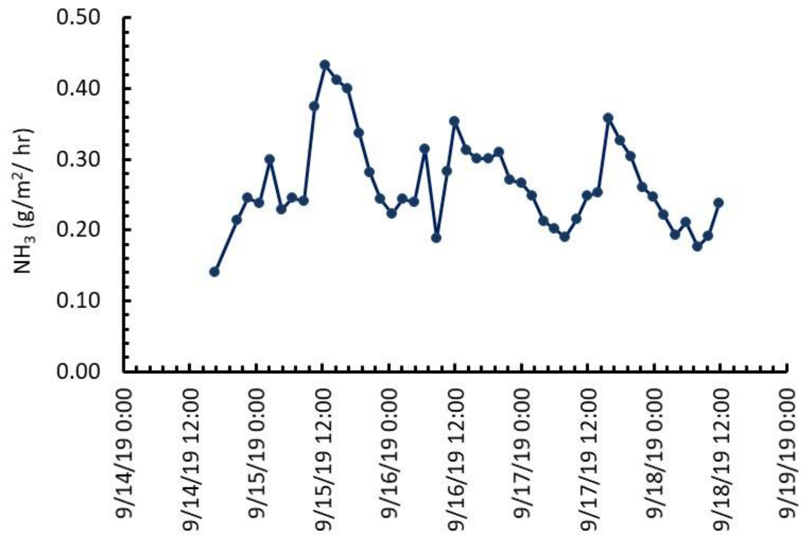


Figure 42. Emission rates of NH_3 from the lagoon at Delta dairy.

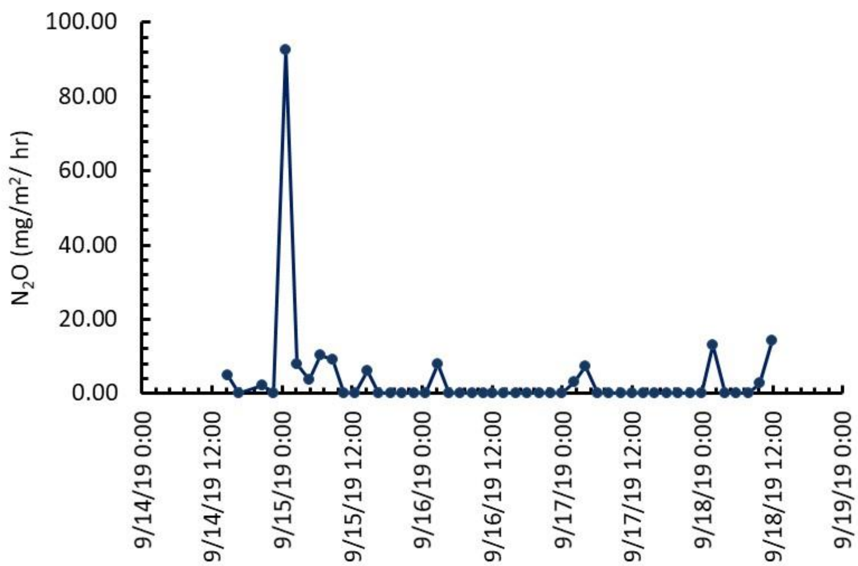


Figure 43. Emission rates of N_2O from the lagoon at Delta dairy.

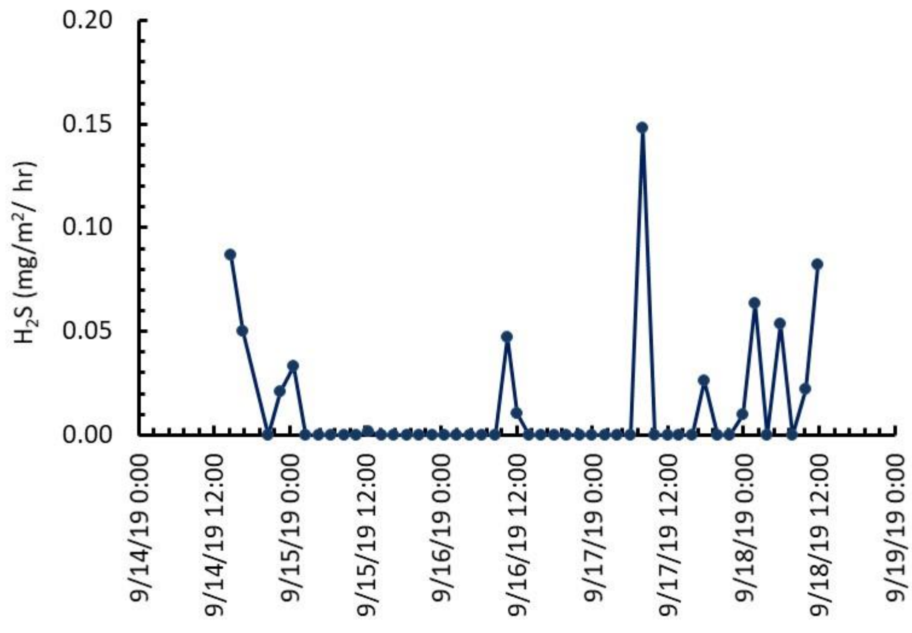


Figure 44. Emission rates of H_2S from the lagoon at Delta dairy.

3.1.8 Delta dairy – settling basin

The emission rates of CH_4, NH_3, N_2O, and H_2S from the settling basin at Delta dairy are shown in Figure 45, Figure 46, Figure 47, Figure 48, respectively. The emission rates of CH_4 gradually decreased during the first five hours after deploying the wind tunnel in the settling basin. Then, relatively constant emission rates were determined. The emission rate NH_3 gradually decreased after deploying the wind tunnel in the settling basin until the end of the monitoring period. The emissions of N_2O were negligible for most of the monitoring time except for one peak of approximately 1.4 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 4.57 to 13.49 and from 0.08 to 0.37 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 1.41, and from 0 to 0.12 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 6.67 and 0.18 g/m^2/hr, respectively and they were 0.12 and 0.03 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 507.44, 14.02, 0.01, and 0.00 g/animal unit/day, respectively (Table 10). Comparing the emissions rates from the lagoon and the settling basin indicated that the lagoon had relatively high emission rates of CH_4, NH_3, and N_2O and lower emission rates of H_2S than the settling basin.

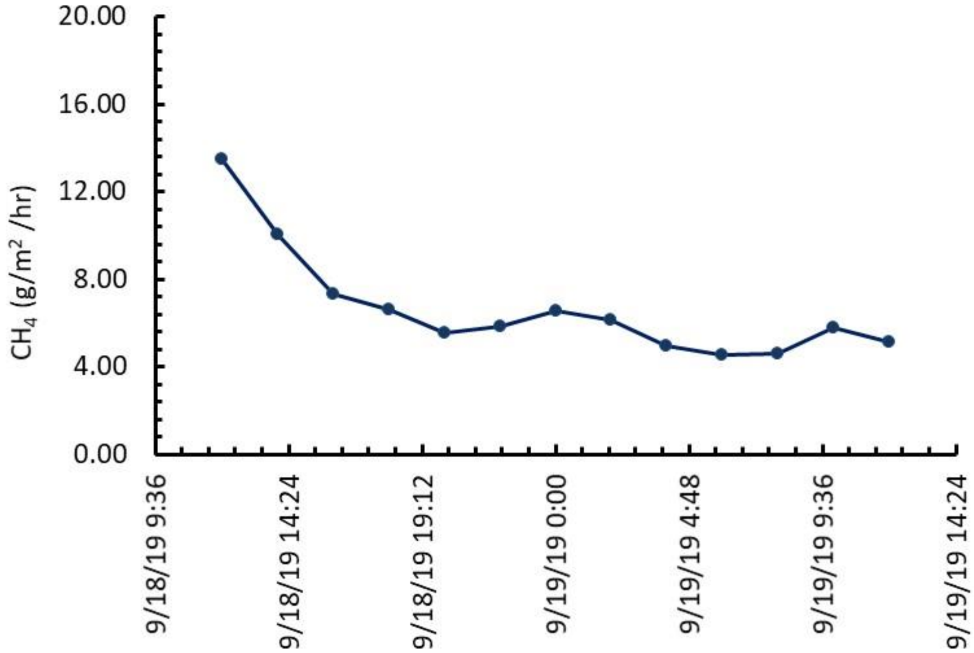


Figure 45. Emission rates of CH_4 from the settling basin at Delta dairy.

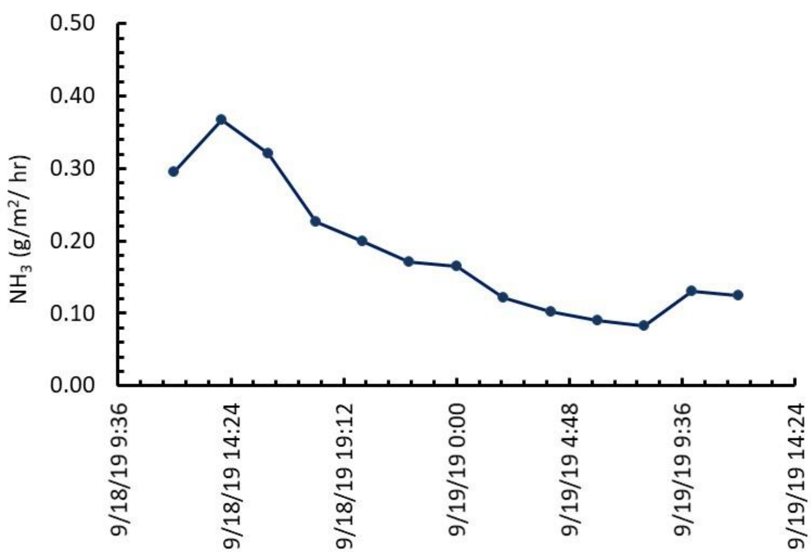


Figure 46. Emission rates of NH_3 from the settling basin at Delta dairy.

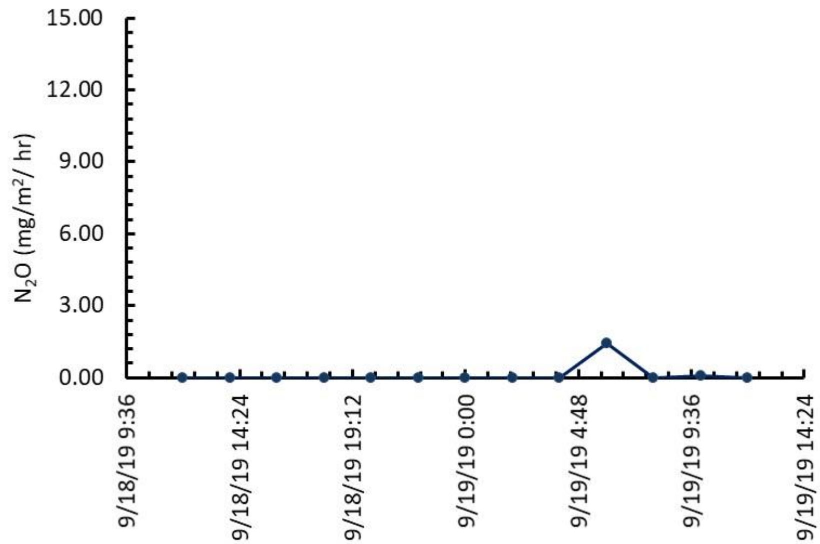


Figure 47. Emission rates of N_2O from the settling basin at Delta dairy.

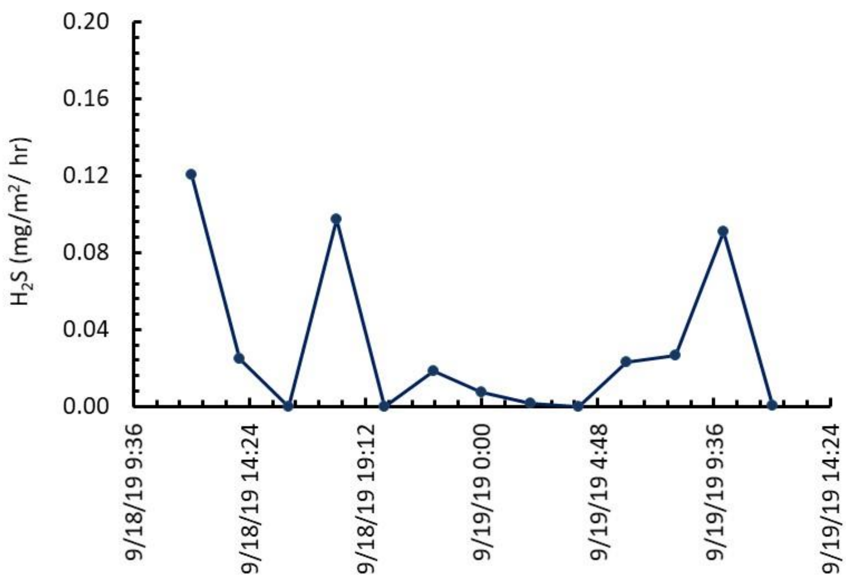


Figure 48. Emission rates of H_2S from the settling basin at Delta dairy.

3.1.9 Delta dairy – solids

The emission rates of CH_4, NH_3, N_2O, and H_2S from solids at Delta dairy are shown in Figure 49, Figure 50, Figure 51, and Figure 52, respectively. As can be seen from Figure 37the emissions of CH_4 decreased after starting the measurements, then two peaks were determined. The emissions of NH_3 sharply decreased after starting the measurements reaching a relatively constant rate after approximately 10 hours from. Then the emission started to increase again. The emissions rates of N_2O were negligible except that there were three peaks of emissions as shown in Figure 51. The emissions of H_2S decreased sharply after the experiment started. Then a few peaks were determined. The emission rates of CH_4, and NH_3 ranged from 0 to 34.61 and from 2.47 to 14.85 g/ton/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 30.38 and from 0 to 3.45 mg/ton/hr, respectively. The average emission rates of CH_4 and NH_3 were 4.19 and 6.63 g/ton/hr, respectively (Table 11) and the emissions of N_2O and H_2S were 2.59 and 0.49 mg/ton/hr, respectively.

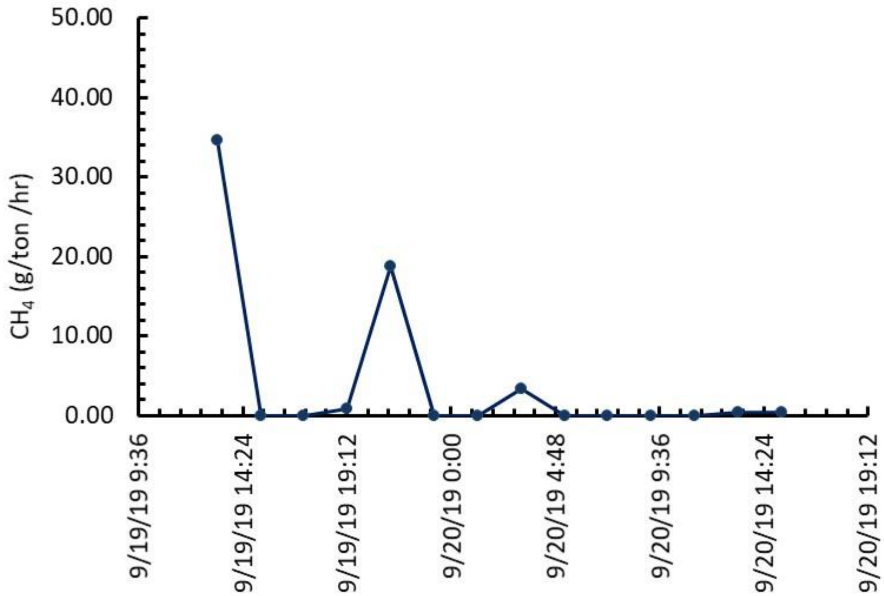


Figure 49. Emission rates of CH_4 from solids at Delta dairy.

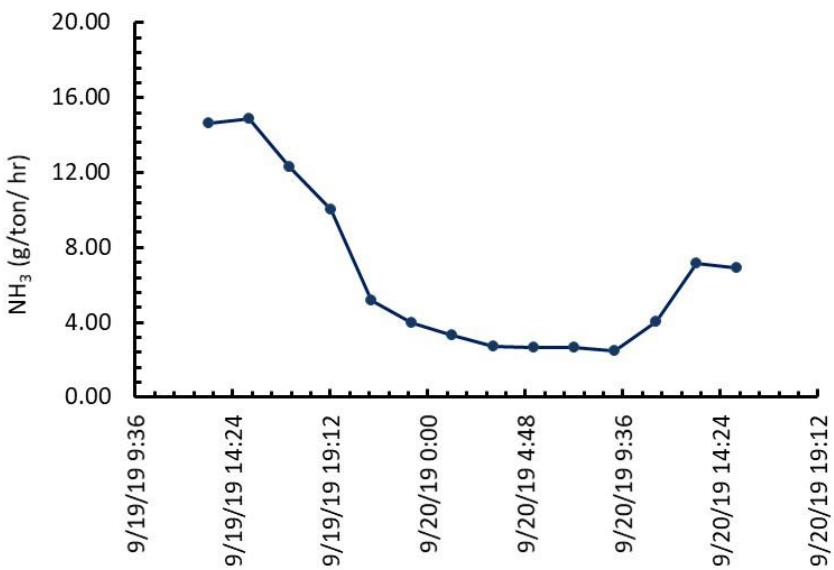


Figure 50. Emission rates of NH_3 from solids at Delta dairy.

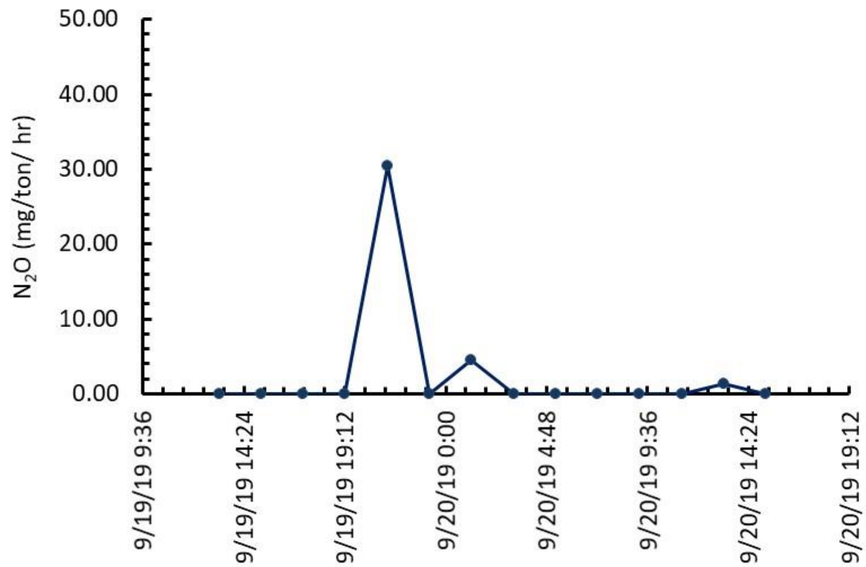


Figure 51. Emission rates of N_2O from solids at Delta dairy.

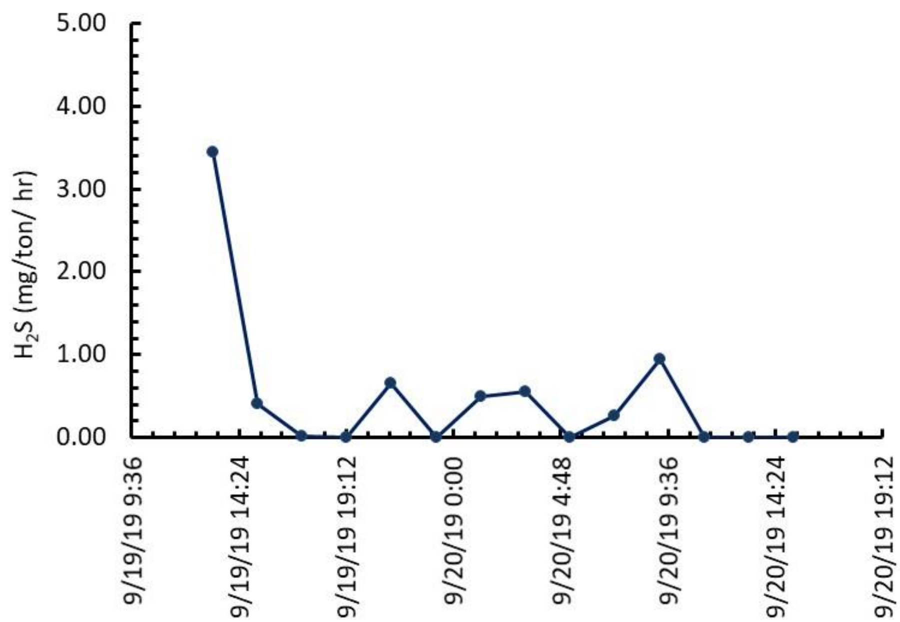


Figure 52. Emission rates of H_2S from solids at Delta dairy.

3.1.10 Echo dairy – lagoon

The emission rates of CH_4, NH_3, N_2O, and H_2S from the lagoon on Echo dairy are shown in Figure 53, Figure 54, Figure 55, and Figure 56, respectively. There was a relatively great peak of CH_4 emissions in the first day of the monitoring period. Then a relatively constant emission rates, with a few peaks, were determined. The emission rates of NH_3 had also two peaks in the first day, then they declined to a relatively constant level except a peak of emissions was determined on the third day of the monitoring period. The emission rates of N_2O were almost negligible for most of the monitoring time except a few peaks were determined. While the emission rates of H_2S were relatively high in the first day. Then they decreased over the rest of the monitoring period. There were also a few peaks of the emissions.

The emission rates of CH_4, and NH_3 ranged from 0.17 to 9.63 and from 0.05 to 0.32 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 30.09 and from 0 to 0.42 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 1.70 and 0.11 g/m^2/hr, respectively and 2.35 and 0.04 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 507.57, 34.01, 0.70 and 0.01 g/ animal unit/day, respectively (Table 10).

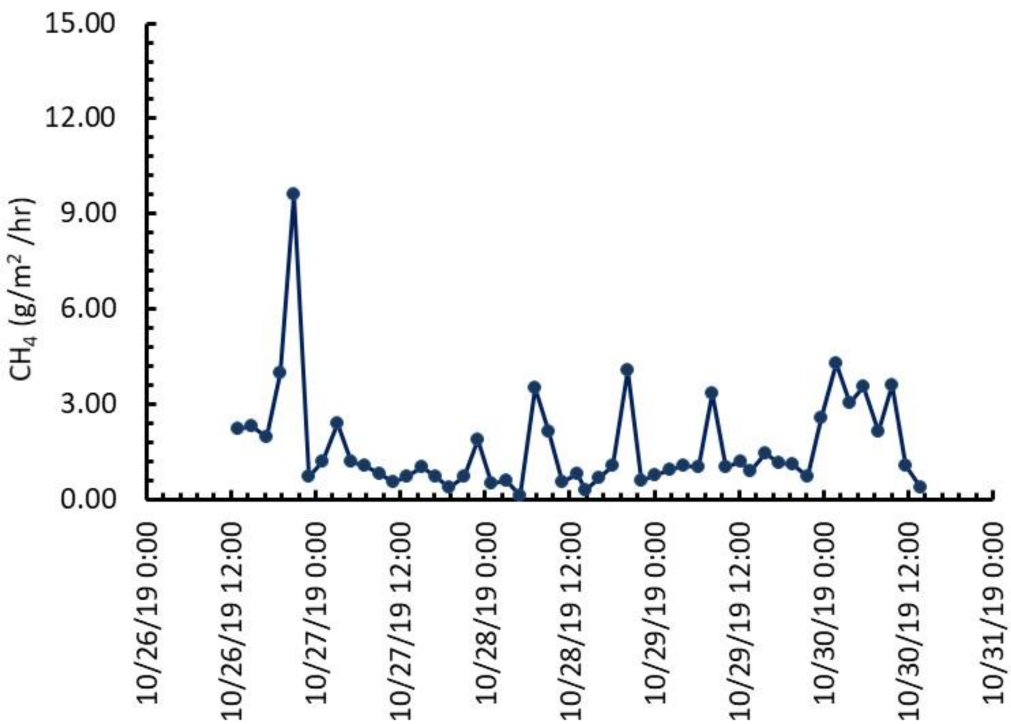


Figure 53. Emission rates of CH_4 from the lagoon at Echo dairy.

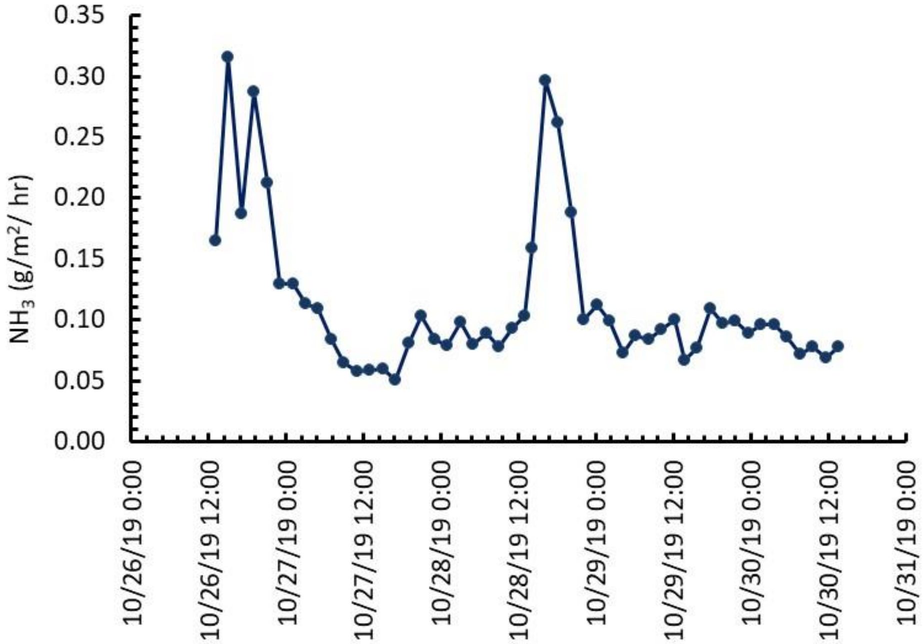


Figure 54. Emission rates of NH_3 from the lagoon at Echo dairy.

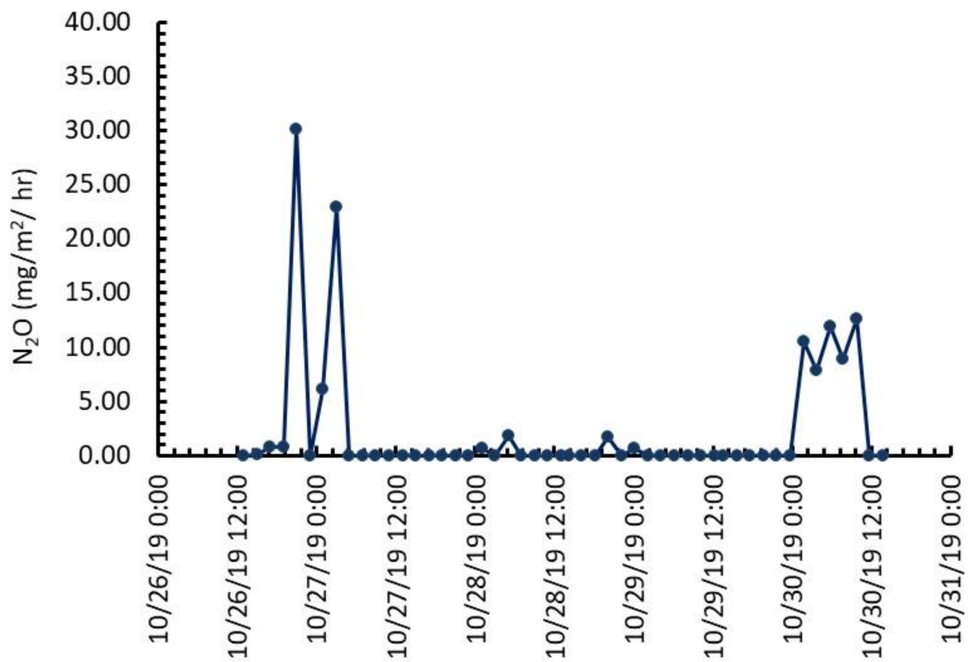


Figure 55. Emission rates of N_2O from the lagoon at Echo dairy.

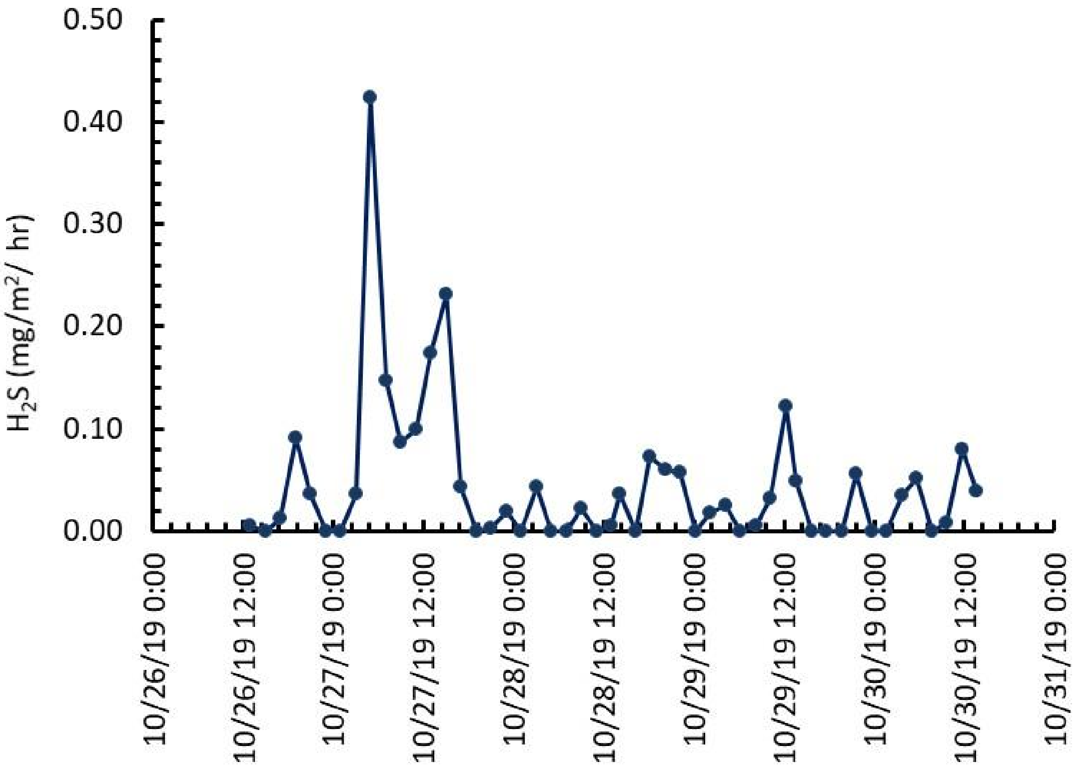


Figure 56. Emission rates of H_2S from the lagoon at Echo dairy.

3.1.11 Echo dairy – settling basin

The emission rates of CH_4, NH_3, N_2O, and H_2S from the settling basin at Echo dairy are shown in Figure 57, Figure 58, Figure 59, and Figure 60 respectively. The CH_4 emission rate was relatively constant during the emissions monitoring period with three peaks that were ranged from approximately 2.7 to 8.2 g/m^2/hr. Ammonia emissions were negligible for the first five hours of the monitoring period. There were three peaks of emissions of approximately 0.02-0.3 g/m^2/hr. The emissions of N_2O and H_2S were negligible, with a few peaks, for most of the monitoring period.

The emission rates of CH_4, and NH_3 ranged from 0.31 to 8.21 and from 0 to 0.03 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 7.26, and from 0 to 0.1 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 2.26 and 0.01 g/m^2/hr, respectively and they were 1.17 and 0.03 mg/m^2/hr, for N_2O and H_2S, respectively (Table 9). The daily emission of CH_4, NH_3, N_2O, and H_2S were 92.77, 0.41, 0.05, and 0.00 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. While it had relatively higher emission rates of other monitored gas than the settling basin.

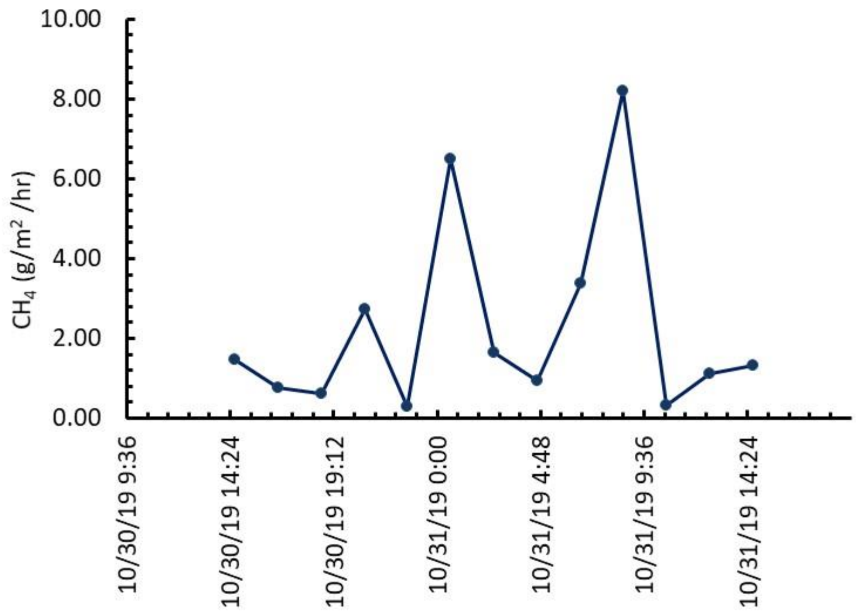


Figure 57. Emission rates of CH_4 from the settling basin at Echo dairy.

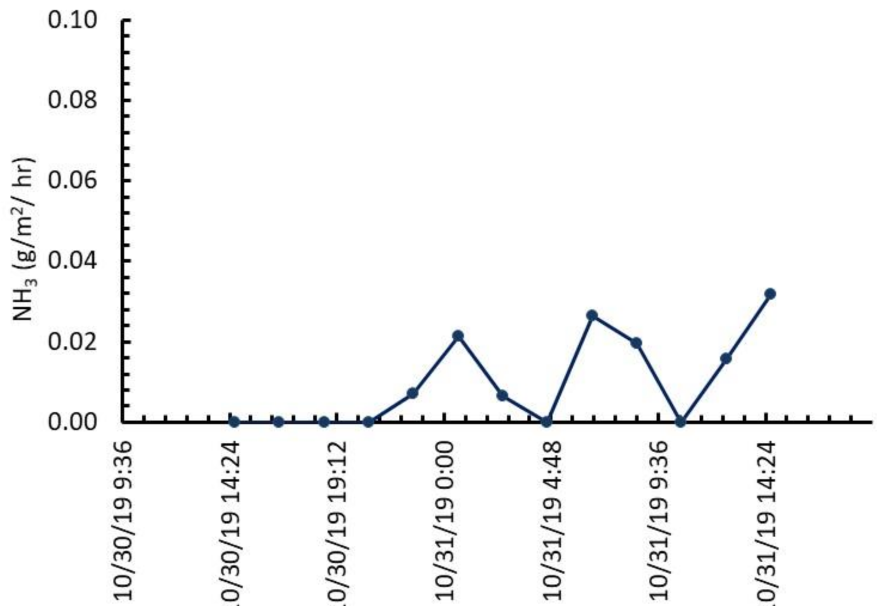


Figure 58. Emission rates of NH_3 from the settling basin at Echo dairy.

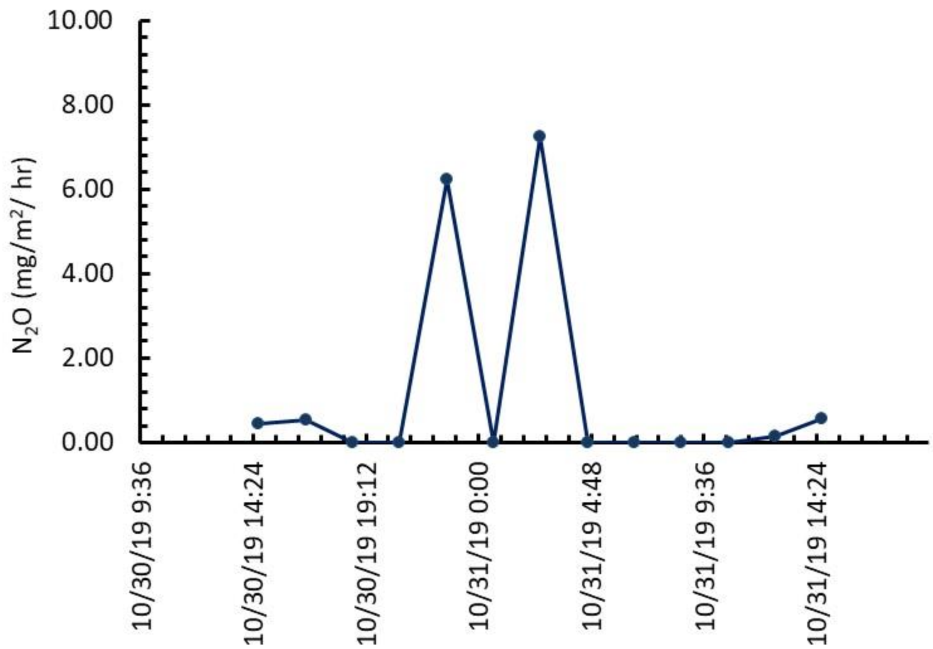


Figure 59. Emission rates of N_2O from the settling basin at Echo dairy.

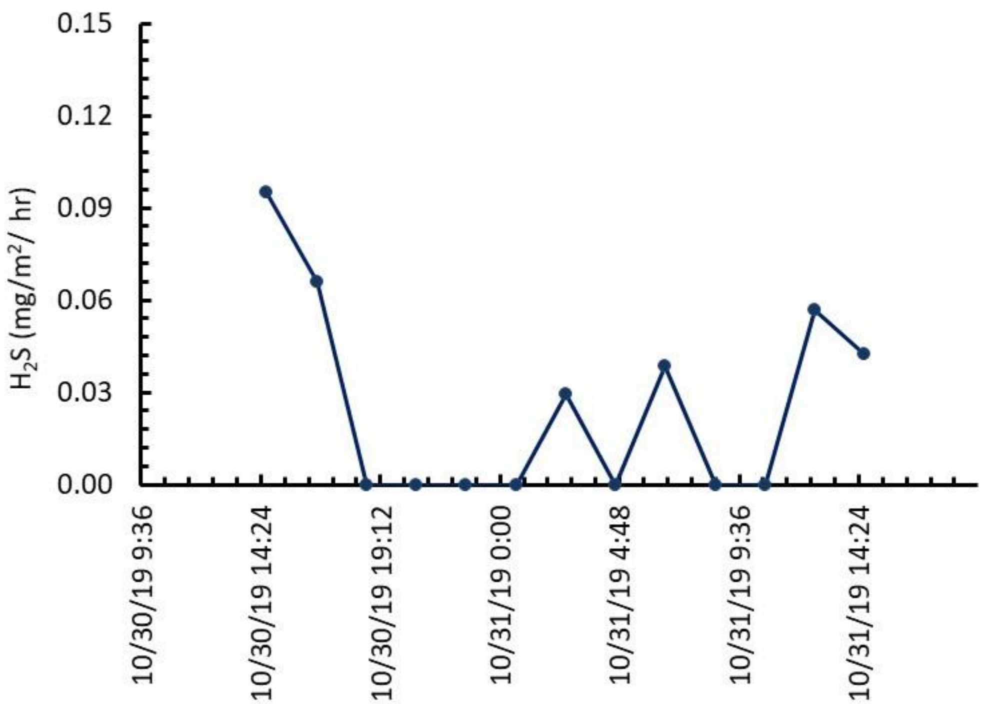


Figure 60. Emission rates of H_2S from the settling basin at Echo dairy.

3.1.12 Echo dairy – surface of the weeping wall

The emission rates of CH_4, NH_3, N_2O, and H_2S from the surface of the weeping wall at Echo dairy are shown in Figure 61, Figure 62, Figure 63, and Figure 64, respectively. At the time of the measurements, the weeping wall was at about one third of its hight at the full capacity. As can be seen from Figure 37 the emissions of CH_4 had a few peaks. The emissions of NH_3 sharply decreased after starting the measurements. A few peaks of emission rates after the first 12 hours of monitoring (Figure 61,). The emissions rates of N_2O and H_2S were negligible for most of the monitoring time with a few peaks (Figure 63, and Figure 64).

The emission rates of CH_4, and NH_3 ranged from 0 to 2.09 and from 0 to 0.03 g/m^2/hr, respectively. The ranges of the emission rates of N_2O and H_2S were from 0 to 36.95 and from 0 to 0.16 mg/m^2/hr, respectively. The average emission rates of CH_4 and NH_3 were 0.36 and 0.01 g/m^2/hr, respectively (Table 11) and the emissions of N_2O and H_2S were 3.05 and 0.02 mg/m^2/hr, respectively.

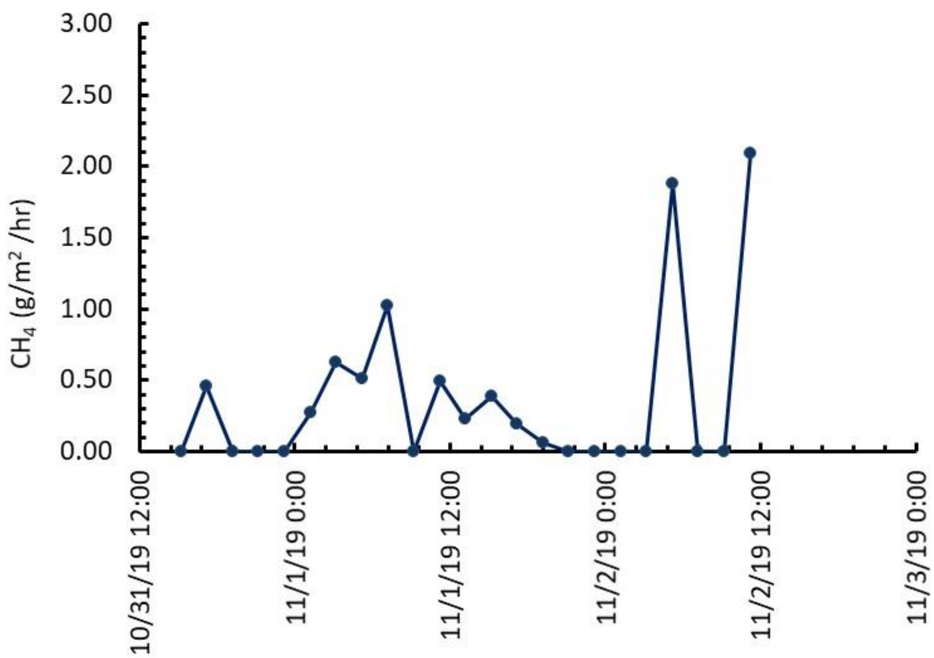


Figure 61. Emission rates of CH_4 from solids at Echo dairy.

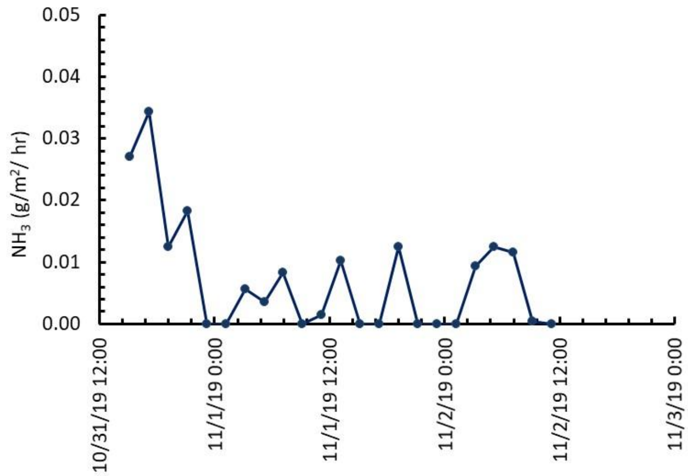


Figure 62. Emission rates of NH_3 from solids at Echo dairy.

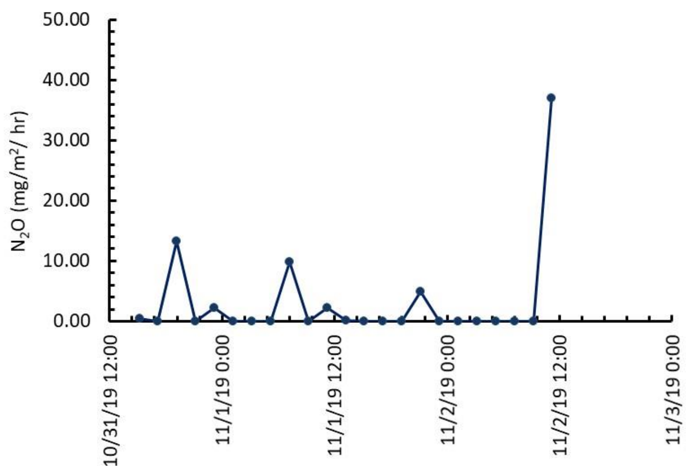


Figure 63. Emission rates of N_2O from solids at Echo dairy.

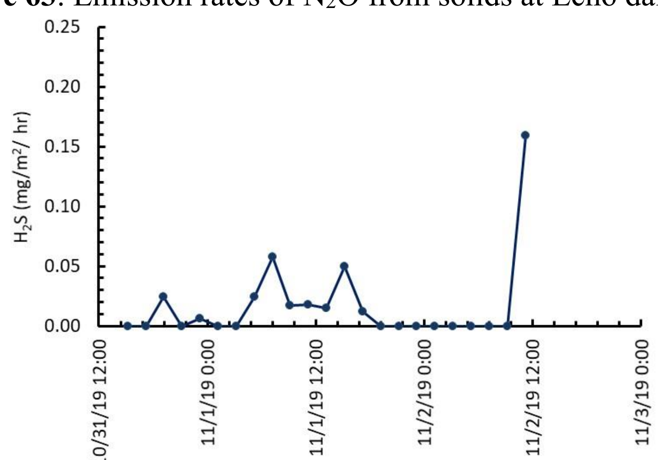


Figure 64. Emission rates of H_2S from solids at Echo dairy.

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
Alpha	Average	20.74	20.80	0.16	0.15	23.67	40.15	23.84	18.50
	Minimum	3.24	1.47	0.07	0.09	0.00	0.00	0.00	0.00
	Maximum	55.61	108.03	0.26	0.26	142.69	241.19	85.49	81.93
Bravo	Average	1.78	2.53	0.02	0.02	1.56	1.13	0.02	0.02
	Minimum	0.22	0.95	0.01	0.01	0.00	0.00	0.00	0.00
	Maximum	12.85	6.22	0.06	0.07	16.34	5.78	0.08	0.07
Delta	Average	11.09	6.67	0.27	0.18	3.95	0.12	0.01	0.03
	Minimum	2.88	4.57	0.14	0.08	0.00	0.00	0.00	0.00
	Maximum	32.09	13.49	0.43	0.37	92.47	1.41	0.15	0.12
Echo	Average	1.70	2.26	0.11	0.01	2.35	1.17	0.04	0.03
	Minimum	0.17	0.31	0.05	0.00	0.00	0.00	0.00	0.00
	Maximum	9.63	8.21	0.32	0.03	30.09	7.26	0.42	0.10

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
Alpha	3,072	1,298.18	618.04	9.89	4.57	1.48	1.19	1.49	0.55
Bravo	1,299	333.42	32.75	3.78	0.32	0.29	0.01	0.00	0.00
Delta	4,719	744.31	507.44	17.87	14.02	0.27	0.01	0.00	0.00
Echo	3,537	507.57	92.77	34.01	0.41	0.70	0.05	0.01	0.00

*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.

3.1.13 All dairies – manure solids

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

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

Dairy	Parameter	Average	Minimum	Maximum
Alpha	CH_4 (g/ton/hr)	319.41	0.00	1,104.09
	NH_3 (g/ton/ hr)	2.78	0.73	9.40

	N_2O (mg/ton/ hr)	395.80	0.00	1,246.34
	H_2S (mg/ton/ hr)	231.03	0.00	1,104.75
Bravo	CH_4 (g/ton/hr)	15.71	0.00	42.07
	NH_3 (g/ton/ hr)	1.12	0.29	4.46
	N_2O (mg/ton/ hr)	14.31	0.00	49.23
	H_2S (mg/ton/ hr)	0.23	0.00	1.35
	CH_4 (g/ton/hr)	4.19	0.00	34.61
Delta	NH_3 (g/ton/ hr)	6.63	2.47	14.85
	N_2O (mg/ton/ hr)	2.59	0.00	30.38
	H_2S (mg/ton/ hr)	0.49	0.00	3.45
Echo	CH_4 (g/m^2/hr)*	0.36	0.00	2.09
	NH_3 (g/m^2/hr)	0.01	0.00	0.03
	N_2O (mg/m^2/hr)	3.05	0.00	36.95
	H_2S (mg/m^2/hr)	0.02	0.00	0.16

* The emissions were calculated per each square meter of the weeping wall surface

3.2 Comparing the emissions of CH_4 Pre- and Post-AMMP

Quartile-Quartile plots for CH_4 emissions from the settling basins and the lagoons at the studied dairies Pre and Post-AMMP are shown in Appendix B (Figures B-1-B-8). As can be seen, most of the measured data are normally distributed with some exceptions for a few outliers that were not removed from the data before applying ANOVA analysis.

3.2.1 Alpha dairy

Measured and temperature-corrected average CH_4 emission rates Pre-AMMP and measured average CH_4 emission rates Post-AMMP from the settling basins and lagoons are shown in Table 12. Results of ANOVA are shown in

Table 13 and Table 14. As can be seen from Figure 65,

Table 13, and Table 14, there was a significant difference ($P<0.05$) in the emission rates of CH_4 from the lagoon in Alpha dairy Pre- and Post-AMMP. Higher CH_4 emission rates were determined Post-AMMP than Pre-AMMP. However, there was no significant difference in the emissions from the settling basin Pre- and Post-AMMP. The data in Table 12 might indicate that weather conditions are not be the only factor affecting the emissions. The changes in the amount and charcateristics of the manure delivered to the lagoon Pre- and Post-AMMP could be other factors responsible for the differences in the emissions Pre- and Post-AMMP. 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. The measured emissions of CH_4 from the settling basin Post-AMMP was lower than what was measured Pre-AMMP corrected for the temperature. However, the measured emissions from the lagoon Post-AMMP was greater than that Pre-AMMP corrected for the temperature. This means that the temperature was not the main reason for the differences in the emissions. The dairy owner mentioned that the mechanical separator was operated for a few months only due to the high cost of energy needed to operate the system.

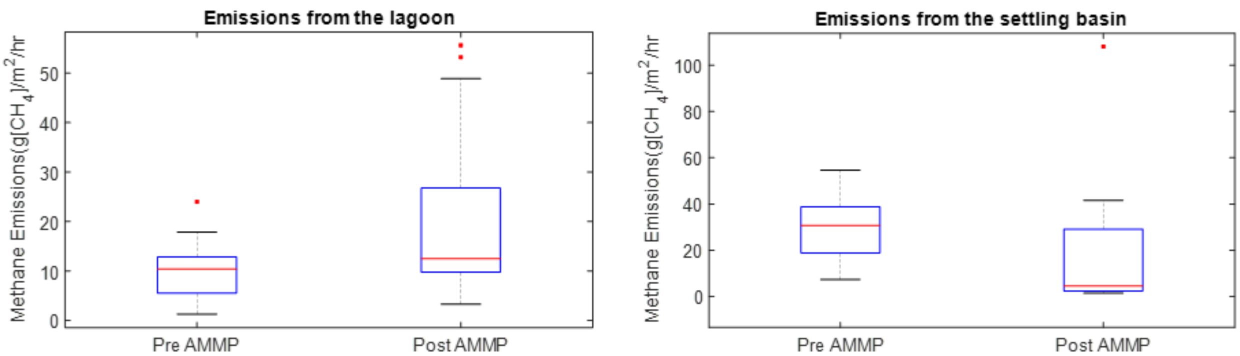


Figure 65. Box plot of average CH_4 emissions from the lagoon Pre and Post AMMP at Alpha dairy

3.2.2 Bravo dairy

For Bravo diary, the emission rates of CH_4 from the lagoon Post-AMMP were lower than that measured Pre-AMMP (Figure 66). However, the differences in the emission rates were not significant. The emissions of CH_4 from the settling basin Post-AMMP were significantly lower than those determined Pre-AMMP. The temperature corrected CH_4 emissions Pre-AMMP from the lagoon and the settling basin was lower than that measured values Post-AMMP (Table 12). This also confirms that the temperature was not the only factor affecting the emissions. Some other factors such as the cleaning of the settling basin and the withdrawal of water for irrigation affect the available amounts of VS for the anaerobic degradation into CH_4 in manure storages. Moreover, the screw press had some down time for maintenance, during that time the Pre-AMMP manure management (i.e., manure flushing to the settling basin and then to the lagoon) was employed.

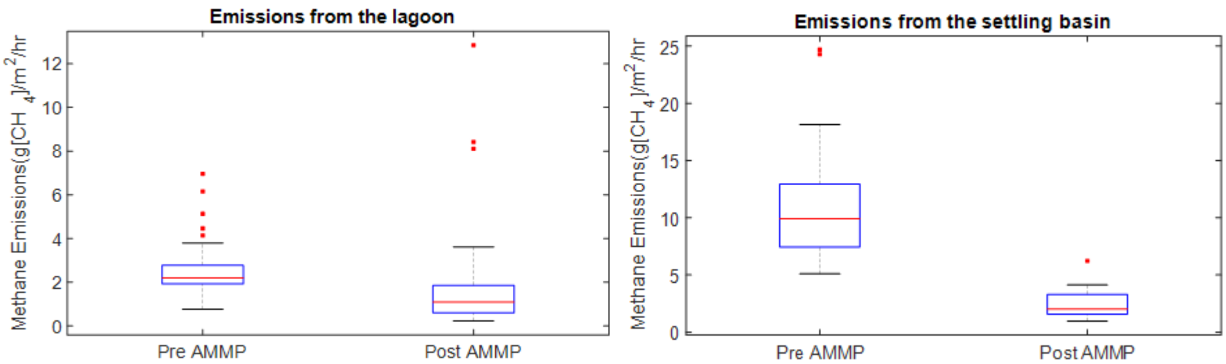


Figure 66. Box plot of average CH_4 emissions from the lagoon and settling basin Pre and Post AMMP at Bravo dairy

3.2.3 Delta dairy

For Delta dairy, the emissions of CH_4 from the lagoon Post-AMMP were significantly higher than those determined Pre-AMMP (Figure 67 and

Table 13). Higher emission rates were also determined from the settling basin Post-AMMP than Pre-AMMP. However, the difference in the emissions was not significant (Table 14). The temperature corrected CH_4 emissions Pre-AMMP from the lagoon was lower than that measured value Post-AMMP. For the settling basin, temperature corrected CH_4 emissions Pre-AMMP was higher than that measured values Post-AMMP (Table 12). The differences in the emissions Pre and Post-AMMP might also be explained by the unknown amounts of manure that was withdrawn for irrigation and the amount of solids removed from the settling basin during its cleaning. The farmer mentioned that setting basins are usually cleaned once per year with 100% removal while lagoons are cleaned 10 times per year with an estimated 10% removal of solids. AMMP practice (vacuum truck and sun drying) was only employed for 1-2 days weekly. The cleanness of barn floors after using the vacuum truck was not determined in this study. Manure left after the vacuum truck on barn floors could also be a factor that might affect the amount of manure delivered to the lagoon.

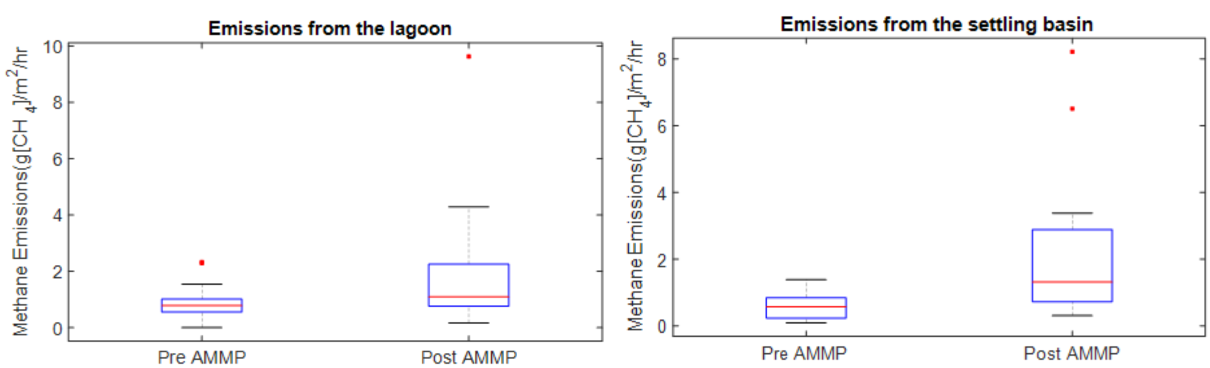


Figure 67. Box plot of average CH_4 emissions from the lagoon and settling basin Pre and Post AMMP at Delta dairy

3.2.4 Echo dairy

For Echo dairy, the emissions of CH_4 from the lagoon and settling basin Post-AMMP were significantly higher than those Pre-AMMP (Figure 68). The measured emissions of CH_4 from the lagoon and settling basin Post-AMMP were higher than those measured Pre-AMMP corrected for the temperature (Table 12).

It was expected that the weeping wall that was installed at Echo should not significantly affect the emissions because the weeping wall was not well designed. It consisted of only one cell and the settling basin was used during the drain and drying phases of the weeping wall. Ideally, three or more cells should be alternately employed so that no manure would be treated in the settling basin.

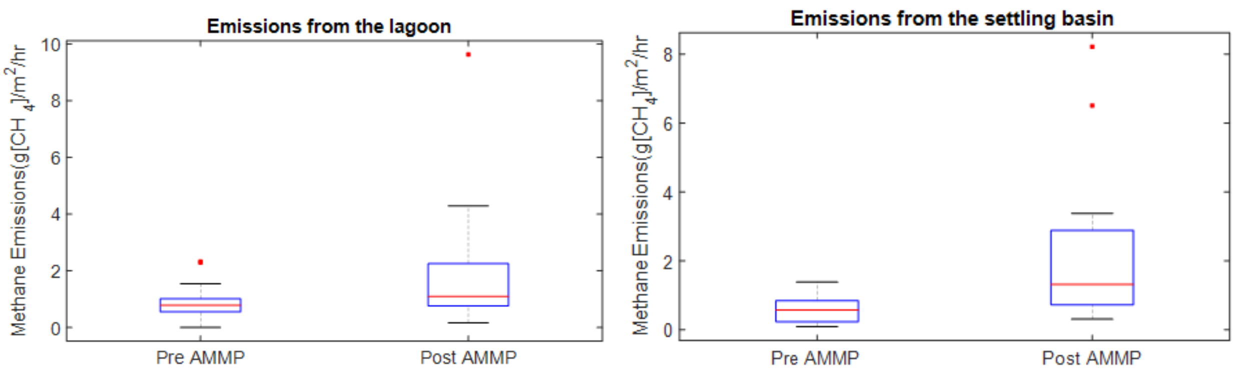


Figure 68. Box plot of average CH_4 emissions from the lagoon and settling basin Pre and Post AMMP at Echo dairy

Table 12. Measured and temperature-corrected average CH_4 emission rates (g/m^2/day) Pre-AMMP and measured average CH_4 emission rates Post-AMMP from the settling basins and lagoons at the studied dairies.

Dairy	Emission rates Pre-AMMP Corrected measured emission rates (Mitloehner et al., 2019)			Measured emission rates Post-AMMP		
	Settling basins	Lagoons	Total	Settling basins	Lagoons	Total
Alpha	918.94	297.94	1,216.88	499.20	497.76	996.96
Bravo	58.06	19.32	77.38	60.72	42.72	103.44
Delta	207.19	153.84	361.02	160.08	266.16	426.24
Echo	8.43	12.24	20.67	54.24	40.80	95.04

Table 13. ANOVA results for the lagoons on the studied dairies

Dairy	Source	Sum of squares (SS)	Degree of freedom (df)	Mean square (MS)	F	Prob>F
Alpha	Groups	1,629.4	1	1629.43	10.47	0.002
	Error	9173.3	59	155.57		
	Total	10,807.8	60			
Bravo	Groups	14.63	1	14.63	3.7	0.058
	Error	315.94	80	3.9492		
	Total	330.57	81			
Delta	Groups	874.91	1	874.91	36.63	4.37E-8
	Error	1,910.78	80	23.89		
	Total	2,785.7	81			
Echo	Groups	14.92	1	14.91	9.11	0.003
	Error	134.33	82	1.64		
	Total	149.25	83			

Table 14. ANOVA results for the settling basins on the studied dairies

Dairy	Source	Sum of squares (SS)	Degree of freedom (df)	Mean square (MS)	F	Prob>F
Alpha	Groups	505.2	1	505.23	0.9	0.353
	Error	12,947.7	23	562.944		
	Total	13,452.9	24			
Bravo	Groups	59271	1	592.71	30.16	4.314E-6
	Error	648.44	33	19.65		
	Total	1,241.14	34			
Delta	Groups	0.004	1	0.004	0	0.98
	Error	186.75	20	9.34		
	Total	186.76	21			
Echo	Groups	17.23	1	17.23	5.34	0.030
	Error	74.22	23	3.23		
	Total	91.45	24			

3.2.5 Justifications for observed emissions

Generally speaking, the increased emissions from the lagoons and settling basins, during the short period of emissions monitoring on the studied dairies, does not mean that the AMMP practices increased emissions. Theoretically, removing organic matter (volatile solids) prior to delivering manure to the settling basin and the lagoon should reduce the emissions from these two storages. More long-term measurements of emissions are needed to determine the reduction of emissions by employing AMMP practices. 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. There was also no information about the exact time and amount of solid removed during each cleaning event.

Non-optimal design and operation of AMMP practices (e.g., one cell weeping wall, and operating the mechanical separator for only part of the time) could be reasons for the increased measured emissions on the studied dairies. The screen mechanical separator at Alpha dairy should be employed everyday so that all flushed manure should first be treated with the mechanical separator prior to the delivery to the settling basin and lagoon. The increased operation time could increase the amount of solids (i.e., volatile solids) that can be averted from the settling basin and lagoon. Reducing the down time of the screw press on Bravo dairy could also reduce the emissions from the settling basin and lagoon. Reducing the amount of volatile solids delivered to the settling basin and lagoon decreases the emissions of CH_4 and other gases from them. For selected mechanical separators at California dairies, Zhang et al. (2018) found that CH_4 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 CH_4 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.

Increasing the time of using the AMMP practice at the Delta dairy may also reduce the amount of volatile solids delivered to the settling basin and lagoon. This can result in the reduction of CH_4 emissions from the settling basin and lagoon. The design of the weeping wall at Echo dairy should be modified by adding at least one more cell that could be used alternately with the current weeping wall cell. Zhang et al. (2018) determined a VS removal efficiency of 79 – 86% from a weeping wall system that consisted of four cells that were alternately employed. Based on this VS removal, a CH_4 reduction potential of 75 – 81% could be determined using CH_4 production potential tests.

The measured emission rates of CH_4 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 CH_4 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 CH_4 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.

Emissions of CH_4 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. CH_4 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.

3.3 Characteristics of manure samples

3.3.1 Total and volatile solids

The characteristics of manure samples collected during the emissions monitoring period are shown in Table 15. The settling basins received flushed manure from the barns at Alpha and Bravo dairies when AMMP practices were not operated. At Delta dairy, the settling basin received all flushed manure on the days in which the vacuum truck was not employed. While at the Echo dairy, the settling basin received the flushed manure when the weeping wall was at the phases of drying and emptying. As can be seen from Table 15, for the settling basin inlets, the higher (7.84) and lower (6.76) pH values were measured at Echo and Bravo dairy, respectively. The pH values for the lagoon inlet were almost similar at Alpha and Echo: 7.62 and 7.61, respectively. The pH of the lagoon surface at Alpha and Echo (7.93 and 7.59) were relatively higher than those measured at the other two dairies (7.20 and 7.27). For Alpha, Bravo, and Delta, the pH values of lagoon surfaces were restively higher than the inlets of the settling basin and the lagoons. While for Echo dairy, the pH value (7.59) of lagoon surface was slightly lower than the lagoon inlet (7.61). The lowest (0.52%) and highest (1.18%) total solids (TS) contents of the settling basin inlet were determined in Bravo and Echo respectively. The low TS content in the settling basin inlet in Bravo could be due to the employing of the screw press prior the settling basin. The TS contents in the inlets of the lagoons at all the studied dairies were lower that the inlets of the settling basin. This is due to the separation of solids by the settling basin. The volatile solids (VS) contents in the total solids in the inlets of the settling basin was relatively higher than the lagoon inlets and surface. This may be due to the separation of the fibrous fraction prior that lagoon. The fibrous fraction contains mainly undigested feed and bedding material.

3.3.2 Dissolved organic carbon and nitrogen contents in liquid samples

As can be seen from Table 16, Dissolved Organic Carbon (DOC) at the inlet of the settling basin at Bravo, Delta, and Echo were similar at 0.05 g/gTS while it was relatively high (0.24 g/gTS) at Alpha dairy with high standard deviation. The DOC in the lagoon inlets and surfaces at Bravo, Delta, and Echo were essentially the same (0.05 g/g TS). However, it was higher for Alpha dairy: 0.08 and 0.12 g/gTS, respectively.

Relatively higher NH_3 concentrations were determined for the samples collected from Alpha dairy than the other three dairies. Generally, for all the studied dairies, low concentrations of nitrate were determined for all samples. The total nitrogen contents in the inlets of the settling basins were similar (0.07 g/gTS) at Alpha and Delta dairies. While there were 0.06 and 0.05 at Bravo and Echo respectively. The total nitrogen in the inlet of the lagoons at Alpha and Delta were also similar (0.08 g/gTS).

3.3.3 Volatile fatty acids in liquid samples

The concentrations of VFAs are shown in Table 17. The concentrations of VFAs were determined as acetic acid equivalent. As can be seen, acetic acid was the predominant VFA in all samples. The settling basin and the lagoon inlets at Alpha dairy had the highest VFAs contents (677.7 and 654.1 mg [acetic acid]/l) as compared with the settling basin and lagoon inlets at the other dairies. The lagoon inlet at Alpha had the highest concentration (654.1 mg [acetic acid]/l) as compared with other lagoon inlets. This may be due to the fact that when the separator is operated the lagoon receives manure directly after the separator. This was the reason for determining almost the same VFAs concentration in the lagoon inlet and separator outlet. The VFAs concentration in the separator effluent was almost similar to that of the flushed manure (i.e., settling basin influent). The inlet of the settling basins at Bravo and Delta had almost similar VFAs concentrations. For each of the studied dairies, lagoon surfaces had the lowest VFAs concentrations among all the other samples. The lagoon inlet in Delta had the lowest VFAs concentration among all the lagoon inlets. This might be due to the relatively low VFAs concentration in flushed manure or long retention time (unknown) in the settling basin. The lagoon inlet in Echo had also relatively high VFAs concentration (353.3 mg [acetic acid]/l). This might be due to the fast seepage of the liquid fraction of manure in the weeping wall.

Table 15. pH, and TS, and VS contents in manure samples during the emission measurements

Dairy	pH			TS (% Total)			VS (% TS)		
	Settling basin inlet	Lagoon inlet	Lagoon surface	Settling basin inlet	Lagoon inlet	Lagoon surface	Settling basin inlet	Lagoon Inlet	Lagoon surface
Alpha	7.63±0.17	7.62±0.08	7.93±0.08	1.00±0.29	0.76±0.06	0.62±0.03	50.50±6.47	48.33±2.52	43.66±1.17
Bravo	6.76±0.05	6.83±0.17	7.20±0.17	0.52±0.03	0.47±0.07	0.31±0.06	60.11±2.25	58.96±6.16	44.40±6.78
Delta	7.26±0.14	7.16±0.05	7.27±0.04	0.83±0.36	0.83±0.36	0.55±0.02	56.22±7.79	44.42±1.53	43.69±4.58
Echo	7.84±0.08	7.61±0.07	7.59±0.05	1.18±0.22	1.18±0.22	0.72±0.08	64.17±15.88	54.89±1.63	50.43±1.13

Table 16. 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		
	S.B. Inlet	Lg Inlet	Lg Sf	S.B. Inlet	Lg Inlet	Lg Sf	S.B. Inlet	Lg Inlet	Lg Sf	S.B. Inlet	Lg Inlet	Lg Sf	S.B. Inlet	Lg Inlet	Lg Sf
Alpha	0.24±0.12	0.08±0.02	0.12±0.01	0.02±0.00	0.02±0.01	0.03±0.00	0.04±0.01	0.05±0.01	0.06±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.07±0.01	0.08±0.01	0.09±0.00
Bravo	0.05±0.03	0.07±0.02	0.06±0.01	0.02±0.00	0.03±0.00	0.04±0.00	0.03±0.01	0.03±0.01	0.04±0.00	0.004±0.001	0.001±0.002	0.002±0.002	0.06±0.01	0.06±0.01	0.08±0.00
Delta	0.05±0.00	0.05±0.00	0.05±0.00	0.02±0.02	0.03±0.01	0.03±0.01	0.03±0.01	0.04±0.00	0.05±0.01	0.011±0.014	0.004±0.005	0.00±0.00	0.07±0.00	0.08±0.00	0.08±0.00
Echo	0.05±0.01	0.05±0.00	0.05±0.00	0.03±0.01	0.03±0.00	0.02±0.00	0.02±0.00	0.03±0.00	0.03±0.00	0.00±0.00	0.00±0.00	0.001±0.002	0.05±0.01	0.06±0.00	0.06±0.00

S.B. Inlet: settling basin inlet/flushing water outlet
Lg Inlet: lagoon Inlet/ settling basin outlet
Lg Sf: lagoon surface water
Lg Inlet: lagoon Inlet/ settling basin outlet

Table 17. Volatile fatty acids 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
Alpha*	Settling basin inlet	529.7±160.0	72.0±28.0	7.5±1.3	16.9±12.4	2.6±3.0	677.7±228.2
	Lagoon inlet	447.1±20.2	125.1±13.8	9.2±0.8	8.7±1.4	0.0±0.0	654.1±39.4
	Lagoon surface	241.1±9.3	49.3±3.5	5.1±0.3	5.0±0.0	0.0±0.0	327.8±14.3
	Separator outlet	526.8±29.6	62.7±17.2	7.6±0.6	15.7±1.8	5.0±0.2	664.4±17.2
Bravo	Settling basin inlet	231.6±16.7	104.8±9.2	5.6±0.1	32.0±4.9	12.1±1.8	466.5±41.3
	Lagoon inlet	75.54±81.95	16.92±21.69	2.58±2.92	3.1±3.9	3.3±2.7	115.4±129.4
	Lagoon surface	10.6±9.7	1.1±0.3	0.4±0.5	0.3±0.1	1.8±2.5	16.7±15.0
Delta	Settling basin inlet	306.8±0.6	67.4±15.0	8.30±2.8	20.6±1.6	4.6±0.9	459.8±25.5
	Lagoon inlet	61.2±9.4	6.5±1.9	0.5±0.0	0.9±0.2	0.0±0.0	72.7±11.8
	Lagoon surface	25.2±0.6	0.2±0.3	0.9±1.3	0.7±0.2	1.0±1.4	30.0±6.2
Echo	Settling basin inlet	460.5±21.7	53.5±15.2	11.1±0.8	21.0±4.4	4.8±0.9	599.6±53.6
	Lagoon inlet	294.0±63.7	16.0±18.4	8.2±1.4	8.7±6.6	4.2±0.8	353.3±105.0
	Lagoon surface	166.7±13.2	0.9±0.0	5.6±0.5	1.2±0.2	0.6±0.1	180.9±14.6

* Analyses were conducted by Dairy one lab, NY; other samples were analyzed at UC Davis

3.4 Model predictions

3.4.1 Baseline concentration fields

Figure 69 illustrates the baseline future concentrations of ozone and $PM_{2.5}$ predicted under the Low Carbon Energy (GHGAi) scenario and the Business as Usual (BAU) scenario. Each concentration illustrated in Figure 2 is calculated based on 224 simulated days randomly distributed across a 10 year period between 2046 - 2055.

The 4th highest 8-hr ozone concentrations peak in the regions over the San Joaquin Valley and into the Sierra Nevada Mountain Range at the interface between urban oxides of nitrogen (NOx) emissions and biogenic volatile organic compound (VOC) emissions. Maximum values of the 4th highest 8-hr ozone concentrations over the eastern and southern portions of the San Joaquin Valley (SJV) are approximately 65 ppb in the Low Carbon Energy scenario and 68 ppb in the BAU scenario.

Long-term PM2.5 concentrations are predicted to reach 12-13 $\mu g/m^3$ in the regions around major cities in the BAU scenario and 18 $\mu g/m^3$ and 17-18 $\mu g/m^3$ in the SJV between Fresno and Bakersfield. $PM_{2.5}$ concentrations predicted in the Low Carbon Energy scenario follow a similar spatial pattern but with concentrations that are 1-2 $\mu g/m^3$ lower than the BAU values.

The results illustrated in Figure 69 show that the baseline atmospheric conditions are cleaner under the Low Carbon Energy scenario than the BAU scenario due to reduced emissions. The reductions in the NOx and VOC emissions that lead to the cleaner atmosphere in the Low Carbon Energy scenario could potentially shift the atmospheric chemistry from a VOC-limited regime to a NOx-limited regime. This issue will be explored further in the following sections that examine how changes in dairy emissions influence ozone and $PM_{2.5}$ concentrations.

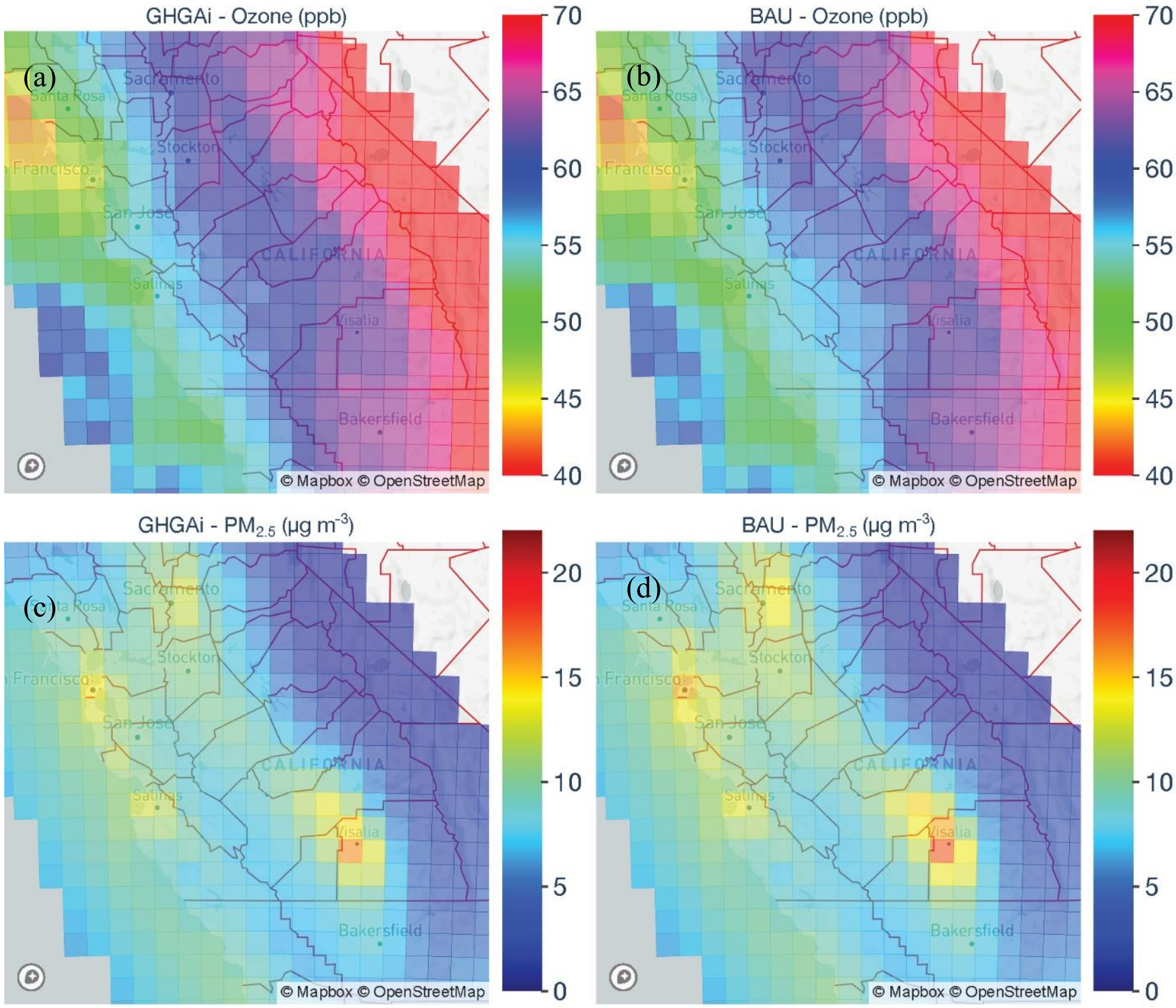


Figure 69. (a, b) Absolute baseline concentrations of 4th highest maximum 8-hour daily average of ozone concentration among 224 days of simulations and (c, d) total average $PM_{2.5}$ concentrations of 32 simulations. (a, c) Show conditions under a Low Carbon Energy scenario, while (b, d) show conditions under a Business as Usual (BAU) scenario.

3.4.2 Perfect AMMP concentration fields in BAU future

Figure 70 shows the ozone concentration changes from the Perfect AMMP scenario where all the dairy waste emissions are removed from the emission inventory using an AMMP with 100% efficiency (see complete description in Section 2.2.2). Each panel shows the average changes in 8-hour maximum daily O_3 concentrations for four seasons, average of all 32 simulations, and the 4^{th} maximum of O_3 concentrations. Universally, the O_3 concentration decreased over the SJV in response to removing VOC emissions from the dairy farms. Across the seasons, changes in the spring are minimal, changes in the summer and fall are approximately equal, and changes in the winter are greatest, but all seasonal changes in 8-hr maximum daily average O_3 concentrations are less than 1 ppb. The lower right panel of Figure 70 shows the changes to the 4th highest 8-hr maximum daily O_3 concentration over the entire 224 simulated days in response to removing the dairy waste emissions entirely. The 4^{th} highest O_3 concentrations decrease by approximately 0.6 ppb in response to the complete elimination of emissions from dairy waste. This response suggests that the baseline ozone chemical regime in the SJV under the BAU future is VOC-limited, but that dairy waste VOCs are not a strong component of the O_3 formation.

Figure 71 shows the difference in the total average of $PM_{2.5}$ concentrations due to adoption of the Perfect AMMP in the BAU baseline. $PM_{2.5}$ concentrations decrease by a maximum of 1.5 $\mu g/m^3$ when dairy waste emissions are eliminated, primarily due to the reduction in the "others" chemical species dominated by dust emissions. This indicates that most of the emissions changes were associated by reductions in primary dust from animals walking in dairy freestall barns and adjacent drylot corrals. It is unlikely that AMMPs applied to dairy freestall barns and adjacent drylot corrals will reduce dust emissions, meaning that the majority of the $PM_{2.5}$ reductions illustrated Figure 71 will not be achievable in real-world applications.

It should be noted that NH_3 emissions were also eliminated from dairy waste emissions coded with EIC number 620-618-0262-0101, but excess NH_3 from other agricultural sources in the San Joaquin Valley are sufficient to neutralize all available nitric acid. Particulate nitrate concentrations are relatively unchanged in response to NH_3 reductions from dairy cattle. The minor increases in $PM_{2.5}$ nitrate along the western border of the modeling domain are caused by updated treatments for background $PM_{2.5}$ nitrate blowing in from the ocean rather than changes to the dairy emissions under the Perfect AMMP. This artifact does not influence concentrations in the SJV.

The modest changes to the O_3 and $PM_{2.5}$ concentrations in response to the limiting AMMP scenario involving elimination of all emissions from dairy cattle establishes realistic expectations for the effect of a real-world AMMPs on air quality in the San Joaquin Valley. Expected changes in 8-hr average O_3 are projected to be less than 0.6 ppb and expected changes in $PM_{2.5}$ mass are expected to be less than 0.25 $\mu g/m^3$ (after discounting the effects of altered dust emissions).

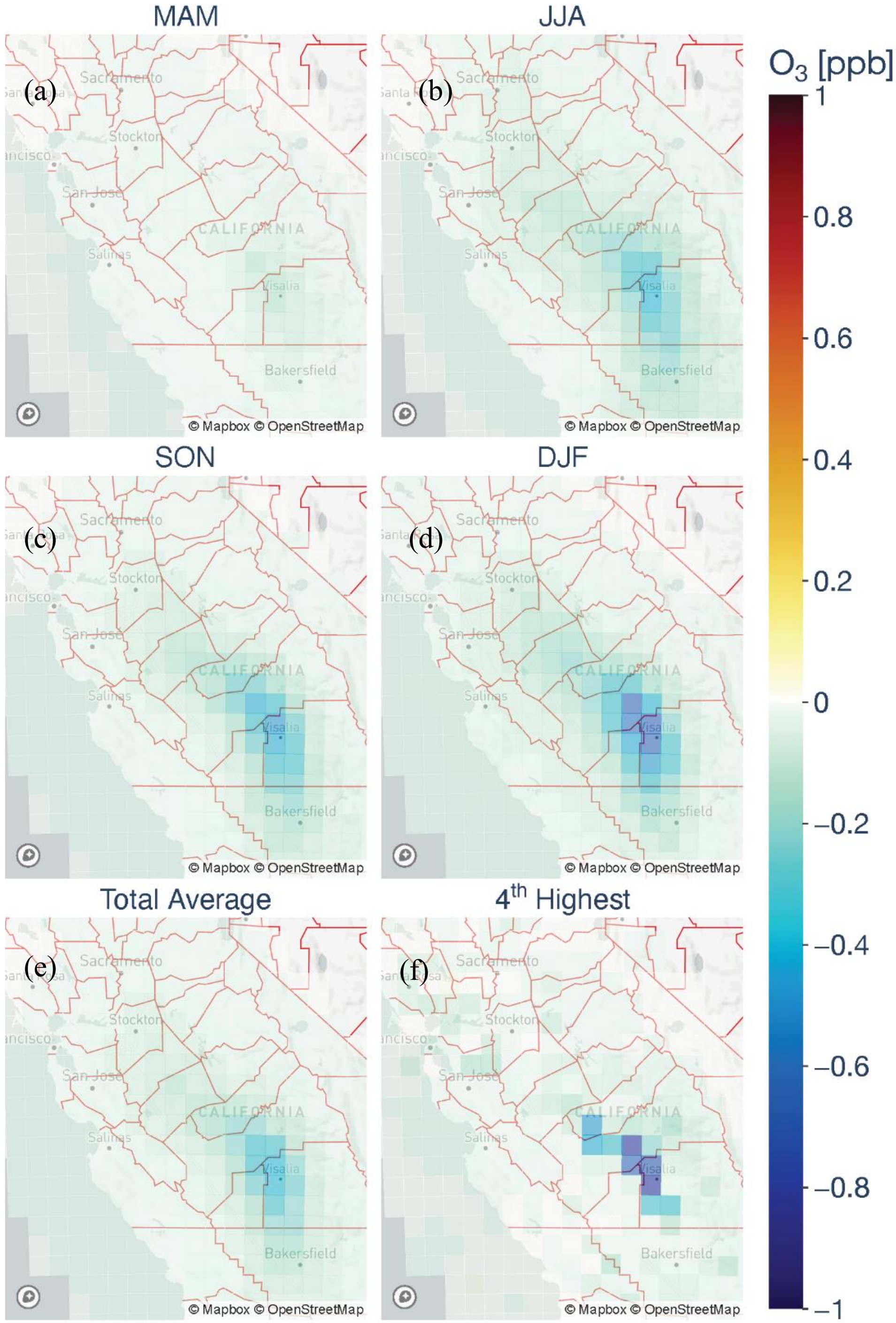


Figure 70. Changes in 8-hour maximum daily O_3 concentration (ppb) under "Perfect AMMP" in a BAU Future. Displayed concentrations are simulations "without dairy waste emissions" minus "with dairy waste emissions". Negative values indicate reduced O_3 concentration under the

"Perfect AMMP". (a) Average of March, April, and May, (b) average of June, July, and August, (c) average of September, October, and November, (d) average of December, January, and February, (e) average of 32 one-week-long simulations, and (f) the 4th highest 8-hour daily maximum O_3 concentration in 224 days of simulations.

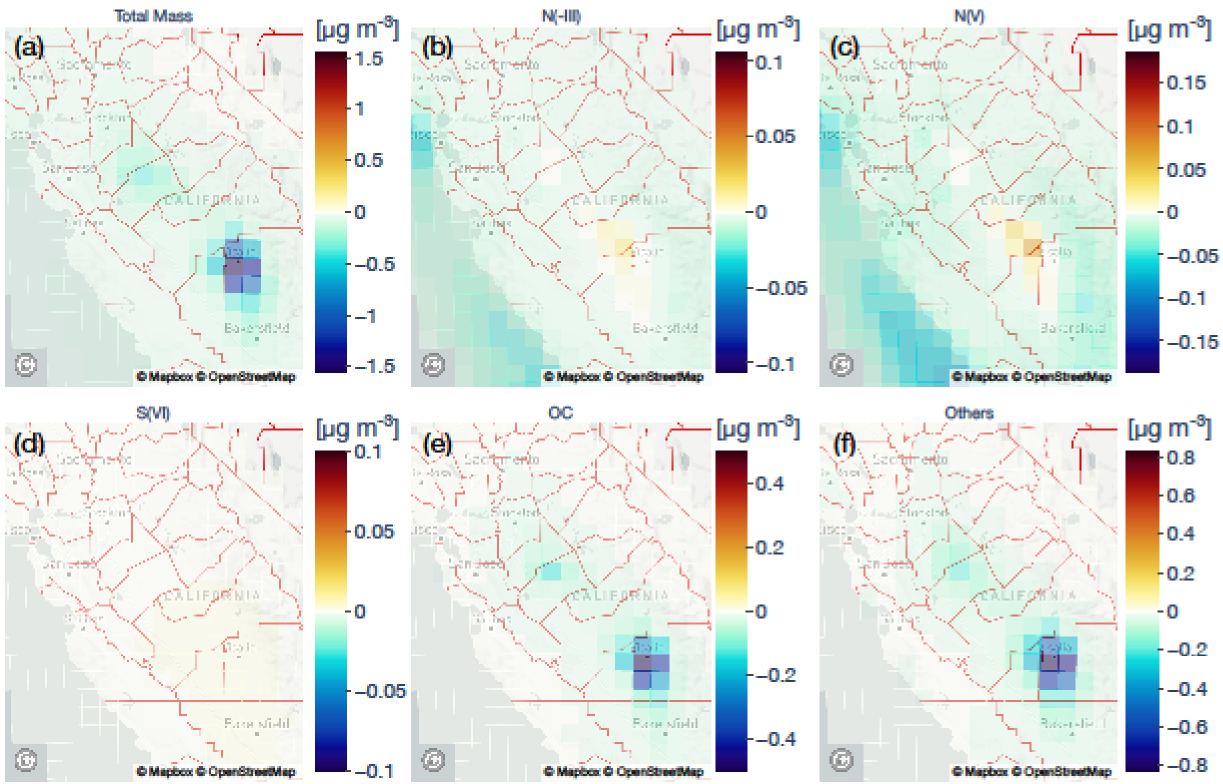


Figure 71. Changes in annual average $PM_{2.5}$ concentrations under "Perfect AMMP" in a BAU Future. Displayed concentrations are simulations "without dairy waste emissions" minus "with dairy waste emissions". Negative values indicate reduced $PM_{2.5}$ concentration under the "Perfect AMMP". All results are averaged across the 32 one-week-long simulations. (a) Total $PM_{2.5}$ mass, (b) ammonium, (c) nitrate, (d) sulfate, (e) organic compounds, and (f) Others (dominated by dust).

3.4.3 Perfect AMMP concentration fields in low carbon future

Figure 72 shows predicted changes in 8-hr maximum daily average O_3 concentrations in response to the adoption of a perfect AMMP in the baseline Low Carbon Energy (GHGAi) atmosphere. The spatial and seasonal patterns of O_3 concentration changes attributable to the Perfect AMMP in the Low Carbon Future atmosphere are similar to the BAU atmosphere but the magnitude of the changes are moderated. Maximum changes in 8-hr maximum daily average O_3 concentrations shown in Figure 72 are less than 0.2 ppb, which is a factor of 3-4 times lower than changes in the BAU atmosphere (see Figure 70).

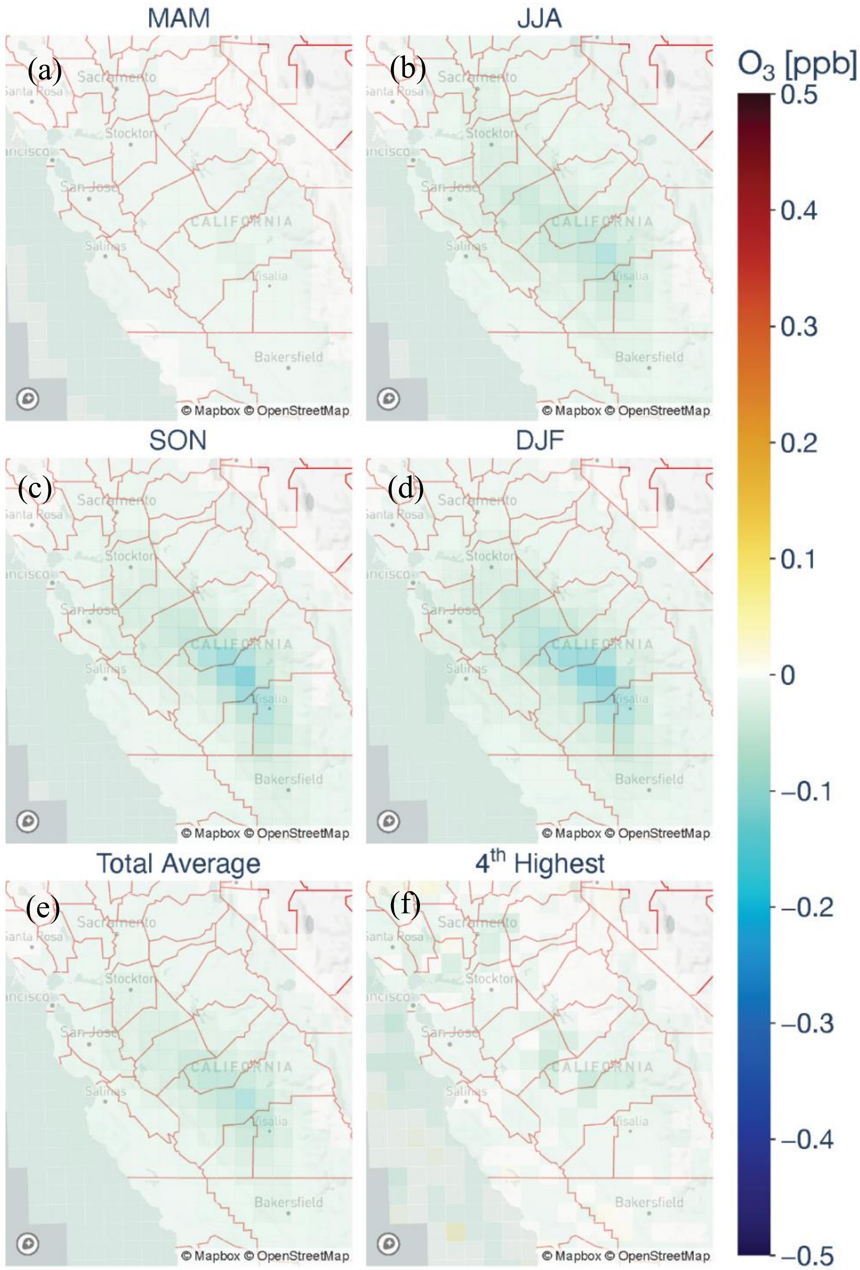


Figure 72. Changes in 8-hour daily maximum O_3 concentration (ppb) under "Perfect AMMP" in a Low Carbon Future. Displayed concentrations are simulations "without dairy waste emissions" minus "with dairy waste emissions". Negative values indicate reduced O_3 concentration under the "Perfect AMMP". (a) Average of March, April, and May, (b) average of June, July, and August, (c) average of September, October, and November, (d) average of December, January, and February, (e) average of 32 one-week-long simulations, and (f) the 4th highest 8-hour daily maximum O_3 concentration in 224 days of simulations.

Figure 73 shows the changes in long-term $PM_{2.5}$ concentrations predicted in the SJV in response to the adoption of a perfect AMMP in a Low Carbon future atmosphere. The spatial pattern and magnitude of the changes in $PM_{2.5}$ concentrations are almost identical in the Low Carbon Future atmosphere (Figure 73) and the BAU atmosphere (Figure 71) because the atmospheric chemical regime has very little influence on the primary PM components that drive most of the changes. The minor changes in $PM_{2.5}$ nitrate concentrations on the western portion of the domain are the product of changing treatments for boundary conditions, not associated with changing dairy emissions. Reduced dust emissions drive all the $PM_{2.5}$ reductions shown in Figure 73, but these are likely not achievable in a real-world AMMP.

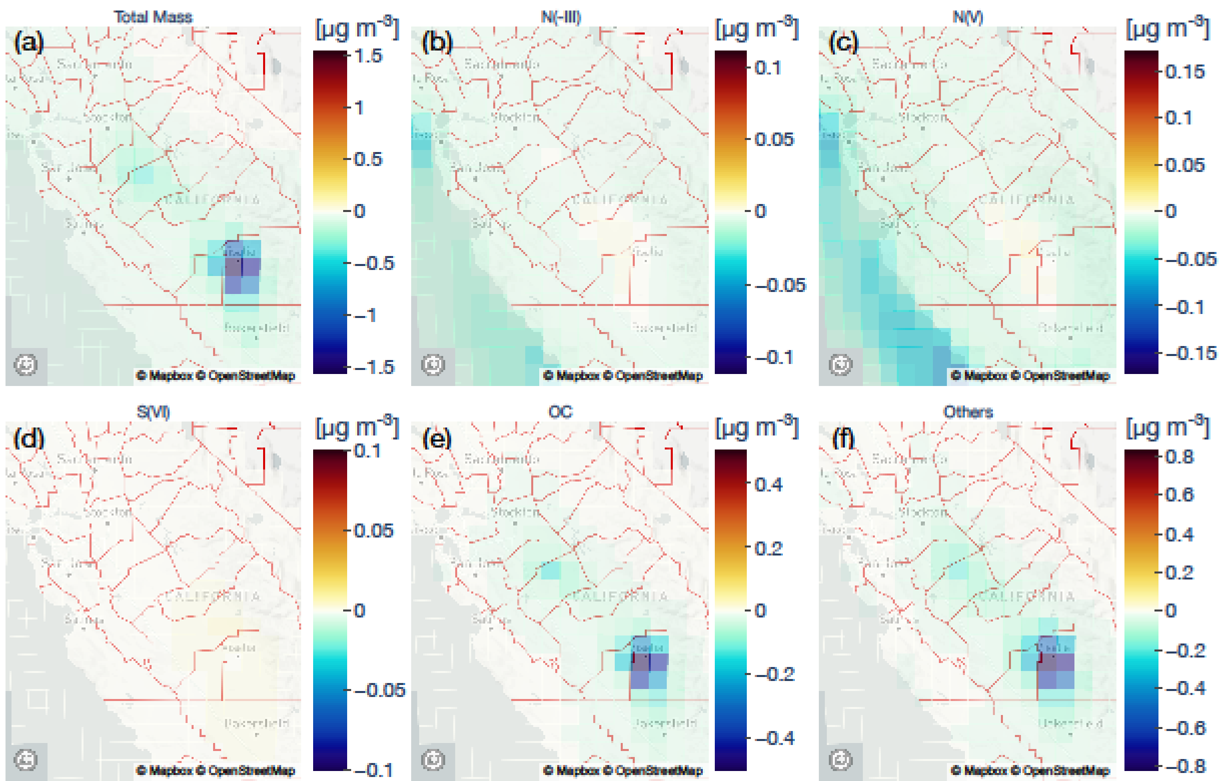


Figure 73. Changes in annual average $PM_{2.5}$ concentrations under "Perfect AMMP" in a Low Carbon Future. Displayed concentrations are simulations "with biogas electricity generation" minus "with dairy waste emissions". Negative values indicate reduced $PM_{2.5}$ concentration under the "Biogas Electricity Generation". All results are averaged across the 32 one-week-long simulations. (a) Total $PM_{2.5}$ mass, (b) ammonium, (c) nitrate, (d) sulfate, (e) organic compounds, and (f) Others (dominant with dust).

3.4.4 Biogas electricity generation concentration fields in BAU future

Figure 74 illustrates predicted changes to 8-hr maximum daily average O_3 concentrations in response to the widespread adoption of biogas production + electricity generation across dairy farms in the SJV. Emissions of traditional VOCs from dairy waste are eliminated under this scenario, and emissions of NOx and $PM_{2.5}$ are increased from the biogas combustion process. Predicted ambient concentrations of NOx increase by approximately 0.15 ppb in response to increased NOx emissions from biogas combustion. This change in NOx concentrations is relatively minor and so the spatial pattern of changing O_3 concentrations under the Biogas Electricity Generation scenario is driven mostly by the reduction in the emissions of VOCs from dairy waste. The spatial pattern of changes to O_3 concentrations in the Biogas Electricity Generation scenario (Figure 74) is therefore very similar to the spatial pattern predicted under the Perfect AMMP scenario (Figure 72). The majority of the O_3 concentration reduction occurs in the agricultural region between Fresno and Bakersfield that has a large number of dairy farms. Maximum reductions in 8-hr average O_3 concentrations are predicted to be 0.6 – 0.8 ppb.

Figure 75 illustrates predicted changes to long-term $PM_{2.5}$ concentrations in the SJV in response to the adoption of Biogas Electricity Generation in a BAU atmosphere. Minor increases in $PM_{2.5}$ nitrate concentrations of 0.05 $\mu g/m^3$ are predicted in the SJV in response to increased NOx emissions from biogas combustion to produce electricity. Changes to $PM_{2.5}$ nitrate concentrations on the western boundary of the simulation domain are associated with changes to model boundary conditions and are not relevant in the current analysis. The biogas scenario assumes that NH_3 and PM emissions from dairies are unchanged, and so the reductions in $PM_{2.5}$ OC and "other" in the SJV that are apparent in the Perfect AMMP scenario (Figure 71) are absent in the Biogas Production scenario (Figure 75). Emissions of primary PM from the biogas engines themselves do not significantly contribute to $PM_{2.5}$ concentrations in the SJV.

Holly, Larson et al. (2017) measured ammonia emissions from digested and separated dairy manure during storage and after land application. The authors concluded that anaerobic digestion significantly increased total ammonia emissions during storage in the absence of aggressive solid-liquid-separation measures and/or storage covers. Even if NH_3 emissions increase due to the widespread adoption of digesters, the impacts of potential increasing NH_3 emissions are modest in the SJV given the excess NH_3 that already exists in the atmosphere. One set of additional model simulations was conducted in the current study to consider the effects of a potential 40% increase in NH_3 emissions under the Biogas Electricity Generation scenario in a BAU atmosphere. Increasing NH_3 emission slightly increased predicted concentrations of $PM_{2.5}$ ammonium nitrate by a maximum value of 0.15 $\mu g/m^3$, with average regional increases less than 0.06 $\mu g/m^3$. Increasing NH_3 emissions had no effect on predicted O_3 concentrations. This sensitivity analysis suggests that the increases in NH_3 emissions due to the widespread adoption of anaerobic digesters will have minor impacts on air quality.

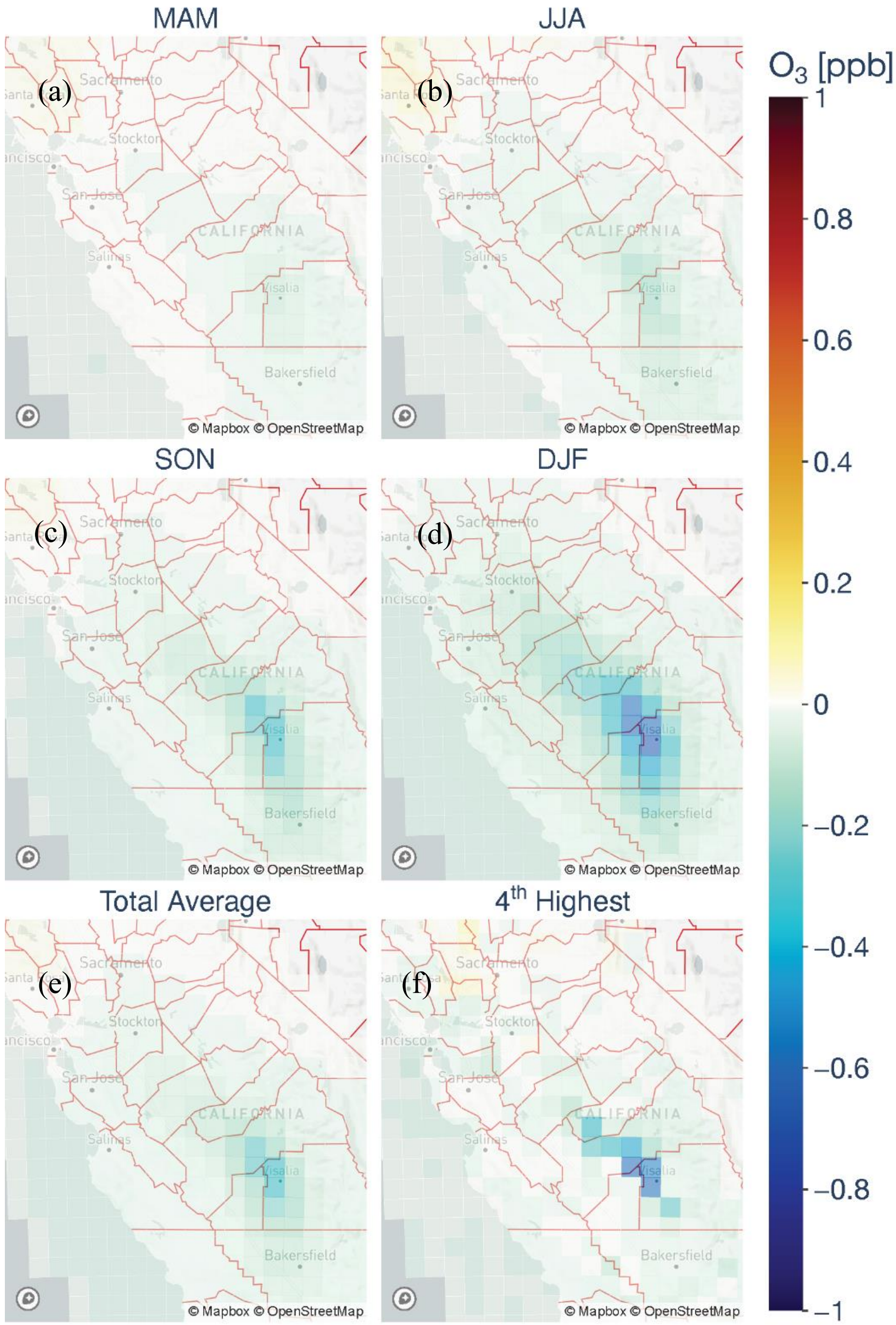


Figure 74. Changes in 8-hour daily maximum O_3 concentration (ppb) under "Biogas Electricity Generation" in a BAU Future. Displayed concentrations are simulations "with biogas electricity generation" minus "with dairy waste emissions". Negative values indicate reduced O_3 concentration under the "Biogas Electricity Generation". (a) Average of March, April, and May, (b) average of June, July, and August, (c) average of September, October, and November, (d)

average of December, January, and February, (e) average of 32 one-week-long simulations, and (f) the 4th highest 8-hour daily maximum O_3 concentration in 224 days of simulations.

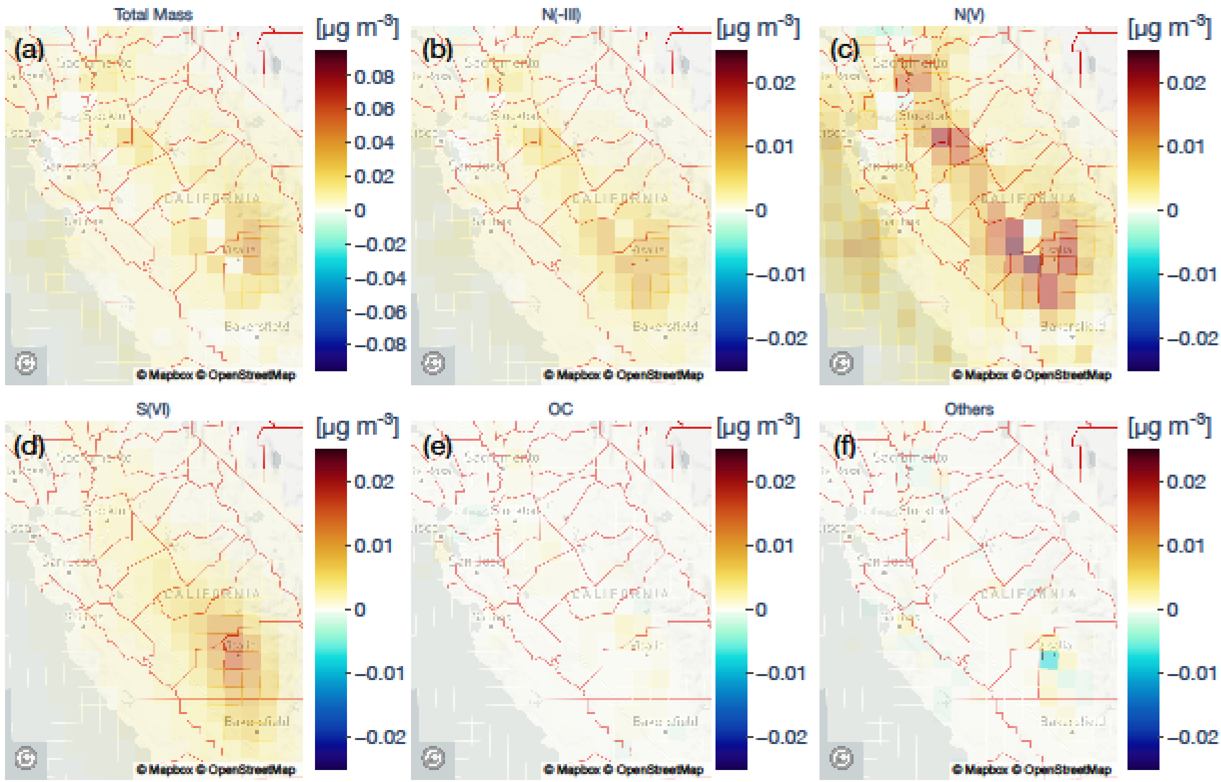


Figure 75. Changes in annual average $PM_{2.5}$ concentrations under "Biogas Electricity Generation" in a BAU Future. Displayed concentrations are simulations "with biogas electricity generation" minus "with dairy waste emissions". Negative values indicate reduced $PM_{2.5}$ concentration under the "Biogas Electricity Generation". All results are averaged across the 32 one-week-long simulations. (a) Total $PM_{2.5}$ mass, (b) ammonium, (c) nitrate, (d) sulfate, (e) organic compounds, and (f) Others (dominated by dust).

3.4.5 Biogas electricity generation in low carbon future

Figure 76 shows changes to predicted 8-hr maximum daily average O_3 concentrations in the SJV in response to the widespread adoption of biogas production in the Low Carbon Future atmosphere. Very minor increases in O_3 concentrations (<0.1 ppb) are predicted during the summer months (JJA) in response to the increased NOx emissions from biogas combustion. The positive O_3 response to increased NOx emission in the Low Carbon Future atmosphere (Figure 76) reflects a change in the atmospheric chemical regime compared to the conditions in the BAU future (Figure 74). This change in chemical regime is mainly associated with changes to emissions from non-dairy sources between the BAU and Low Carbon Future atmosphere. The absolute magnitude of the change in O_3 concentrations is very small in both cases, leading to the conclusion that modern biogas engines emit sufficiently low quantities of NOx that they will not significantly impact ambient O_3 concentrations in the SJV. Never-the-less, NOx emissions should be minimized where possible in any region out of compliance with National Ambient Air Quality Standards.

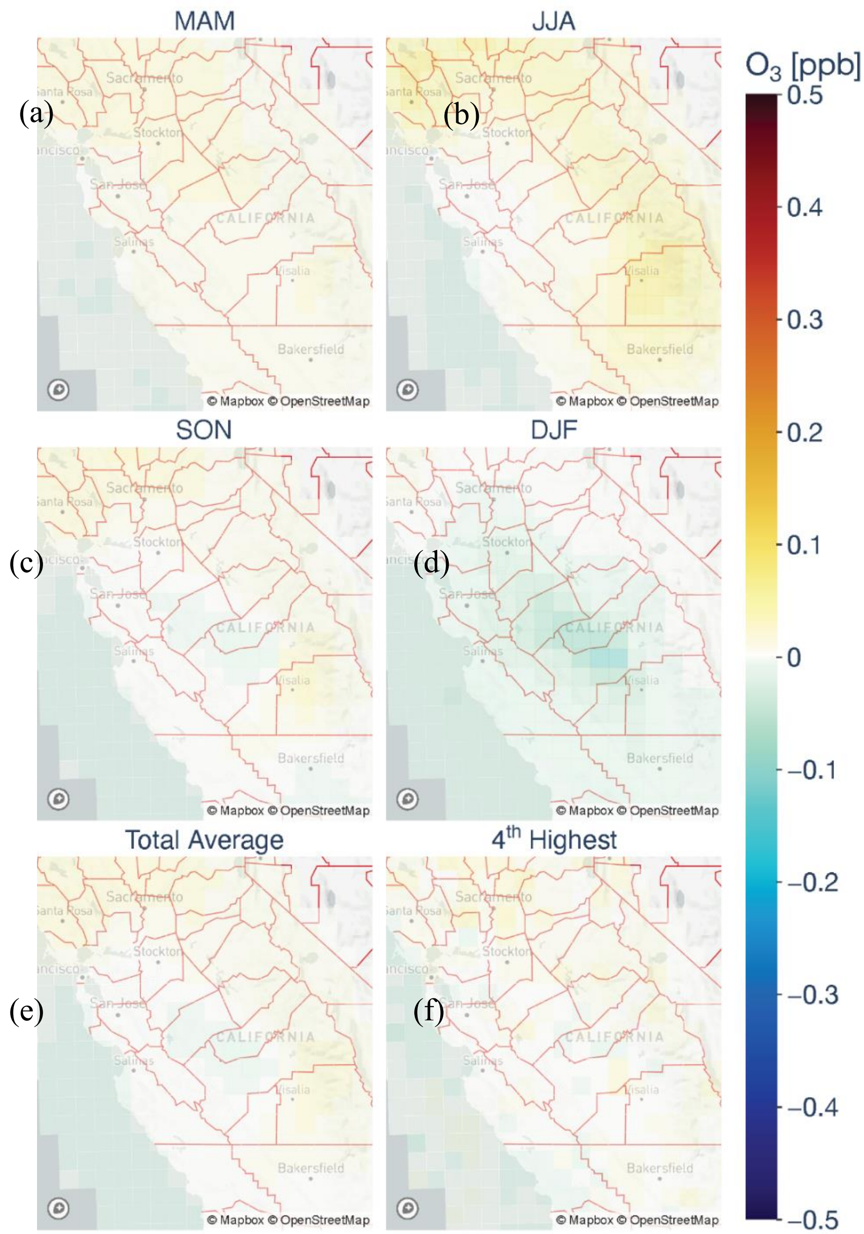


Figure 76. Changes in 8-hour maximum daily O_3 concentration (ppb) under "Biogas Electricity Generation" in a Low Carbon Future. Displayed concentrations are simulations "with biogas electricity generation" minus "with dairy waste emissions". Negative values indicate reduced O_3 concentration under the "Biogas Electricity Generation". (a) Average of March, April, and May, (b) average of June, July, and August, (c) average of September, October, and November, (d) average of December, January, and February, (e) average of 32 one-week-long simulations, and (f) the 4th highest 8-hour daily maximum O_3 concentration in 224 days of simulations.

Figure 77 shows predicted changes in long-term $PM_{2.5}$ concentrations in the SJV associated with the widespread adoption of biogas production and electricity generation in a Low Carbon Future atmosphere. As expected, changes to primary $PM_{2.5}$ components are minimal due to the low emissions of primary PM from biogas engines. Changes to secondary $PM_{2.5}$ nitrate are similar under the Low Carbon Future atmosphere (Figure 77) and the BAU atmosphere (Figure 75). The highest nitrate production occurs during winter months when low temperatures favor the condensation of ammonium nitrate to the particle-phase. The chemical regime in the winter months appears similar for the Low Carbon future atmosphere and the BAU atmosphere (compare O_3 response in DJF in Figure 74 and Figure 76). Once again, changes to $PM_{2.5}$ nitrate concentrations along the western border of the model domain are an artifact of the treatment for boundary conditions that does not affect the response in the SJV.

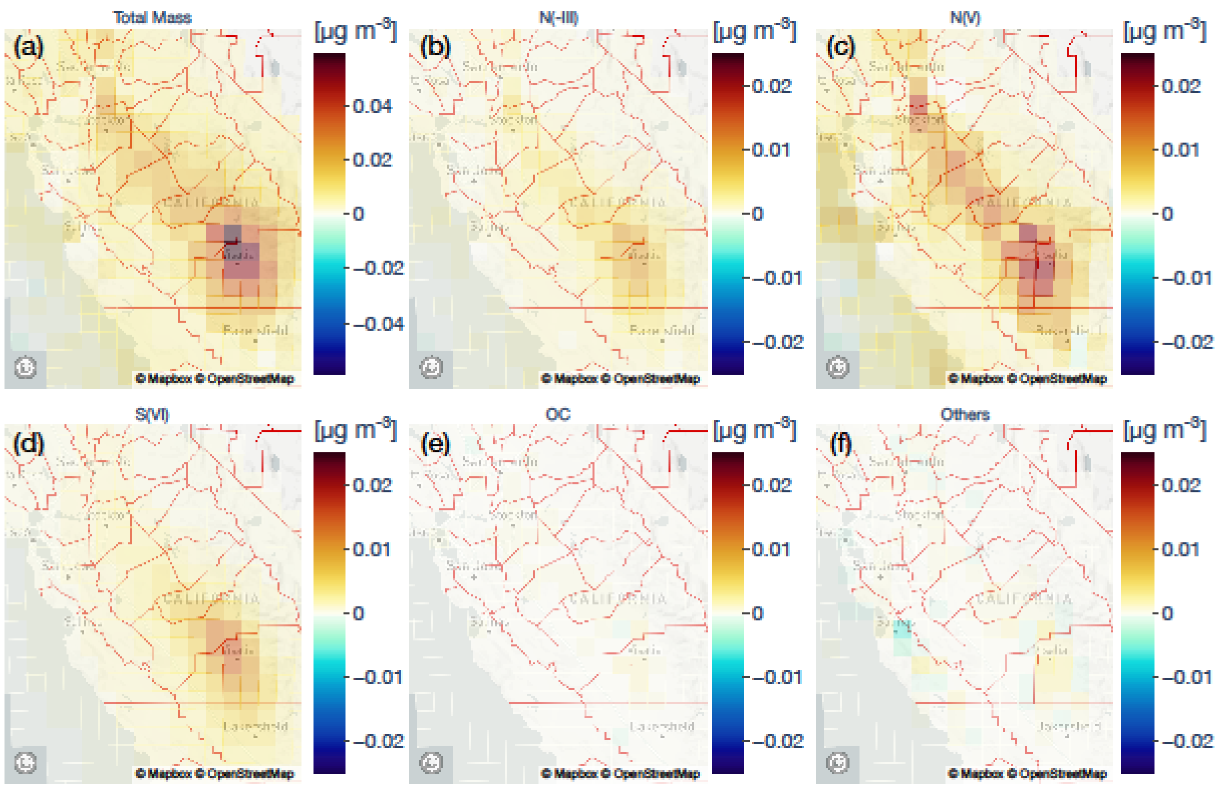


Figure 77. Changes in annual average $PM_{2.5}$ concentrations under "Biogas Electricity Generation" in a Low Carbon Future. Displayed concentrations are simulations "with biogas electricity generation" minus "with dairy waste emissions". Negative values indicate reduced $PM_{2.5}$ concentration under the "Biogas Electricity Generation". All results are averaged across the 32 one-week-long simulations. (a) Total $PM_{2.5}$ mass, (b) ammonium, (c) nitrate, (d) sulfate, (e) organic compounds, and (f) Others (dominant with dust).

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 Delta dairy, the farmer mentioned that vacuum scraping and sun drying of manure works well during the dry parts of year. It is a simple low-tech option, and it keeps 100% of the nutrient content out of the lagoon. It does require a skilled operator and timing is an issue in that it must operate when cows are out of corral. Moreover, the material isn't great for reuse as freestall bedding because it contains sand and rock. The dairyman also indicated that it is difficult to compost the scraped manure because it requires a large amount of carbon (i.e. almond shell) to start the composting process. Finally, he mentioned that the dairy staff found that it is best to dry down the material to a stackable moisture content and truck away and spread to farmland that does not receive lagoon water from the dairy. For Echo dairy, the farmer indicated that the weeping wall is a gravity separator that does not consume energy. He believes that this is a very efficient way to separate solids.

For Alpha dairy, during the delivery of the monitoring equipment to the site, the owner mentioned that although the mechanical separator is an efficient way to remove solids prior to the lagoon, the separation system consumes a lot of energy, making them to use the system for a few months per year only.

5 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 CH_4 and other gases for longer periods of time during different seasons. That would allow researchers to determine the effect of weather conditions and different manure management on 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 is needed to determine seasonal variation of emissions. These measurements could also be used to validate emission models. More research is needed to determine the seasonal variation of manure characteristics and to specify the factors that affect the variability in manure characteristics.

The amount of manure that was delivered to lagoons was not measured in this project. 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 affects the emissions from the settling basin and the lagoons on each dairy. Moreover, most of the dairies do not have exact dates for cleaning the settling basin. They also do not have records for the amount of manure that is removed during the clean out. The longer the presence of the manure in storage areas and the more manure is left in those during the cleanout, the more emissions could be produced. Therefore, it is important to determine dates of cleaning out the storage areas and the amount of manure removed during the cleanout. In addition, the withdrawal of water from the lagoons for irrigation purposes may affect the emissions from lagoons, a parameter that is generally not recorded by farmers. More research is needed to determine these amounts of water. However, the effect of water withdrawal for irrigation on the emissions 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 amount of the accumulated volatile solids between different cleaning events, and volatile solids in the lagoons and settling basins that may undergo anaerobic degradation and produce CH_4. 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. 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.

6 Summary and conclusions

The emissions of methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), and hydrogen sulfide (H_2S) were measured from the manure lagoons at four California dairies, each for at least three days. For the privacy of the dairies/owners, the dairies were named Alpha, Bravo, Delta, and Echo. Alpha, Bravo, Delta, and Echo dairies respectively employed a mechanical separation system, a vacuum truck for scraping of manure and a screw press to dewater manure, a vacuum truck for manure scraping and sun drying for 120 days per year, and a weeping wall. A complementary project was funded by CARB (agreement # 18ISD025 35C10), monitoring the emissions measured at two dairies post application of AMMP practices (compost pack barn in the first dairy and a mechanical screen separator and increased pasture time in the second dairy). Another objective of that study was to evaluate three models for their suitability to predict the emissions from manure on that two dairies and the four dairies reported here.

The measured CH_4 emissions Post-AMMP from the lagoons on Alpha, Delta, and Echo were higher than that of Pre-AMMP. For Bravo dairy, the emissions of CH_4 from the lagoon Post-AMMP was almost similar to that were measured Pre-AMMP. The relatively higher emissions Post-AMMP versus Pre-AMMP, might be due to several factors including the variation on the amount of manure received by the settling basin and the lagoon Pre- and Post-AMMP; the variations in cleaning of the settling basin and amount and quality of lagoon water that was used in irrigation. Knowing the amount of manure delivered to the lagoon and settling basins and the amount of solids removed from the settling basin and amount and quality of water withdrawn from the lagoons for irrigation would have been helpful to determine the factor(s) affecting the emissions. The dynamics of the microbial activity and yields and rates of CH_4 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 the dairies was not sufficient to compare the microbial activity Pre- and Post-AMMP. For example, data were needed for the concentration of VS and VFAs, and methanogenic activities at different depth of the lagoons and settling basin. 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 lagoon water containing VS with high biodegradability during irrigation, may deccrease the emissions from lagoons because more volatile solids can be diverted from the lagoon.

Here is a summary of observations and conversations with dairymen during the on farm emission monitoring. At Alpha dairy, although the AMMP practice seemed well designed, the mechanical separator has not been working all the time due to the high energy consumption. The owner of the dairy said that they plan to employ the separation system for a few month each year only. Therefore, not all manure produced at the dairy was treated by the separator, the lagoon received manure without passing over the mechanical separator. On Echo dairy, the weeping wall was not well designed. There was only one cell and the settling basin was used during the drying and emptying phases of the weeping wall operation. Ideally, more than one cell should be installed and used alternately so that all the flushed manure is treated with the weeping wall prior delivery to the lagoon. Although there were higher CH_4 emissions Post-AMMP application, that does not suggest that these practices are generally 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 CH_4.

Dairy waste emissions in the San Joaquin Valley make modest contributions to regional O_3 and $PM_{2.5}$ concentrations. Complete elimination of all emissions from dairy waste under a Perfect AMMP scenario would reduce 8-hr maximum daily average O_3 concentrations in the SJV by less than 1 ppb and secondary $PM_{2.5}$ concentrations by less than 0.2 $\mu g/m^3$ compared to baseline conditions in the year 2050. Even small changes are beneficial for areas that are marginally out of compliance with air quality standards, but the results of the current study suggest tht it is unlikely that dairy digesters will influence future compliance with National Ambient Air Quality Standards in the SJV. AMMPs that have the potential to reduce primary dust emissions from dairy freestall barns and adjacent drylot corrals could reduce ambient $PM_{2.5}$ concentrations by as much as 2 $\mu g/m^3$, but this type of AMMP is not part of the current implementation study and the technical feasibility of primary PM control through an AMMP is therefore unknown.

Widespread adoption of biogas production from dairy waste and combustion to produce electricity achieves most of the benefits of a perfect AMMP. Biogas production and combustion eliminates the majority of the CH_4 and VOC emissions from dairy waste. The primary PM emitted from the biogas production facilities is negligible and does not increase regional $PM_{2.5}$ concentrations. The NOx emitted from the biogas combustion to produce electricity increases concentrations of secondary $PM_{2.5}$ nitrate by less than 0.2 $\mu g/m^3$. The NOx emitted from biogas combustion reduces 8-hr maximum daily average O_3 concentrations in a future SJV atmosphere that is VOC-limited and slightly increases 8-hr maximum daily average O_3 concentrations by less than 0.1 ppb in a future SJV atmosphere that is NOx-limited.

The future treatment options for dairy waste in the SJV explore the limits of anticipated air quality impacts and find only weak connections to O_3 or $PM_{2.5}$ concentrations. Within the limits of the current analysis, manure management strategies should be selected based on benefits for GHG emissions, cost, implementation difficulty, and second order environmental benefits. Impacts on O_3 and $PM_{2.5}$ concentrations should be approximately equal under all treatment options.

References

Amon, B., et al., Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agriculture Ecosystems & Environment, 2006. 112(2-3): p. 153-162.

Arndt, C., A.B. Leytem, A.N. Hristov, D. Zavala-Araiza, J.P. Cativiela, S. Conley, C. Daube, I Faloona, and S.C. Herndon. 2018. Short-term methane emissions from 2 dairy farms in California estimated by different measurement techniques and US Environmental Protection Agency inventory methodology: A case study. J. Dairy Sci 101:11461-11479

CARB (2015). California's methane inventory based on the 2015 edition the CARB greenhouse gas inventory. Retrieved from https://ww2.arb.ca.gov/ghg-slcp-inventory. Accessed on February 16, 2022

CDFA (2018). California dairy statistics annual 2017 Data. https://www.cdfa.ca.gov/dairy/pdf/ Annual/2017/2017_Statistics Annual.pdf. Accessed Sept. 27, 2018.

CDFA (2019). Agricultural Statistics Review. https://www.cdfa.ca.gov/statistics/PDFs/2018-2019AgReportnass.pdf. Accessed on February 10, 2021.

Chastain, J.P. (2006). Estimation of sludge accumulation in lagoons. ASABE paper Number: 064114

Chastain, J.P.; Vanotti, M.B. and Wingfield, M.M. (2001). Effectiveness of Liquid-Solid Separation for Treatment of Flushed Dairy Manure: A Case Study. Transactions of the ASAE 17(3): 343-354.

El-Mashad, H.M. and Zhang, R. (2010). Biogas production from co-digestion of dairy manure and food waste. Bioresource Technology 101: 4021-4028.

El-Mashad, H. M., and Zhang, R. (2007). Co-digestion of food waste and dairy manure for biogas production. Trans. ASABE 50(5): 1815-1821.

Elsgaard, L.; Olsen, A.B.; and Petersen, S.O. (2016). Temperature response of methane production in liquid manure and co-digestates. The Sci Total Environ. 539: 78–84

Graves, R. E.; Clayton, J.T.; and Light, R.G. (1971). Renovation and Reuse of Water for Dilution and Hydraulic Transport of Dairy Cattle Manure (PROC-271). St. Joseph, Mich.: ASAE.

Hegg, R.O.; Larson, R.E.; and Moore, J.A. (1981). Mechanical liquid-solid separation in beef, dairy, and swine waste slurries. Transactions of ASAE 24(1):159–163. St. Joseph, MI

Grant, R. H.; Boehm, M.T. and Bogan, B.W. (2015). Methane and carbon dioxide emissions from storage facilities at two free-stall dairies. Agric. For. Meteorol. 213:102–113.

Carlton, A. G., P. V. Bhave, S. L. Napelenok, E. D. Edney, G. Sarwa, R. W. Pinder, G. A. Pouliot and M. Houyoux (2010). "Model representation of secondary organic aerosol in CMAQv4.7." Environmental Science and Technology **44**: 8553-8560.

Carter, W. P. L. and G. Heo (2013). "Development of Revised SAPRC Aromatics Mechanisms." Atmospheric Environment **77**: 404-414.

Held, T., Q. Ying, M. Kleeman, J. Schauer and M. Fraser (2005). "A comparision of the UCD/CIT air quality model and the CMB source-receptor model for primary airborne particulate matter." Atmospheric Enviornment **39**: 2281-2297.

Holly, M. A., R. A. Larson, J. M. Powell, M. D. Ruark and H. Aguirre-Villegas (2017). "Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land application." Agriculture, Ecosystems & Environment **239**: 410-419.

Hong, S. Y., Y. Noh and J. Dudhia (2006). "A new vertical diffusion package with an explicit treatment of entrainment processes." Monthly Weather Review **134**(9): 2318-2341.

Hu, J., H. Zhang, Q. Ying, S. H. Chen, F. Vandenberghe and M. J. Kleeman (2015). "Long-term particulate matter modeling for health effect studies in California – Part 1: Model performance on temporal and spatial variations." Atmospheric Chemistry and Physics **15**(6): 3445-3461.

Hu, X.-M., Y. Zhang, M. Z. Jacobson and C. K. Chan (2008). "Coupling and evaluating gas/particle mass transfer treatements for aerosol simulation and forecast." J. Geophys. Res. **113**(D11208).

Kleeman, M. J., G. R. Cass and A. Eldering (1997). "Modeling the airborne particle complex as a source-oriented external mixture." Journal of Geophysical Research-Atmospheres **102**(D17): 21355-21372.

Nenes, A., C. Pilinis and S. N. Pandis (1998). "ISORROPIA: A new thermodynamic equilibrium model for multiphase multicomponent marine aerosols " Aquat. Geochem **4**: 123-152.

Parker, D. (2008). "Reduction of Odor and VOC Emissions from a Dairy Lagoon." Applied engineering in agriculture **24**: 647-655.

Xiu, A. J. and J. E. Pleim (2001). "Development of a land surface model. Part I: Application in a mesoscale meteorological model." Journal of Applied Meteorology **40**(2): 192-209.

Ying, Q., M. P. Fraser, R. J. Griffin, J. J. Chen and M. J. Kleeman (2007). "Verification of a source-oriented externally mixed air quality model during a severe photochemical smog episode." Atmospheric Environment **41**(7): 1521-1538.

Ying, Q., J. Lu, P. Allen, P. Livingstone, A. Kaduwela and M. Kleeman (2008). "Modeling air quality during the California Regional PM10/PM2.5 Air Quality Study (CRPAQS) using the UCD/CIT source-oriented air quality model - Part I. Base case model results." Atmospheric Environment **42**(39): 8954-8966.

Ying, Q., J. Lu, A. Kaduwela and M. Kleeman (2008). "Modeling air quality during the California Regional PM10/PM2.5 Air Quality Study (CPRAQS) using the UCD/CIT Source Oriented Air Quality Model - Part II. Regional source apportionment of primary airborne particulate matter." Atmospheric Environment **42**(39): 8967-8978.

Yu, X., M. Venecek, J. Hu, S. Tanrikulu, S. T. Soon, C. Tran, D. Fairley and M. J. Kleeman (2018). "Sources of Airborne Ultrafine Particle Number and Mass Concentrations in California." Atmos. Chem. Phys. Discuss. **2018**: 1-37.

Zapata, C. B., C. Yang, S. Yeh, J. Ogden and M. J. Kleeman (2018). "Estimating criteria pollutant emissions using the California Regional Multisector Air Quality Emissions (CA-REMARQUE) model v1.0." Geosci. Model Dev. **11**(4): 1293-1320.

Zapata, C. B., C. Yang, S. Yeh, J. Ogden and M. J. Kleeman (2018). "Low-carbon energy generates public health savings in California." Atmos. Chem. Phys. **18**(7): 4817-4830.

Houlbrooke, D.; Longhurst, B.; Orchiston, T.; and Muirhead, R. (2011).Characterising dairy manures and slurries. Surface Water Integrated Management (SWIM).

Laubach, J.; Heubeck, S.; Pratt, C.; Woodward, K.B.; Guieysse , B.; van der Weerden, T.J.; Chung, M.L.; Shilton, N.A.; and Craggs, R.J. (2015). Review of greenhouse gas emissions from the storage and land application of farm dairy effluent. New Zealand Journal of Agricultural Research 58 (2): 203-233.

Leytem, A.B.; Bjorneberg, D.L.; Koehn, A.C.; Moraes, L.E.; Kebreab, E.; and Dungan, R.S. (2017). Methane emissions from dairy lagoons in the western United States. J. Dairy Sci., 100:6785-6803.

Leytem, A. B.; Dungan, R.S.; Bjorneberg, D.L.; and A. C. Koehn, A.C. (2013). Greenhouse gas and ammonia emissions from an open freestall dairy in southern Idaho. J. Environ. Qual. 42:10–20.

Meyer, D.; Price, P. L.; Rossow, H. A.; Silva-del-Rio, N.; Karle, B. M.; Robinson, P. H.; DePeters, E. J.; Fadel, J. G. (2011). Survey of dairy housing and manure management practices in California. Journal of Dairy Science, 94: 4744–4750.

Meyer, D. M.; Heguy, J.; Karle, B.; Robinson, P. (2019). Characterize Physical and Chemical Properties of Manure in California Dairy Systems to Improve Greenhouse Gas (GHG) Emission Estimates. Draft Final Report to the California Air Resources Board and the California Environmental Protection Agency Contract No. 16RD002.

Meyer, D.; Harner, J. P.; Tooman, E. E.; and Collar, C. (2004). Evaluation of weeping wall efficiency of solid liquid separation. Applied Eng. in Agric. 20(3): 349-354.

Mitloehner, F.; Zhang, R.; Zhao, Y.; El Mashad, H.; Zicari, S.; Gooch, C.; Kaffka, S.; and Rowe, S. (2019). Benchmarking of pre-AMMP dairy emissions. Final Report to the California Department of Food and Agriculture. Grant Number: #16-0747-SA

Mukhtar, S.; Borhan, M.S.; and J. Beseda II, J. (2011). Evaluation of a weeping wall solid-liquid separation system for flushed dairy manure. Applied Engineering in Agriculture 27(1): 135-142.

Noonyen (2018). Tri-Bars. http://www.nooyenky.com. Accessed on July 9, 2018.

NRCS (2014). Waste separation facility – Conservation Practice Standard 632. Natural Resources Conservation Service.

NRCS, NHCP (2017). Waste treatment lagoon. https://www.valleyair.org/Workshops/postings /Prior To2008/2005/7-11-05/Appendix%2020%20%20NRCS%20Guideline.pdf

Owen, J., & Silver, W.L. (2016). Greenhouse gas emissions from dairy manure management in a Mediterranean environment. Ecological Applications 27(2), 545–559.

Petersen, S.O.; Olsen, A.B.; Elsgaard, L.; Triolo, J.M.; and Sommer, S.G. (2016). Estimation of methane emissions from slurry pits below pig and cattle confinements. PLoS ONE 11(8): e0160968. doi:10.1371/journal.pone.0160968

Rico, J.L.; García, H.; Rico, C.; and Tejero, I. (2007). Characterisation of solid and liquid fractions of dairy manure with regard to their component distribution and methane production. Bioresource Technology, 98(5): 971-97

Ross, E.G.; Peterson, C.B.; Zhao, Y.; Pan, Y.; Mitloehner, F.M. Manure Flushing vs. Scraping in Dairy Freestall Lanes Reduces Gaseous Emissions. Sustainability 2021, 13, 5363. https://doi.org/ 10.3390/su13105363

Sustainable Conservation. (2005). Cost-effective and environmentally beneficial dairy manure management practices. Capturing Nutrients in Dairy Manure: Innovative Solid-Liquid Separation Systems. K. Hughes and A. C. Wilkie, eds. San Francisco, Calif. Available at: www.suscon.org/dairies/pdfs/ NDESCreportCostEffective.pdf. Accessed 04 September 2009.

Williams, R.; El-Mashad, H.; Kaffka, S. (2020). Research and technical analysis to support and improve the alternative manure management program quantification methodology. Research Report CARB Agreement No. 17TTD010

Witarsa, F. and S. Lansing, Quantifying methane production from psychrophilic anaerobic digestion of separated and unseparated dairy manure. Ecological Engineering, 2015. 78: p. 95-100

Zhang, R.; Edalati, H.; El-Mashad, H. M.; and Chen, Y. (2019). Effect of Solid Separation on Mitigation of Methane Emission in Dairy Manure Lagoons - DRAFT FINAL. University of California, Davis. Project Report #15-0610-SA to CDFA

Appendix A

Dairy Farm Questionnaire: Post-AMMP

1. What is number of lactating, and dry cows; heifers, and calves?
   ………………………………………………………………………………………………
   ………………………………………………………………………………………………
   …………………………………………………………………………………
2. Please describe the operational details of the AMMP technology? What is your evaluation of the technology?
   ………………………………………………………………………………………
   ………………………………………………………………………………………
   ………………………………………………………………………………………………
   …………………………………………………………………………………….
   ………………………………………………………………………………………….
   ………………………………………………………………………………………….
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?

……………………………………………………………………………………..

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

……………………………………………………………………………………..

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

……………………………………………………………………………………..

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

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

17. How are manure solids handled and processed?

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

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

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

………………………………………………………………………………………..

Appendix B

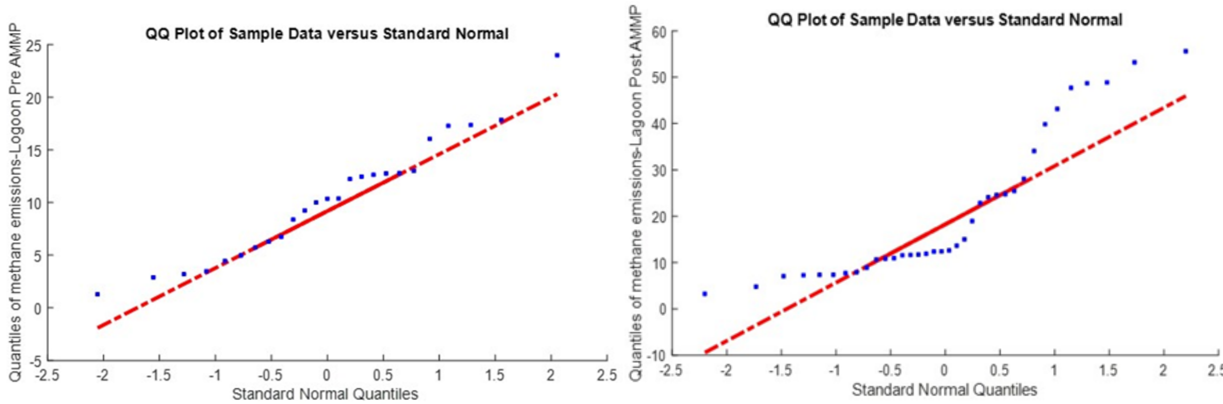


Figure B-1. Quartile-Quartile plot for methane emissions from the lagoon Pre and Post AMMP at Alpha dairy

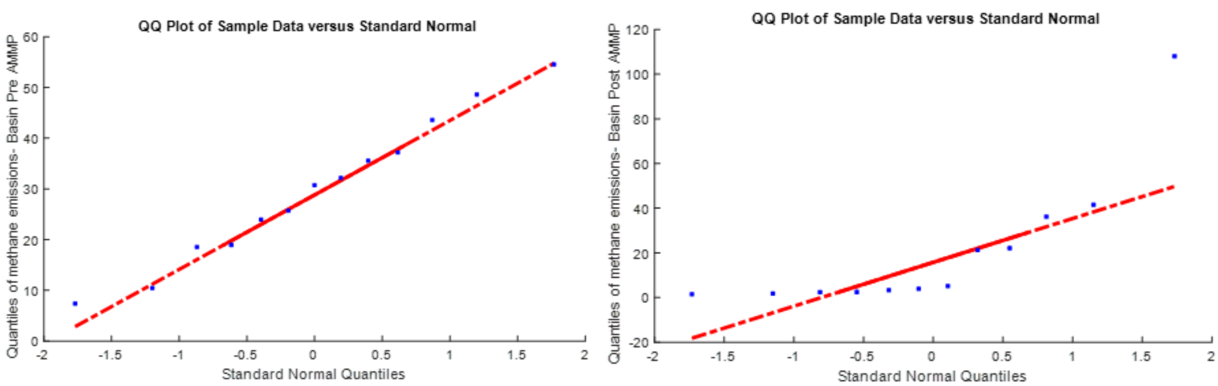


Figure B-2. Quartile-Quartile plot for methane emissions from the settling basin Pre and Post-AMMP at Alpha dairy

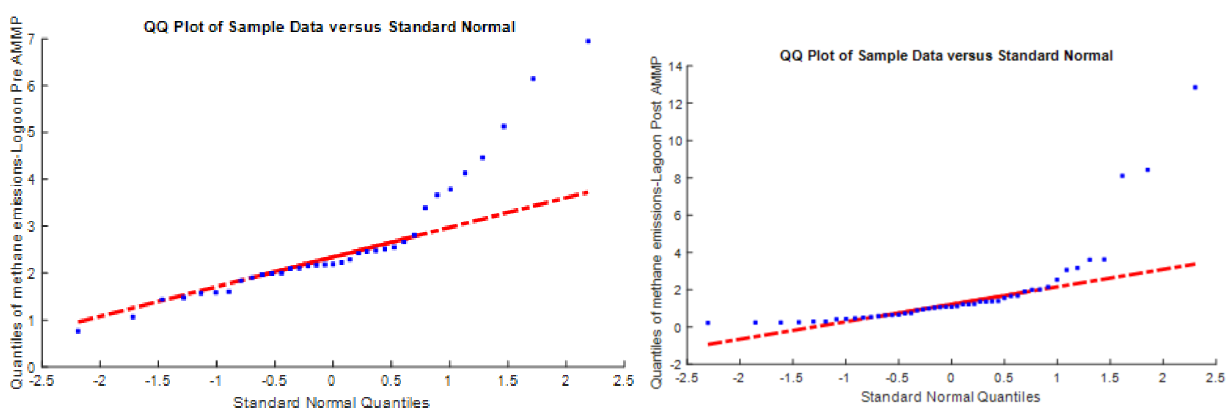


Figure B-3. Quartile-Quartile plot for methane emissions from the lagoon Pre and Post AMMP at Bravo dairy

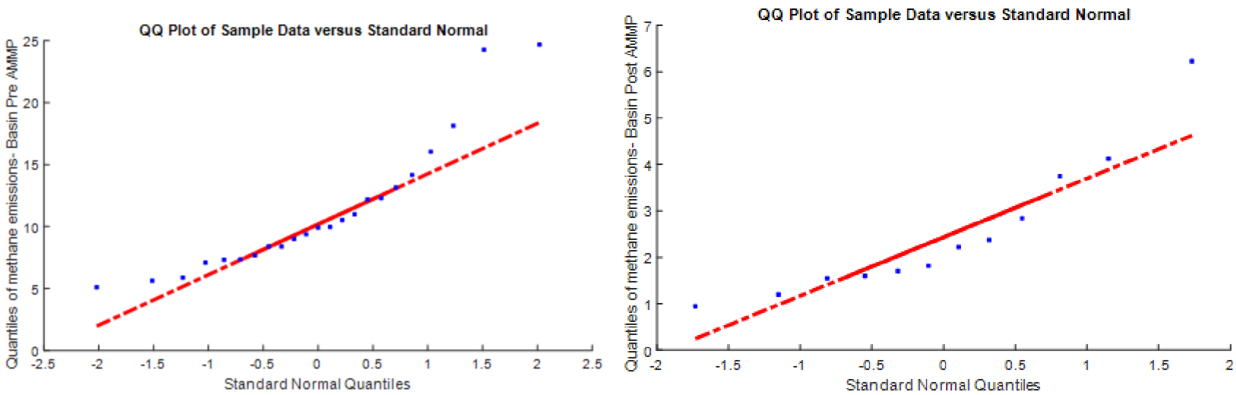


Figure B-4. Quartile-Quartile plot for methane emissions from the settling basin Pre and Post-AMMP at Bravo dairy

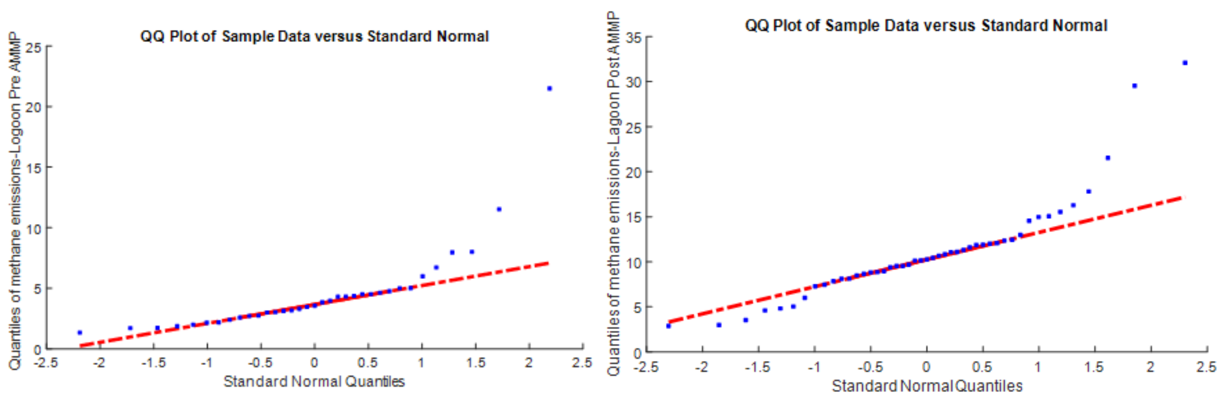


Figure B-5. Quartile-Quartile plot for methane emissions from the lagoon Pre and Post AMMP at Delta dairy

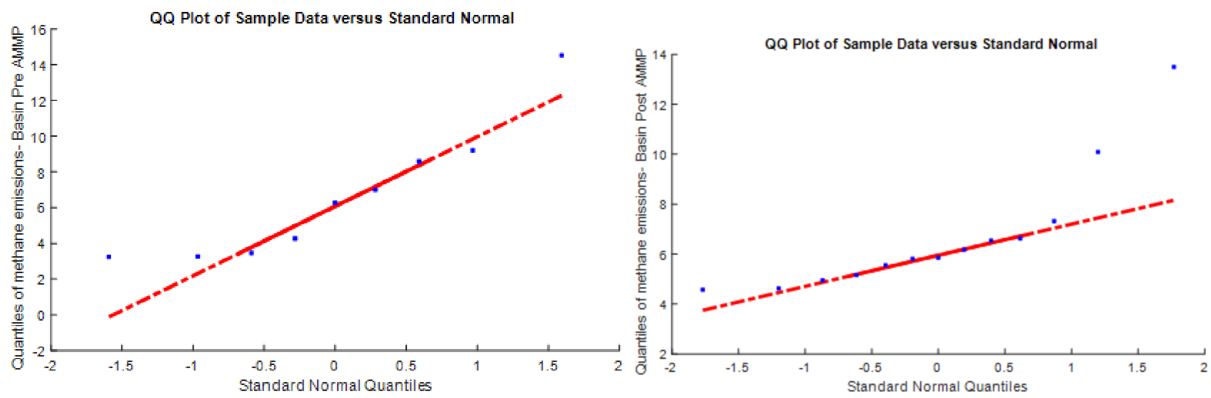


Figure B-6. Quartile-Quartile plot for methane emissions from the settling basin Pre and Post-AMMP at Delta dairy

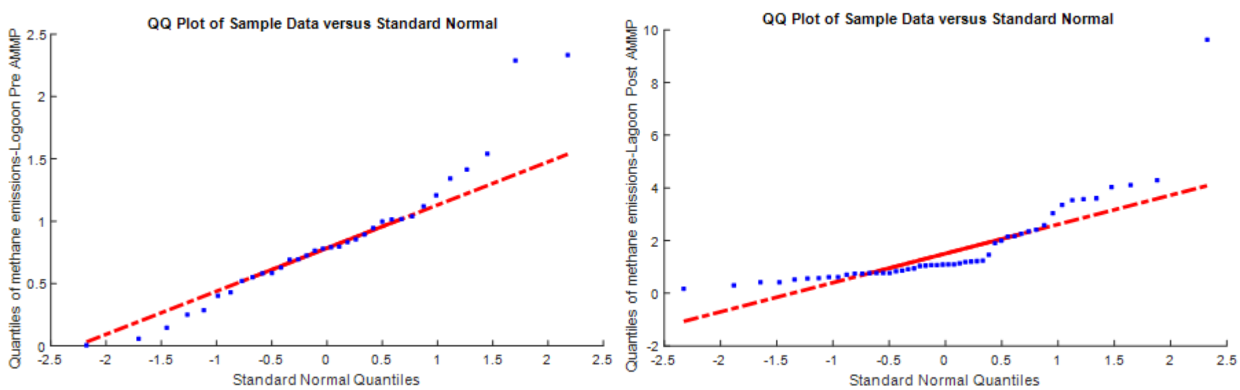


Figure B-7. Quartile-Quartile plot for methane emissions from the lagoon Pre and Post AMMP at Echo dairy

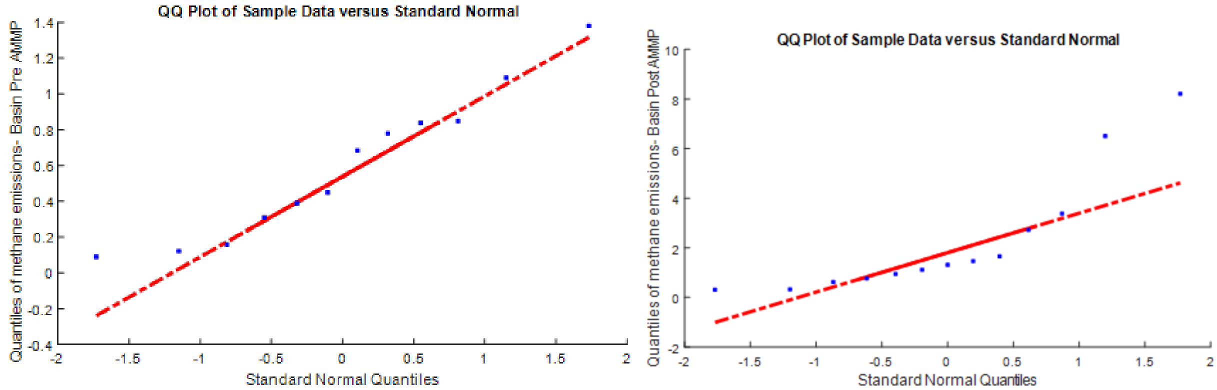


Figure B-8. Quartile-Quartile plot for methane emissions from the settling basin Pre and Post-AMMP at Echo dairy