# Benchmarking of pre-AMMP dairy emissions

**Final Report to the California Department of Food and Agriculture**

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**Project Objectives**

1) Evaluation of farm-scale dairy manure management emissions modeling tools
2) Conduct baseline emissions measurements for selected dairies
3) Data analysis and reporting

**Summary**

A literature review was conducted on different methods employed for measuring the emissions from farms and wastewater lagoons. Different models applied for predicting the emissions of methane and nitrous oxide ($N_2O$) were also reviewed. The emissions of methane ($CH_4$), ammonia-N ($NH_3$), $N_2O$, and hydrogen sulfide ($H_2S$) from manure storage were measured on six dairies named Alpha, Bravo, Charlie, Delta, Echo, and Foxtrot. Five of the studied dairies had settling basins and lagoons. Whereas the sixth dairy (Charlie dairy) had only a lagoon for manure storage. The emissions were measured during the late summer and early fall of 2018. The lagoons were monitored for at least two and settling basins for at least one day. The Air Quality Laboratory (MAQ Lab) of UC Davis was used to measure the emissions of different gases. The MAQ Lab was equipped with the state of art gas analyzers and supporting equipment. A floated wind tunnel was used to capture the emitted gases from certain areas of the source surfaces. The measured emission data were used to calculate the emission flux of different gases after measuring the airflow rate inside the wind tunnel. Manure samples were collected in the late summer/early fall and late winter/early spring from the inlets of the settling basins and lagoons and lagoons surface. The emissions of $CH_4$ from settling basins and lagoons were estimated using the models of California Air Resources Board (CARB) and Intergovernmental Panel on Climate Change (IPCC). For Charlie dairy, the emission of methane was also estimated using the DairyGEM and Manure-DNDC. The last two models were not employed to predict the emissions from the other five dairies because these models do not have the capability for predicting the emissions from the settling basins and lagoons when they are arranged in series.

The average emission rates of $CH_4$ from the settling basins on the Alpha, Bravo, Delta, Echo, and Foxtrot dairies were 1207, 195, 921, 43, and 809 g/milking cow equivalent/day, respectively. While they were 973, 663, 1462, 549, 441, and 419 g/milking cow equivalent/day from the lagoons on the Alpha, Bravo, Charlie, Delta, Echo, and Foxtrot dairies, respectively. The average emission rates of $NH_3$ from the settling basins on the Alpha, Bravo, Delta, and Echo dairies were 2.2, 1.6, 25.8, 10.8, and 9.5 g/milking cow equivalent/day, respectively. While they were 7.0, 31.1, 13.8, 27.2, 34.0, and 15.0 g/milking cow equivalent/day from the lagoons on the Alpha, Bravo, Charlie, Delta, Echo, Foxtrot dairies, respectively. Low emission rates of $N_2O$ and $H_2S$ were determined from the settling basins and the lagoons. The highest emission rates of $N_2O$ were 0.74 and 4.4 g/milking cow equivalent/day from the settling basin on Delta dairy and the lagoon on Foxtrot dairy, respectively. While, for $H_2S$, they were 1.06 and 0.1 g/milking cow equivalent/day from the settling basin on Alpha dairy and the lagoon on Bravo dairy. Manure characteristics profoundly varied among different sources in the studied dairies. Relatively higher total solids and volatile solid contents were determined during the Winter/early Spring than late Summer/early Fall. The modeled emissions of $CH_4$ using CARB/IPCC model seemed reasonable for most of the studied settling basins and lagoons. Long-term measurements of emissions are needed to determine the reason(s) for the differences in the emissions among studied dairies and validate and calibrate the CARB/IPCC, DairyGEM, and Manure-DNDC models. Settling basins should be included in the DairyGEM and Manure-DNDC models.

## Introduction

The California Air Resources Board (ARB) recently adopted the Short-Lived Climate Pollutant Strategy (SLCP) to reduce emissions of black carbon, methane and other SLCPs, including emissions of manure methane from California dairies. Recent legislation (SB 1383, Lara 2016) requires implementation of the SLCP strategy by January 1, 2018. The strategy includes a 40% methane emission reduction from 2013 levels by 2030. The ARB developed a scoping plan and set forth recommendations aimed at reducing GHG emissions from six major focal areas: energy, transportation, agriculture, water, waste management, and natural and working lands.

California is the national leader in milk production. The total sale of milk and its products represented about $65 billion annually. However, the GHG emissions from dairy farms in California were estimated to be 19.6 Tg $CO_2$eq per year, accounting for 4.3% of all California GHG emissions and 57% of those from California Agriculture (ARB, 2015). GHG emissions from dairy manure accounts for 11.4 Tg $CO_2$eq/yr, of which 9.04 Tg are attributed to emissions from anaerobic lagoon manure storage, which are predominantly methane. There are an estimated 1,780,000 adult dairy cattle in the state with an additional 800,000 heifers. There are about 1600 registered dairies in California (CDFA, 2013). Due to the high installation costs and the low return on investment, anaerobic digesters, as a technology for mitigation of emissions that produce bioenergy in the form of biogas, are installed in only 1.3% of the number of dairy farms in California. Due to the high installation costs and the low return on investment, anaerobic digesters, as a technology for mitigation of emissions that produce bioenergy in the form of biogas, are installed on only 1.3% of California dairies. Therefore, Alternative Manure Management Program (AMMP) practices that are cost effective in emissions reduction, are sought after, that might be applied by dairies. There is a need to understand these emissions and quantify methane and other air quality emissions on dairies that are considering the use of AMMP. The quantification of the emissions prior the installation of the AMMP technologies is important to determine the effect of the AMMP on the reduction of the emissions from dairies in California.

Objectives:

1- Evaluate farm-scale dairy manure management emissions modeling tools
2- Conduct baseline emissions measurements for selected dairies.
3- Data analysis and reporting.

## Task 1a: Review existing emission modeling tools in the literature

### Greenhouse gas and other air emission from manure

Animal agriculture is a source of the anthropogenic greenhouse gas (GHG) emissions resulting from methane ($CH_4$) and nitrous oxide ($N_2O$) emissions, and emits other pollutants such as volatile organic compounds (VOCs), ammonia-N ($NH_3$), and hydrogen sulfide ($H_2S$). Most of these pollutants are emitted during gathering, conveying, transporting, storage, and application of manure. The specifics about emission of each of the various pollutants depend on many factors such as feed composition, manure composition, manure handling and management systems, application practices, and weather conditions. Emissions are the result of several biochemical processes that occur during manure handling and management.

Methane

Methane is produced when manure is stored in anaerobic conditions (e.g., covered lagoons/long-term storages, and portions of uncovered lagoons/long-term storages) by methanogens that are obligate anaerobes (methanogenic archaea). Methane can be emitted year-round from long-term manure storages though at reduced rate in cold weather. Manure is a complex substrate that undergoes several sub-processes during anaerobic storage (Pavlostathis and Giraldo-Gomez, 1991; Batstone et al., 2002) as shown in Figure 1. In the hydrolysis process, polymers are consumed, by extracellular enzymes and hydrolytic bacteria, into simple compounds such as amino acids, long-chain fatty acids (LCFA), and sugars. Then these compounds are converted by acidogenic bacteria into volatile fatty acids (VFAs) and alcohols by acidogenic bacteria. The VFAs, other than acetic acid, are converted to acetic acids, $CO_2$, and $H_2$. Acetate and/or $CO_2$ and $H_2$ are converted to methane and carbon dioxide by methanogenesis archaea. The pathway shown in Figure 1 is similar to that for the production of methane during enteric fermentation. However, there is a few differences between manure handling and rumen (Monteny et al., 2001); mainly in temperatures in rumen and ambient conditions; and homogeneity of the feed and manure. During manure storage, the manure degradation intermediates (e.g., VFAs and alcohols) can be emitted contributing to the VOCs emissions from manure.

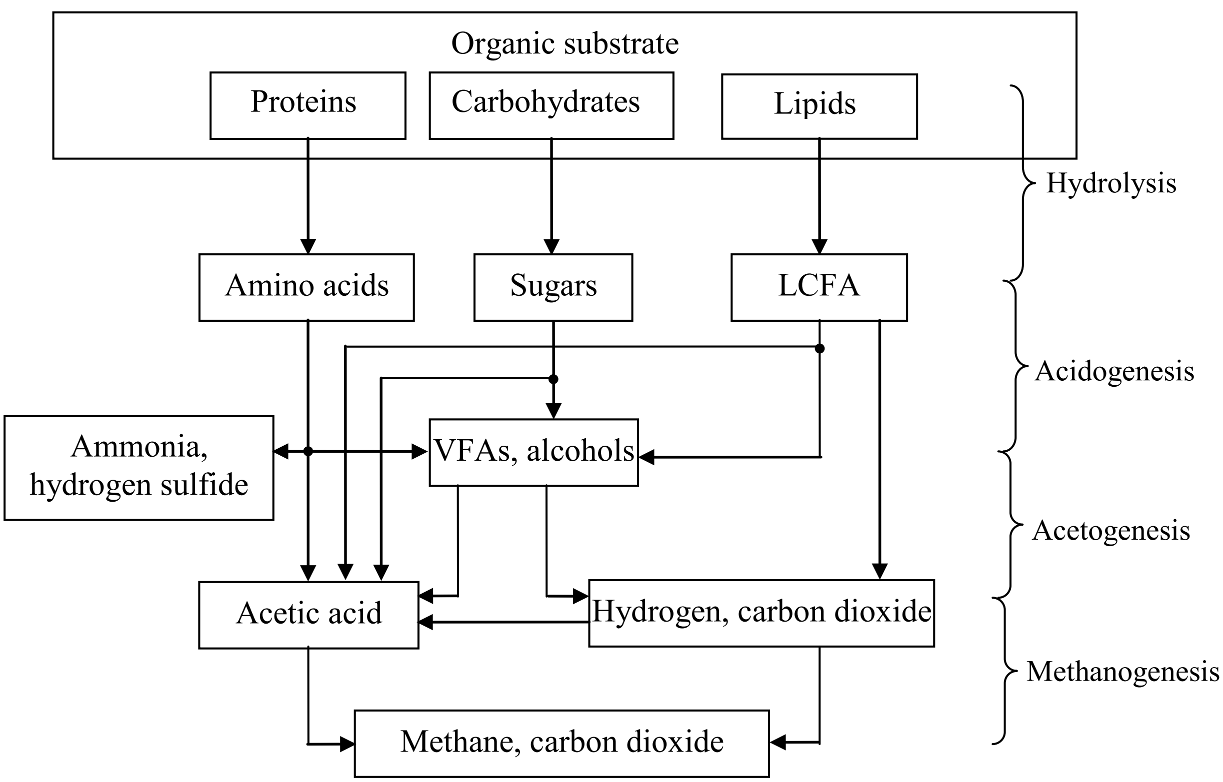


**Figure 1. Main sub-processes involved in anaerobic digestion process (adapted from Pavlostathis and Giraldo-Gomez, 1991; Batstone et al., 2002).**

Nitrous Oxide

Nitrous oxide can be emitted directly from manure or more so indirectly from soils after land application. As shown in Figure 2, direct $N_2O$ emissions from manure occur via combined nitrification and denitrification of its nitrogen. The emissions from manure depend on the nitrogen and carbon content of manure, and on the duration of the storage and type of treatment. Organic nitrogen in dairy manure is in the form of urea that is within urine excrement. This organic nitrogen is converted to $NH_3$ via hydrolysis. During the nitrification, $NH_3$ nitrogen is aerobically (i.e., free oxygen present) oxidized to nitrite ($NO_2$)-nitrate ($NO_3$) nitrogen. The oxidized N are anaerobically transformed to $N_2O$ and nitrogen ($N_2$) during the denitrification process.

Other emissions

In additions to the emissions of GHG, the biochemical degradation of manure can produce other pollutants such as ammonia, hydrogen sulfide, and volatile organic compounds (e.g., volatile fatty acids (VFAs), ketones, aldehydes, alcohols). Ammonia can react with NOx to form ammonium nitrate, which is classified as fine particulate matter (Chang et al., 2006). VFAs have been considered to be high odor intensity compounds on dairy farms (Rabaud et al., 2003). Local air districts in California are concerned with these pollutants (Chang et al., 2006).

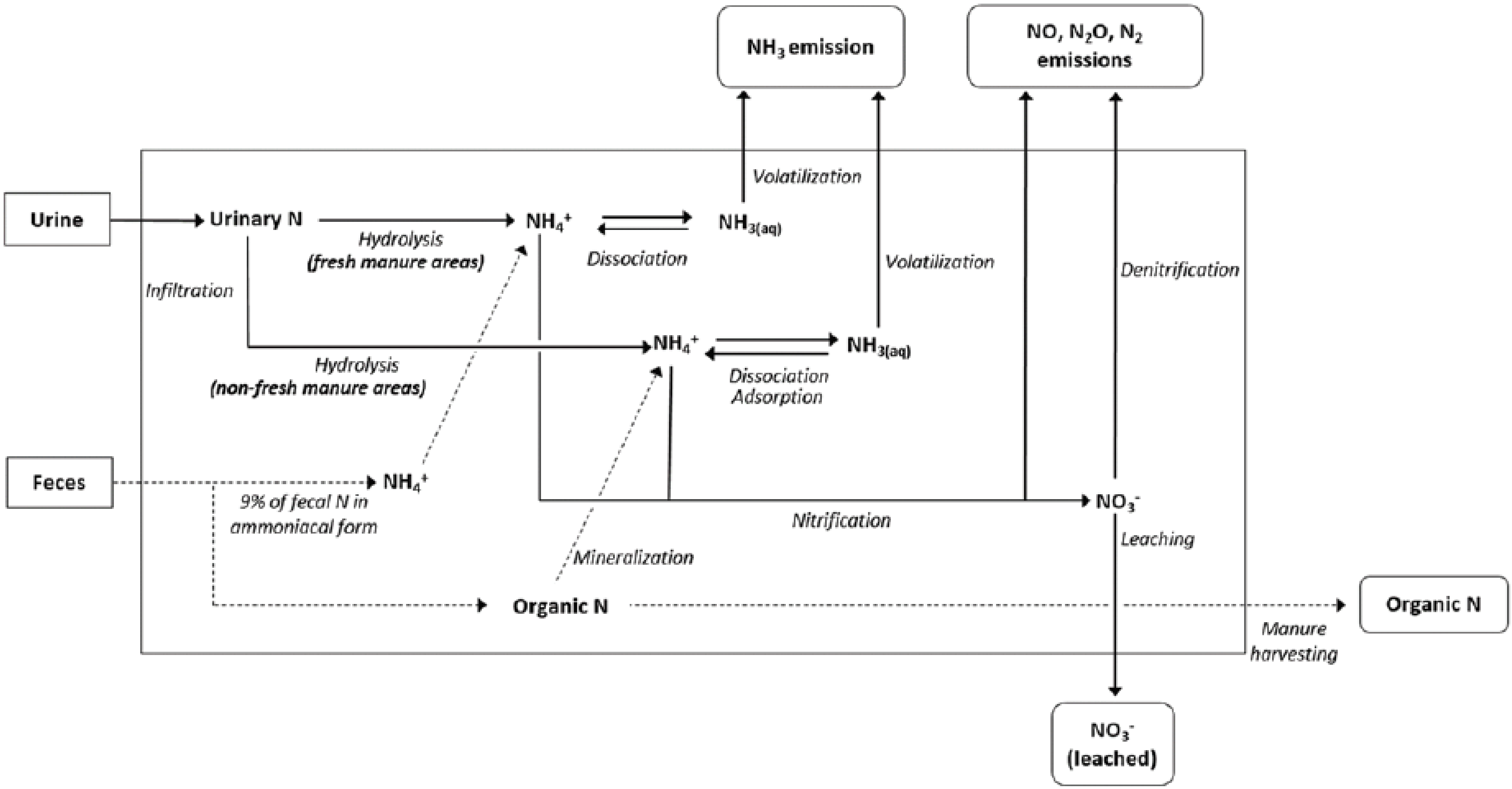


**Figure 2. Nitrogen flow through processes as simulated for open lots (Bonifacio et al., 2015)**

**Models for predicting manure-based GHG emissions**

There are several models to predict the emissions of GHG from manure. They are categorized as empirical, process-based, and life-cycle assessment models.

1) Empirical: These models rely on relatively simple regression relationships, typically averaged over large or diverse datasets, which are relatively easy and transparent to use. Empirical models do not capture the effects of spatial and temporal variability on GHG dynamics at finer scales and can be less flexible in handling variable management combinations.
2) Process-based: These models use bio-geochemical mechanistic equations based on substantial long-term research to represent GHG dynamics in water, air, and soils. The models might include some empirical relationships but strive to predict individual source emissions and capture differences across time and spatial scales.
3) Life-Cycle Assessment: Life-cycle assessment (LCA) models involve a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or system throughout its life cycle. LCA's combine inventory data and empirical or process-based models and may include economic metrics.

Several existing and available models were reviewed based on the predicted gas emission, and their application by other researchers in the United States and other countries. The models were assessed for their suitability for farm-scale quantification of GHGs and manure management alternatives on CA dairies. Table 1 shows the categories of the selected models for manure-based GHG emissions from barn floors and manure management. In addition to the model shown in Table 1. There are several other models that are not reviewed herein because they predict the emission of one gas, determine emission from a few sources on farm management system, or they are similar to the models shown in Table 1. For example, FARMIN was proposed to estimate the emissions of $N_2O$ from animal housing using empirical/emission factors (Van Evert et al., 2003; Schils et al., 2005).

**Table 1. Categories of selected models for quantifying GHG missions from manure on floor of dairy houses and manure management.**

| Model | Manure on houses floor | | Manure management | | References |
|---|---|---|---|---|---|
| | $CH_4$ | $N_2O$ | $CH_4$ | $N_2O$ | |
| IPCC | N/A | N/A | Empirical/emission factors | Empirical/emission factors | Olander et al. (2011) |
| CARB | N/A | N/A | Empirical/emission factors | Empirical/emission factors | CARB (2014) |
| MANURE tool | N/A | N/A | Empirical/emission factors | Empirical/emission factors | Eastern Research Group (2009) |
| DairyWise model | N/A | N/A | Empirical/emission factors | Empirical/emission factors | Schils et al. (2007) |
| SIMS Dairy | N/A | N/A | Empirical/emission factors | Empirical/emission factors | Del Prado et al. (2011) |
| DairyGEM/ Integrated Farm System Model | Empirical/ emission factors | Empirical/ emission factors | Process-based (for liquid) Empirical/ emission factors (Temporary Stack & Long-Term Stockpile) | Empirical/emission factors | Rotz et al. (2010) |
| FarmGHG | Process-based | Empirical/ emission factors | Empirical/emission factors | Empirical/emission factors | Olesen et al. (2006) |
| Manure-DNDC | Process-based | Process-based | Process-based | Process-based | Li et al. (2012) |
| COMET-Farm | Empirical/ emission factors | Empirical/ emission factors | Process-based (for liquid) Empirical/ emission factors (solid manure piles) | Empirical/ emission factors | Paustian et al. (2014); Powers et al. (2014) |
| LEAP-LCA | | | Empirical/emission factors | Empirical/ emission factors | Fao (2016) |

## Intergovernmental Panel on Climate Change (IPCC) model

*Methane emission from manure management*

The Intergovernmental Panel on Climate Change (IPCC) model can be used to estimate $CH_4$ emission from manure treatment and storage, and from manure deposited on pastures. IPCC uses methane emission factors on a per animal per year basis. Total estimation of methane emissions for a farm using the IPCC methods is normally accomplished in four steps: 1) collect herd demographics/population information; 2) use appropriate emission factors for each livestock management group, ; 3) multiply the number of livestock in management group by appropriate emission factor, and 4) sum across the management groups to estimate total emissions by farm. The national $CH_4$ emission can be determined by summing the emissions from all defined livestock species using the four-step process for representative farms in the US.

The IPCC includes three tiers to estimate $CH_4$ emissions from livestock manure:

***Tier 1:*** It is a simplified method that only requires livestock population data by animal species/category and climate region or temperature, in combination with IPCC default emission factors, to estimate emissions. The tier is a national-scale and annual-resolution and has limited land-use and management activity and coarse delineation of soils and animal populations. It has a high uncertainty when applied at a project scale. In this method, default methane emission factors by livestock category or subcategory are used. The emission factors are based on the temperature, volatile solids content in manure, and management practices used in each region. A weighted average emission factor is usually estimated based on the percentage of animal populations in different temperature zones. However, if this was not possible, the annual average temperature for the entire country could be utilized.

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

***Tier 3:*** Some countries for which livestock emissions are particularly important may wish to go beyond the Tier 2 method and develop models for country-specific methodologies or use measurement–based approaches to quantify emission factors.

*Emissions of $N_2O$ from manure management*

The emission of $N_2O$ from manure can occur directly via combined nitrification and denitrification of nitrogen contained in the manure; or indirectly via volatile nitrogen losses that occur primarily in the forms of $NH_3$ and NOx.

*Direct emissions of N2O from manure management*

Similar to the emissions of methane from manure, the IPCC model has three tiers to estimate the emissions of $N_2O$:

***Tier 1:*** The emissions of $N_2O$ are estimated by multiplying the total amount of N excreted from each animal subcategory for each type of manure management system by an emission factor for that type of manure management system. Then, the total emission is estimated by the summation of the emissions from all manure management systems.

***Tier 2:*** This method is similar to Tier 1 but it would include the use of country-specific data for some or all of manure types and management systems.

***Tier 3:*** In this method, alternative estimation procedures such as mass balance approach could be applied. In the mass balance approach, nitrogen flow is determined throughout the system starting with feed input through final use/disposal.

The $N_2O$ emission factor for direct emission of $N_2O$ depends on manure management systems and their conditions such as aeration and temperature, and duration of storage. The emissions of $N_2O$ was considered negligible for the liquid/slurry systems without a natural crust cover, anaerobic lagoons, and anaerobic digesters due to low rate of nitrification resulted from the absence of nitrogen oxidation.

*Indirect emissions of $N_2O$ from manure management*

***Tier 1*****:** In this method, N volatilization in forms of $NH_3$ and $NO_x$ from manure management systems is based on multiplication of the amount of nitrogen excreted, from all livestock categories, and each manure management system by default fractions of volatilized N.

***Tier 2*****:** This method uses the same calculation equation as Tier 1 but include the use of country-specific data for fraction of volatilized N.

***Tier 3:*** This method could be developed using actual measurements for country-specific emission factors for volatilization and nitrogen leaching and runoff.

**CARB model**

California's GHG emissions from dairy manure storage systems are currently estimated by the Air Resources Board and generally follow the U.S. EPA and IPCC Tier 2 methods and sources (CARB, 2014). For estimating methane emissions, these methods estimate volatile solids (VS) excretion values for different categories of dairy cows and apply an average calculated methane emission factor (MCF) to an assumed theoretical maximum for major types of manure management systems. Similarly, for estimating the emissions of nitrous oxide ($N_2O$), emissions factors are applied based on nitrogen content in the manure for direct emissions, and emissions from runoff/leached fractions. Methane and $N_2O$ are assigned respective global warming potentials (GWPs) to facilitate GHG assessment on a carbon dioxide equivalent ($CO_2e$) basis. In the CARB model, the van't Hoff-Arrhenius equation is used to determine the effect of temperature on the proportions of VS that are biologically available for conversion to $CH_4$. The CARB model has been used to estimate GHG emissions from dairy farms before and after application of anaerobic digestion, and to estimate GHG emission reductions after the application of manure solid-liquid separation.

It should be mentioned that the Global Warming Potential (GWP) was defined by the IPCC (2013) as an emission metric that can be used to quantify and communicate the absolute and relative contributions to climate change of emissions of different pollutants. The GWP integrates the radiative forcing (RF) of a pollutant over a chosen time horizon (commonly 20, 100, or 500 years), relative to that of $CO_2$. RF is the net change in the energy balance of the Earth's system due to some imposed perturbation. It quantifies the energy imbalance that occurs when the imposed change takes place (IPCC, 2013). Briefly, GWP is the ratio of the amount of heat trapped by one unit mass of a GHG to the amount of heat trapped by one unit mass of $CO_2$ over the same period of time (IPCC, 2001)

**Manure and Nutrient Reduction Estimator (MANURE) tool**

The MANURE tool estimates the emissions of total methane, direct $N_2O$, and indirect $N_2O$ from a dairy farm. The tool is used to calculate the total baseline emissions before and after the installation of an anaerobic digester (Eastern Research Group, 2009). Like IPCC and CARB models, MANURE tool was developed based on the emission factors and empirical models. The model is used to estimate direct and indirect $N_2O$ emissions from manure. In addition to GHG emissions, MANURE tool is used to estimate the emission of $NH_3$ using its emission factors that were used by the U.S. EPA.

**SIMS Dairy model**

SIMS (DAIRY) is a farm-scale model (Del Prado et al., 2011). The model simulates the effect of the interactions between farm management, climate, genetic traits, and soil characteristics on: flows and losses of nitrogen, phosphorus and carbon; GHG emissions and potential soil C storage; animal performance and nutrition requirements; farm profitability; and attributes of farm sustainability (biodiversity, food quality for human health, soil quality and animal welfare). The emissions of methane and $N_2O$ from manure management were calculated using emission factors.

**DairyWise model**

DairyWise is an empirical model for dairy farms (Schils et al., 2007). The model was developed based on the on crop and animal experiments that were conducted in the Netherlands. It simulates technical, environmental, and financial processes on dairy farms. The processes included feed and fertilizer import, crop management and feed production, animal feeding and production, manure production and utilization, and milk and meat exports. Modular structure of DairyWise is shown in Figure 3. The model inputs include traits of dairy farms. It has several submodels for nitrogen and phosphorus cycling, nitrate leaching, $NH_3$ emissions, GHG emissions, energy use, and a financial farm budget. Methane emission are calculated from manure storage and from enteric fermentation. Methane, direct and indirect $N_2O$, and carbon dioxide emissions are calculated using emission factors that were used in Dutch emission inventories (Schils et al., 2006).

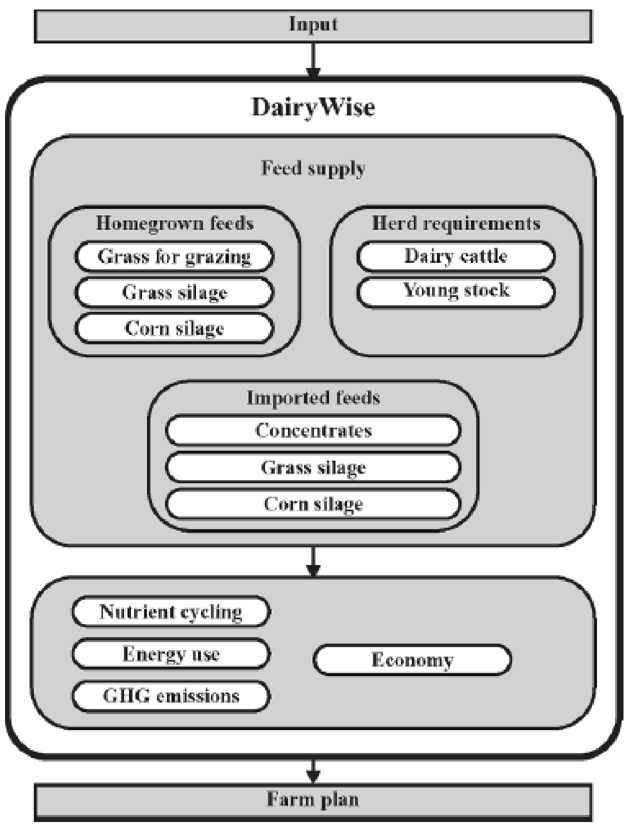


**Figure 3. Modular structure of DairyWise (Schils et al., 2007).**

## FarmGHG model

FarmGHG is a whole-farm model that was designed to quantify the flows of C and N on dairy farms (Olesen, 2006). The model can be used to study the effect of different farm practices on the direct and indirect gaseous emissions from dairy farms. Figure 4 shows the flows of C and N in the FarmGHG model. In addition to a default methodology to estimate the emissions of GHG, the model has a capability to use different methodologies for emissions estimations including the Tier 1 and Tier 2 methodologies of the IPCC (1997) and the IPCC Good Practice Guidance (IPCC, 2000). The default methodology includes empirical and process-based sub models for estimating the emissions of GHG from enteric fermentation, slurry in houses, and manure storage. The FarmGHG model was used to simulate farm N flows, and GHG emissions for a set of European model dairy farms. To our knowledge, no study was conducted to validate the results of FarmGHG on California dairy Farms. The input parameters for the submodules of the emissions of GHG on dairy farms are shown in Table 2.

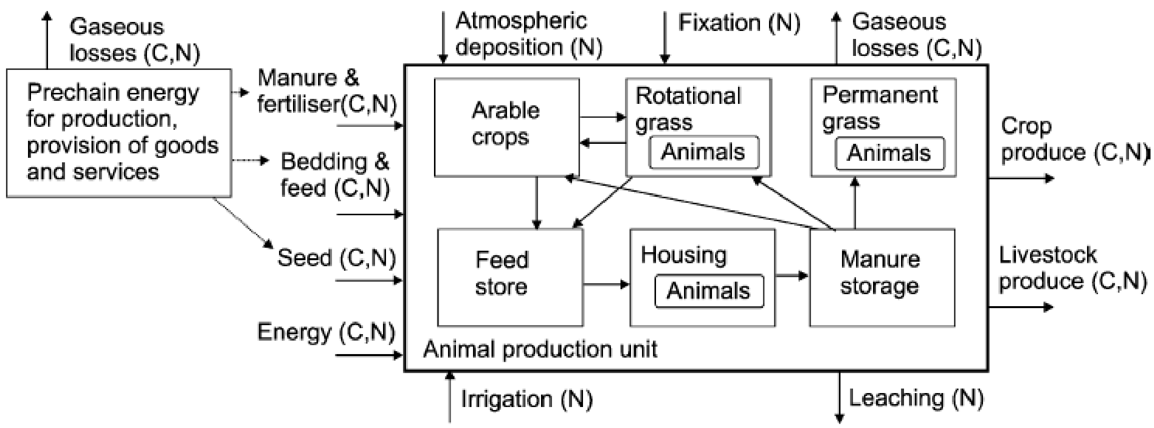


**Figure 4. Flows of C and N in the FarmGHG model (Olesen et al., 2006).**

**Table 2. Input parameters for the FarmGHG model.**

| Category | Input parameters |
|---|---|
| Weather data | Temperature of dairy house |
| Animals and housing | Type of cows (milking cows and heifers); and housing types (tied stall; cubicles; and deep litter) |
| Animal feed | Feed plan over the year for each animal type; intake of crude fibers; intake of nitrogen free extracts; intake of crude protein; and intake of crude fat |
| Manure handling | Amount of manure and its organic matter contents; and methods of manure handling (manure separation; manure collection in channels or pits beneath slats). |
| Manure storage and treatment | Storage time; and type of storage (tanks for fresh liquid manure, and anaerobically digested slurry; and heap and composting for solid manure and deep litter). |

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

Several models and computer software tools for estimating the GHG emissions and carbon footprint of dairy production systems have been developed over the past three decades as led by USDA researchers. IFSM is a computer model that integrates the major biological and physical processes of a crop, livestock, or dairy farm to predict performance, economics, and environmental impacts including various GHG and other gas emissions and a partial LCA of carbon, energy, water, and reactive nitrogen footprints of the feed, meat, or milk produced (Rotz et al., 2014). The quantity and nutrient content of the manure produced is a function of the feed consumed. Nutrient flows through the farm are modeled to predict nutrient accumulation in the soil and loss to the environment. Whole-farm mass balances of nitrogen, phosphorus, potassium and carbon are determined as the sum of all nutrient imports and exports. The DairyGEM model is a subset of the IFSM model that can be used to determine the emissions of GHG, $NH_3$, and $H_2S$ from different components of dairy farms. GHG emissions include those from enteric fermentation, the barn floor, manure storage, and feces deposited in pasture. The model uses empirical and process-based models to estimate the emissions of GHG. A carbon footprint is determined through a partial LCA of the production system, which includes the secondary emissions that occur during the manufacture or production of resources used on farms. Results of the DairyGEM model were validated using emission data from the US dairy farms. Figure 5 shows a flow chart of different components of the IFSM and DairyGEM modeling tools. Table 3 shows the input parameters for the DairyGEM model.

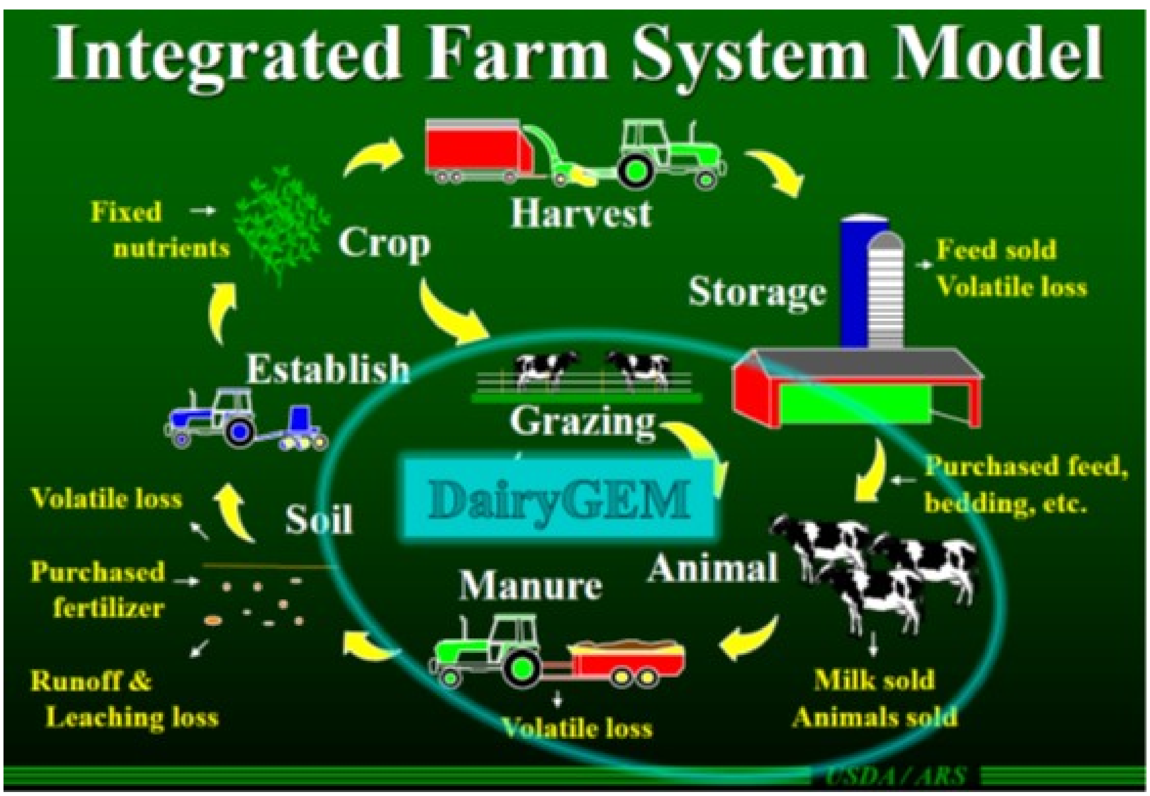


**Figure 5. IFSM and DairyGEM modeling tools.**

**Table 3. Input parameters for the DairyGEM model.**

| **Category** | **Input parameters** |
|---|---|
| Weather data | Daily solar radiation, average temperature, maximum temperature, minimum temperature, total precipitation, and wind velocity for many years |
| Farm | Animal breed, number of animals at various ages, feeds and pasture available, housing facilities (cow and heifer housing), and manure handling methods |
| Animal feed | Type of feed and its composition (e.g., protein, degradable protein, net energy for lactation, etc.), and supplemental feeds (e.g., crude protein and energy supplement) |
| Bedding | Type and amount of bedding added every day |
| Manure handling | Manure handling systems: a primary system that would handle most of the manure; and a secondary system that would handle a portion of the total manure dry matter.<br><br>Manure collection method: hand scraping and gutter cleaning; scrape with a loader, vacuum, and slurry pump; and flush system. |
| Manure storage and treatment | Storage time; type of storage; and storage capacity and dimensions. Type of storages includes stack or compost; top loaded lined earthen pit; top loaded concrete tank; bottom loaded tank or pit; bottom loaded steel tank; covered tank or pit; and enclosed tank and flare. |

## Manure-DNDC Modeling tool

The Denitrification-Decomposition (DNDC) model was originally developed for quantifying C sequestration and trace gas emissions for U.S. agroecosystems (Li et al., 1992; Li et al., 1994; Li et al., 1996; Li, 2000). The DNDC is a process-based model that has several sub-models as shown in Figure 6. The DNDC sub-models of manure management was latter developed as a dedicated model called Manure-DNDC (Figure 6). A Manure-DNDC model is biogeochemical process model to predict GHG and $NH_3$ emissions from manure management systems (Li et al., 2012). It includes feedlot (barns or outdoor corrals), manure storage/treatment facilities (lagoon, tank, compost and anaerobic digester) and field application. The effect of Eh, pH, temperature, moisture content, the concentrations of dissolved organic carbon (DOC) and $CO_2$ were used as drivers to quantify $CH_4$ production in Manure-DNDC. In addition, the model involves the oxidation of $CH_4$ when it is diffused into the aerobic microsites. The framework of Manure-DNDC was developed based on the manure life cycle within the farm. Results of the Manure-DNDC model were validated using emissions data from several dairies in the USA. Table 4 shows the input parameters for the Manure-DNDC model.

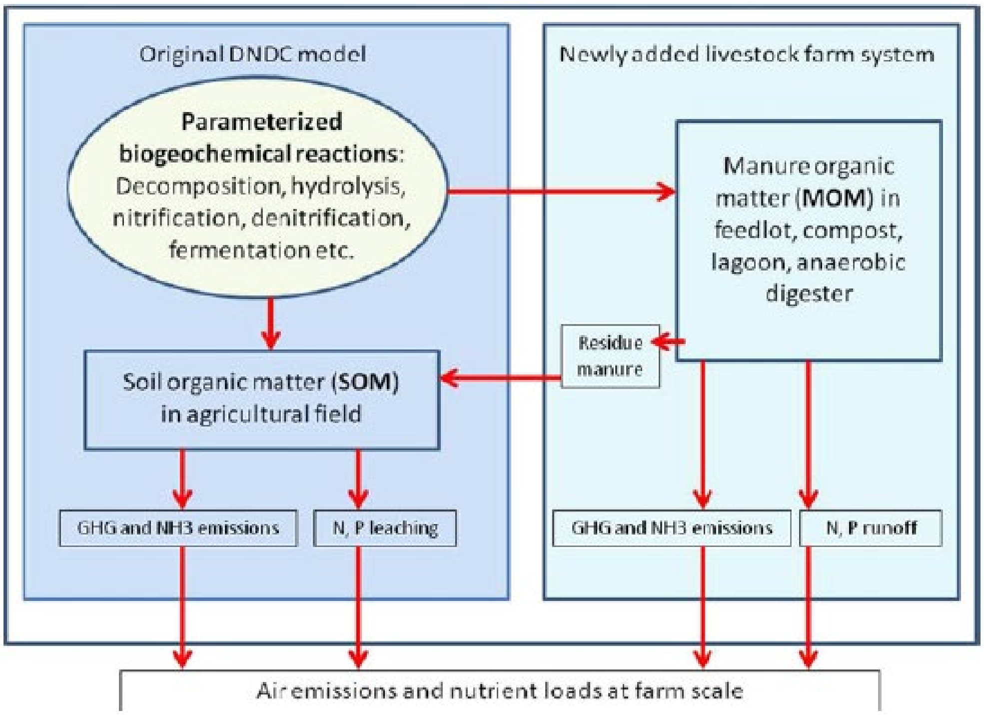


**Figure 6. DNDC Model (Li et al., 2012).**

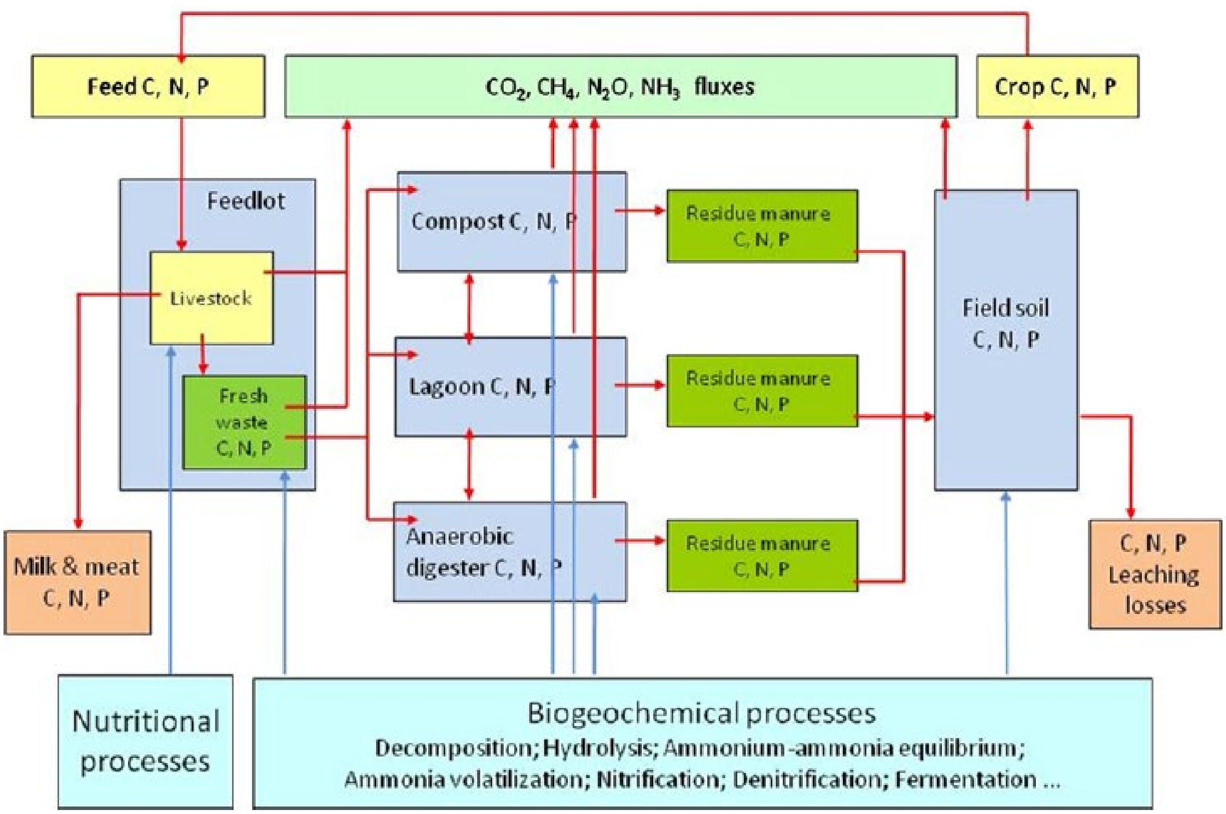


**Figure 7. Manure-DNDC Model (Li et al., 2012).**

**Table 4. Input parameters for the Manure-DNDC.**

| Category | Input parameters |
|---|---|
| Weather data | Maximum and minimum air temperature, precipitation, and wind speed |
| Animal inventory | Livestock type (dairy cows, beef cows, other animals), and number of heads |
| Animal feed | Feed rate (kg dry matter/head/day), crude protein, and P concentration (%) in the feed |
| Feedlot | Type (barn or outdoor pen); floor conditions (concrete or slatted with under-floor gutter); floor surface area; and ventilation system |
| Bedding | Type (sand, manure solids, straw, etc.); amount (dry matter per application); and frequency of addition |
| Manure removal | Frequency; and fraction of manure removed to lagoon, compost, anaerobic digester, or crop field. |
| Manure storage and treatment | Manure characteristics: redox potential, pH, and concentration of DOC and $CO_2$<br>Lagoon or tank: capacity, surface area, coverage (none, loose, tight), retention time, and fraction of residue slurry removed to anaerobic digester or crop field.<br>Anaerobic digester: digester temperature, hydraulic retention time, and fraction of residual manure removed to lagoon or crop field.<br>Compost: density, storage duration, additives quantity and quality, and fractions of residue manure removed to lagoon, anaerobic digester, or crop field |

**COMET-FARM**

The CarbOn Management Evaluation Tool (COMET-FARM) has recently been released by Colorado State University and USDA to predict the emissions from dairy farms (Paustian et al., 2014). COMET-FARM is a web-based software that was designed to quantify whole farm GHG emissions (Figure 8). It can be applied non-GHG specialists (farmers, consultants, NRCS field staff, etc.) to estimate farm-scale GHG emissions. It estimates the carbon footprint for every part of the farm/ranch operation. It also explores alternative management and land use strategies. For the emissions from animals, the tool uses statistical models based on USDA and university research results (Powers et al., 2014). For manure management, the IPCC Tier 2 methodology was used for $CH_4$ emissions from temporary stack and long-term stockpile, $CH_4$ and $N_2O$ emissions from composting, and $N_2O$ emissions from aerobic lagoons. Similar to DairyGEM, COMET applies Sommer model to estimate $CH_4$ emissions from anaerobic lagoons. Table 5 shows the input parameters for the COMET-Farm Model.

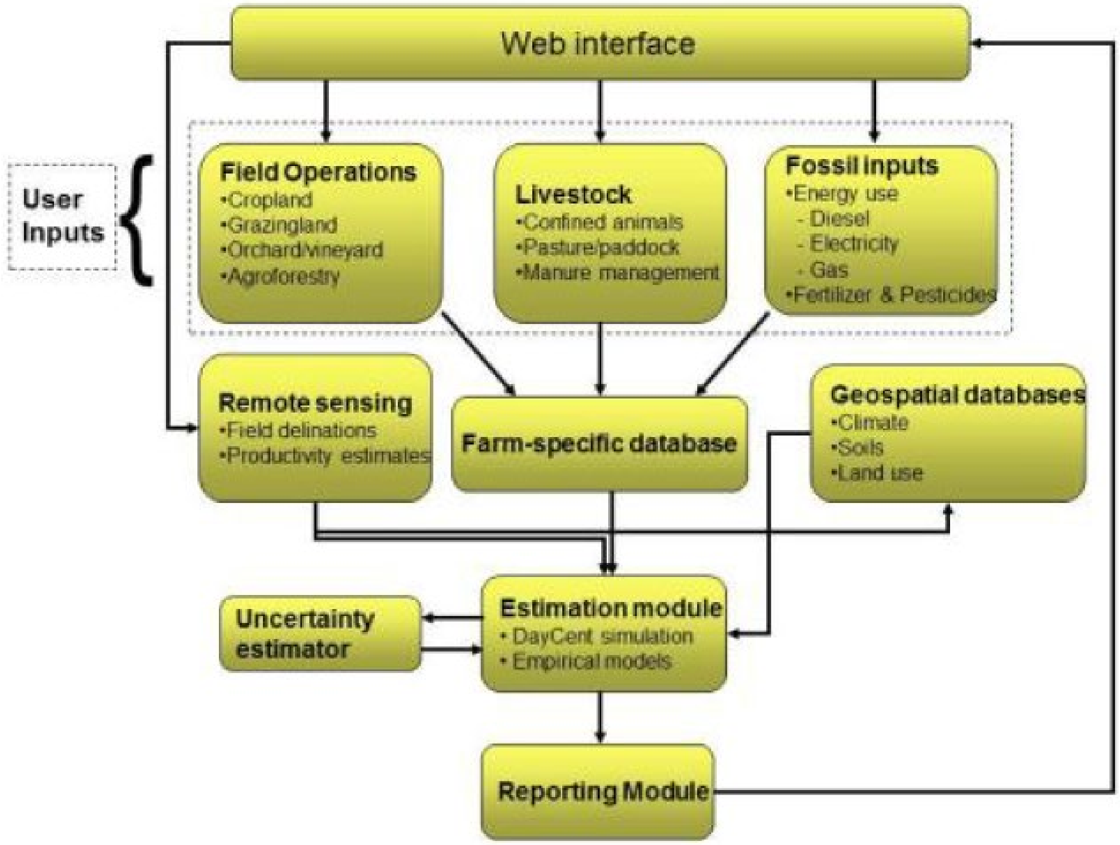


**Figure 8. COMET-Farm model framework.**

**Table 5. Input parameters for the COMET-Farm Model.**

| **Category** | **Input parameters** |
|---|---|
| Weather data | Zip code for the farm |
| Animal inventory | Livestock type (dairy cows (lactating and dry), beef cows, other animals), monthly average number of heads, and average body weight |
| Animal feed | Feed rate, and feed type |
| Feedlot | Type (roofed facility, dry lot, and pasture range paddock) |
| Manure management | Amount of manure produced per head each month; nitrogen content in the manure; application of liquid/solid separation; storage method (anaerobic lagoon, temporary stack and long-term stockpile, thermochemical conversion, etc.); storage duration; and application of storage covering |

**LEAP-LCA Methodology**

The UN's Food and Agriculture Organization (FAO) established a Livestock Environmental Assessment and Performance Partnership (LEAP) that engaged over 300 scientists in a milestone effort to develop global benchmarking methods for livestock and feed sectors. The main goal of LEAP is improving the environmental performance of livestock supply chains. The project developed and adopted a Life Cycle Assessment (LCA) methodology that harmonized quantification efforts and allows accurate measurements for various livestock species and regions. The environmental performance guidelines for large ruminant's supply chains were recently released (FAO, 2016). The scope of the LEAP is to produce detailed guidelines and refine guidance for existing standards that are specifically relevant to the livestock sector. The overall system boundary of the LEAP's LCA for dairy and beef farms represents the cradle to- primary-processing-stages of the life cycle of the main products from dairy cows (Figure 9). Figure 10 shows the various required inputs needed to calculate the carbon footprint of products from different processes of the cradle-to-farm-gate stage.

In the LEAP-LCA model, methane emissions from manure management systems are calculated using emission factors as described in the IPCC (2006). The model is used to estimate the direct and indirect emissions of $N_2O$. The direct emissions represent the direct release of $N_2O$ to the atmosphere. While the indirect emissions result from the $NH_3$ released from manure into the atmosphere and deposited back onto soil, and from nitrate leached to ground and surface waterways. Tier 2 method of the IPCC (2006) is used to calculate emissions of $N_2O$. Table 6 shows the input parameters for the LEAP emission model.

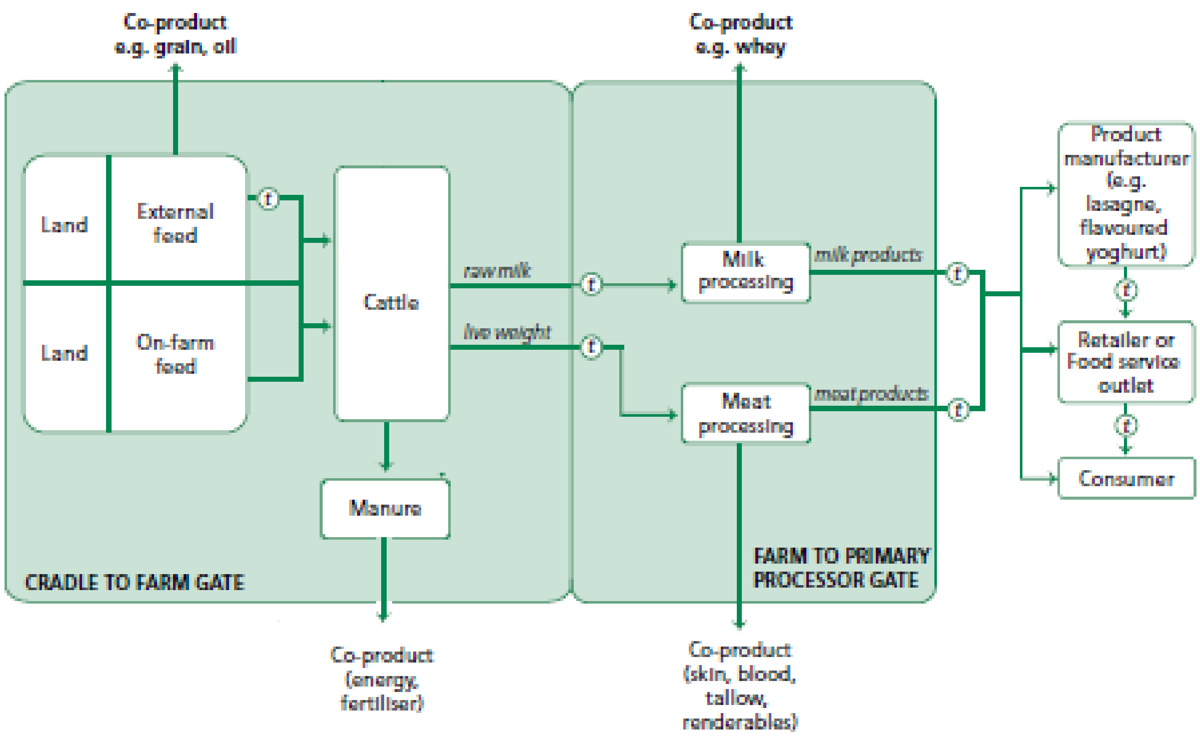


**Figure 9. System boundary for the LCA of beef and dairy cattle. The encircled t symbol refers to the main transportation stages.**

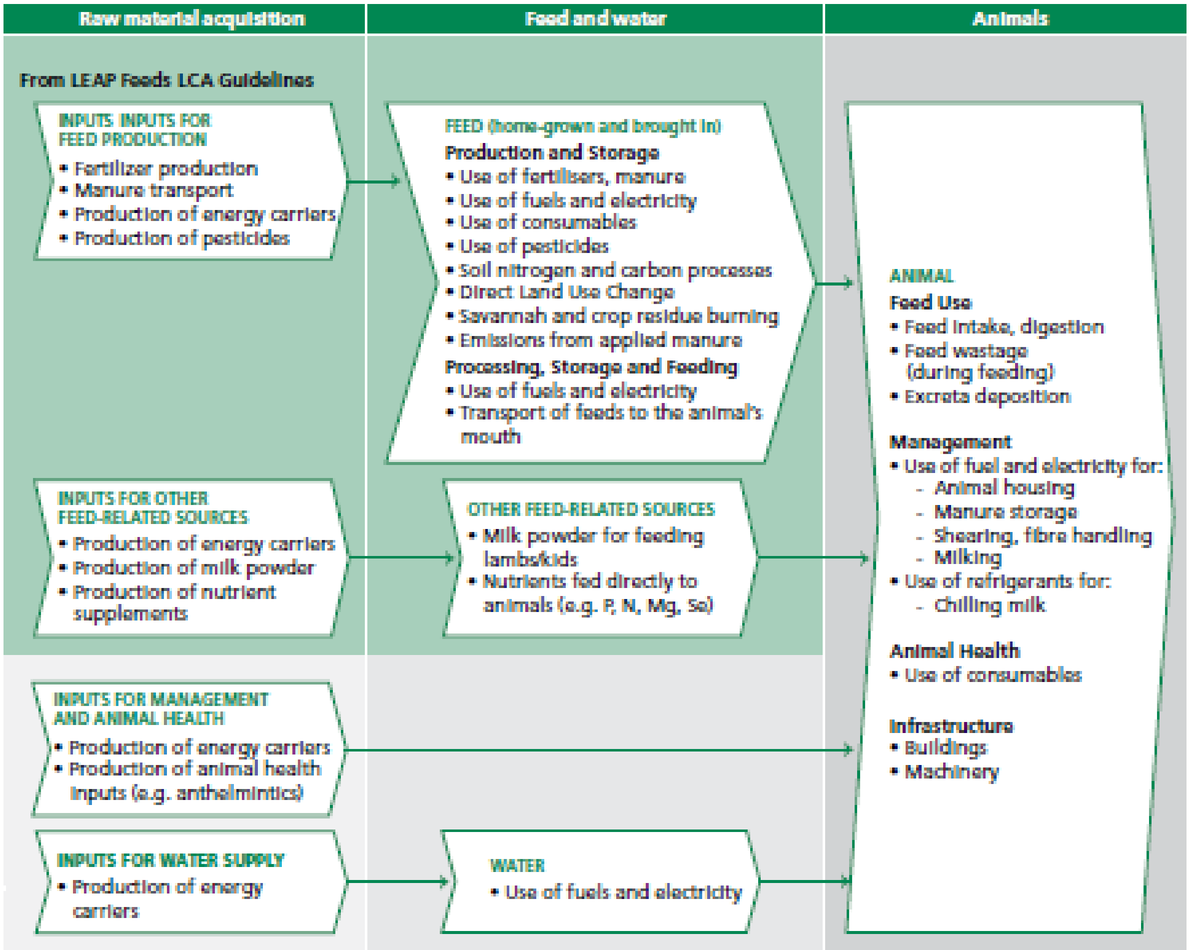


**Figure 10. Different inputs for different processes in the LCA.**

**Table 6. Input parameters for the LEAP emission model.**

| **Category** | **Input parameters** |
|---|---|
| Location | Country specific emission factors |
| Animal inventory | Number of heads, milk production, herd replacement rate, fertility (calving percentage), death rate, average age at first calving, growth rate of young cattle, and age of replacements at first mating. |
| Animal feed | Feed rate, and feed quality (e.g., nitrogen content) |
| Feedlot | Type housing type; application of grazing system; and time duration that the herd spends in each location |
| Manure characteristics and management system | Amount of manure produced per head; nitrogen content in the manure; manure management system (e.g., dry lot, aerobic pond, uncovered anaerobic lagoons, and composting); and storage duration |

**Task 1b: Recommend an emission model for validation on selected dairies**

**Selection of a model for estimating GHG emission on the selected Californian Dairies**

As described under Task 1a, there are several models available to estimate GHG emissions from dairy farms, ranging from simple to highly complex process-based models. The IPCC methodology provides a simplistic method that may be suitable for a rough determination of emissions and for country inventory purposes (Rotz et al., 2016). However, there are large uncertainties in the emission factors and the biodegradability of manure. This negatively affect the accuracy of these models. Moreover, the in some cases it is difficult to find published national statistics or even farm by farm data regarding the fraction of manure that is managed by each system. Rotz et al. (2016) mentioned that the IPCC methods are, in some cases, derived based on very limited data and may not be very representative of emissions at the farm level.

Empirical models such as DairyWise are built on experimental data. Therefore, applicability of these models is restricted to the condition at which they were driven. Most of the reviewed models are not mechanistic ones to simulate the biochemical processes involved in the production and emission of GHG. Some of the models were mixed of empirical and process-based models such as DairyGEM. In the DairyGEM model, the model of Sommer et al. (2004) was selected to predict methane emissions from manure storage because it employs empirical relationships that enable the prediction of emissions under wide range of weather conditions. The model also used values of biodegradability that are commonly used by several researchers under different weather conditions. Moreover, the model was developed for the application for either digested or untreated slurry manure. Mechanistic and process-based models are more suitable and accurate to predict the emissions of GHG as affected by management and climatic conditions. However, to our knowledge only DNDC is the only model that mechanistically predicts the emissions from manure.

There are several criteria affecting the selection of a model to use to predict the emissions of GHG on the selected dairy farms. Chianese et al (2008) presented five criteria for selecting a model to predict the emissions from large sources on farms. They included:

1. The model had to be capable of simulating important processes and farm practice that affect emissions.

2. The model had to provide a process-level representation of emission components.

3. The model had to satisfactorily predict observed data over a full range of potential conditions.

4. The model had to be consistent with the current scale of other components in Integrated Farm System Model (IFSM).

5. Model inputs and parameters were limited to readily available data.

For this project, we identified several criteria to use in selecting select a model to predict baseline (pre-AMMP) emissions. The criteria include:

1- The model should be a process-based model

The model should be processed-based that enables the determination of the emissions from each component (e.g., housing and manure storage) of a dairy farm. Processed-based models enable users to study the effect of different farm practices and weather conditions on the emissions of GHG from dairy farms.

2- The model should have input parameters that values for are readily available

The input parameters for the selected model should be readily available to obtain from literature, weather station, and/or farm records.

3- The model should have been validated with data from US dairy farms

Model validation is very important to determine the accuracy of model predictions for GHG emissions. The selected model should have been validated on dairy farms in the USA and preferably on California dairies.

4- The model equations and software should available

The model equations and software should be available and easy to apply for selected farms in California.

Manure-DNDC and DairyGEM are the models, among the reviewed ones, to predict the emissions from dairy farms including manure lagoons. These two models met majority of our formulated criteria for model selection. Li et al. (2012) validating the applicability of Manure-DNDC for livestock farms using seven datasets of air emissions measured from farms across the U.S. plus a Scotland pasture. The DaryGEM has been validated on selected farms in the USA. In addition, CARB/IPCC model can be employed to predict the emissions from lagoons and settling basins because it calculates the emissions based on the destruction of VS contained in the flushed manure.

**Task 2a: Literature review of best measurement practices for farm-scale dairy manure emissions monitoring.**

Greenhouse gas is mitted from different potential sources on dairy farms (Owen et al., 2015). Figure 11 shows different sources of GHG emissions on dairy farms.

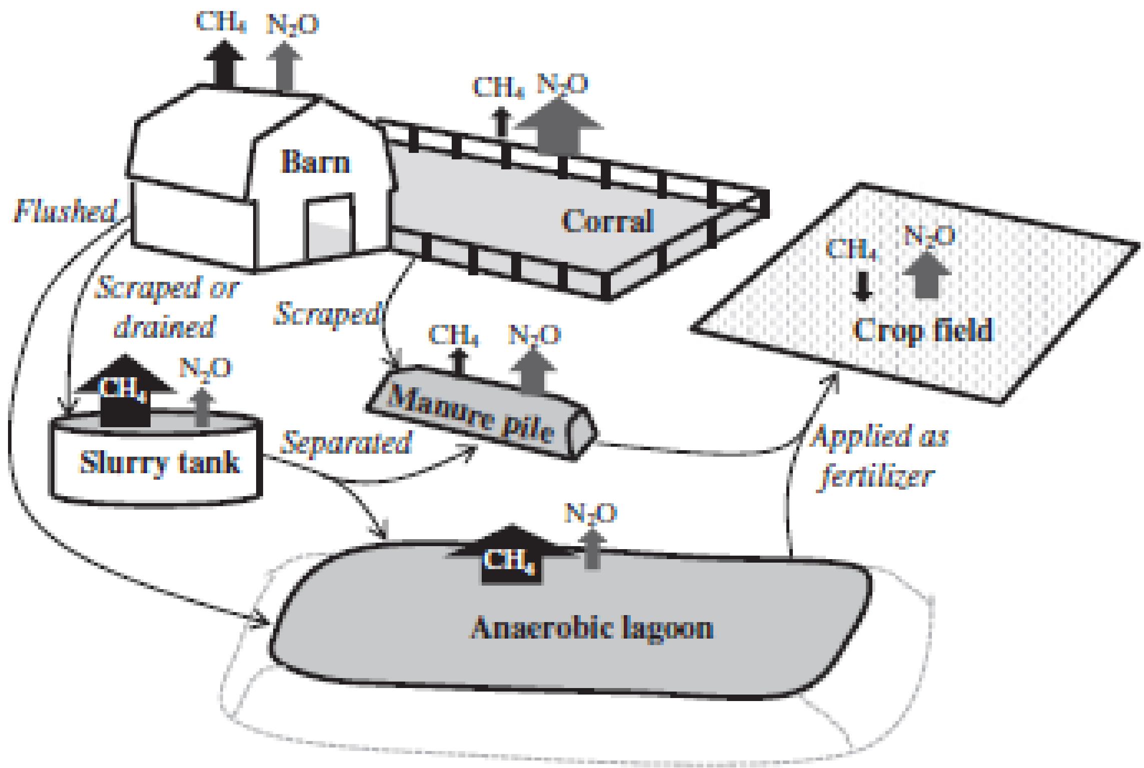


**Figure 11. Emissions of potential GHGs from different sources on a dairy farm (Owen et al., 2015).**

There are several methods that are currently applied to measure the emissions of different gases. CAEAFO (2002) mentioned that all of the measurement methods, there exist considerable uncertainties, as well as advantages and disadvantages. CAEAFO (2002) stated that, to measure the emissions from small scale (< 100 $m^2$) enclosure techniques are used. In these techniques, a chamber is placed either on or around the emission source. Two basic approaches exist for the chamber approach, non-aspirated and aspirated. In the non-aspirated approach, no air is moved thru the chamber, and with the aspirated approach, a fan or blower us used to move air at a controlled and known rate thru the chamber. The concentration of the gases of interest are measured, over time, at the camber air inlet and outlet. This technique is suitable for measuring the effect of different factors affecting the emissions in small-scale studies and needs less infrastructure than those required by other techniques (e.g., micrometeorological techniques used in the larger-scale studies). However, the enclosure techniques are not suitable to determine the spatial variability of the emission rates unless several chambers are strategically placed over the emission source. They may also alter the environment of the emission source; therefore, the measured emissions may be biased. For surface layer scale (> 100 $m^2$), micrometeorological techniques or mass balance methods can be applied to measure emission fluxes. Micrometeorological methods include eddy correlation, eddy accumulation and other conditional sampling techniques, and gradient and difference methods (Harper et al., 2011; McGinn, 2013). In these methods, measuring instrumentation is installed on tower platforms, thus requiring substantial experimental infrastructure.

There are several measuring instruments that are commonly used to measure the emission of GHG. Among them are high resolution Fourier transform infrared (FTIR) spectroscopy, Photoacoustic spectroscopy, and gas chromatography (e.g., Thermo Scientific™ Model 55i Methane). The principal of the FTIR spectroscopy measurement is based on the fact that each gas has a distinct infrared absorption features. Therefore, a FTIR spectroscopy instrument can be used to simultaneously measure several gases. Photoacoustic spectroscopy measures the effects of light absorption by solids, liquids, and gases by means of acoustic detection (Malkin and Cahen, 1979). The light absorbance of a certain gas is converted to acoustic signal. INNOVA analyzers are examples of these devices that measure multiple gases such as $CO_2$, $N_2O$, and $CH_4$, among others.

**Methods of emissions measurements**

**Enclosure techniques**

<u>Description</u>

The enclosure techniques can be used to measure the emissions from liquid manure storages (lagoons), solid manure piles, silage and feed piles, and cropland that received manure application. The enclosed chamber method is commonly used. The chambers are enclosures made of different materials. They cover a certain area of the emitting source. The chambers have an inlet and outlet for air. Fresh air is continuously drawn into the chamber and forced to flow over the covered surface and exits from the outlet. The flux of gas from the covered surface is calculated from concentration difference, flow rate, and area covered by the chamber. The applied flow rate and changes in the concentration of different gases between the inlet and outlet are used to calculate the emission rates.

Dynamic chamber technique has been applied for measuring the emissions of different gases from different sources on-farm. Different designs of the floating chambers are used for manure lagoons and wastewater treatment plants. Different designs of the emissions chambers are available that are made of metal, acrylic that are carried above Styrofoam plates or tubes. The dimensions of dynamic chambers vary with the purpose. We have developed a floating wind tunnel that was used for measuring the emissions of different gases from manure lagoons and from slurry (Figure 12). Moreover, we have developed wind tunnel to determine the emissions form manure storage in laboratory. The wind tunnel has a transparent top to observe the changes on manure surfaces. The tunnel was used to measure the emissions from laying hen manure. The concentrations of the gases in the inlet and outlet of the wind tunnels were measured using different devices such as INNOVA Gas Analyzer.

**Figure 12. A floating wind tunnel for measuring the emissions from lagoons (left); a wind tunnel used for measuring the emissions from slurry (right).**

<u>Application</u>

Safley and Westerman (1992) used a floating cover to collect the gas produced from a portion of anaerobic lagoon treating manure produced from a 200-head dairy farm that was one of North Carolina State University's agricultural research facilities. The amount of the biogas collected by the floating cover was measured using a gas meter, and the methane concentration was determined by analyzing regularly collected biogas samples with a gas chromatograph. Biogas production decreased during the autumn and winter seasons wherein temperatures were low. Biogas production rate ranged from 0.05 to 0.5 $m^3/m^2$/day depending on the ambient temperature. Craggs et al. (2008) measured the emissions of methane from dairy and pig manure anaerobic ponds. They used a floating gas collection cover that was positioned on a portion of the pond surface. The four sides of the cover were extended down into the anaerobic pond to a depth of 0.5 m. The gas collected under the cover was measured using a flow meter. The methane content of the collected gas was analyzed at monthly intervals using a portable gas analyzer. The calculated $CH_4$ emissions from dairy cow manure treated in anaerobic ponds was 6.4 kg /cow/year (9 $m^3$ /cow/year).

We have used flux chambers and wind tunnel for measuring the emissions of volatile organic compounds (VOCs) from silage samples in the laboratory and in the field. El Mashad et al. (2011) used a wind tunnel to measure the emission of ethanol, in the laboratory, from thin layers of corn silage. Figure 13 shows a flux chamber and wind tunnel located on the fact of a corn silage bunker silo pile. The concentration of selected VOCs in the inlet and outlet of the wind tunnel and flux chamber were measured continuously with an INNOVA gas analyzer. The INNOVA is based on the photoacoustic infrared spectroscopy. Samples of the inlet and outlet air were analyzed using gas chromatography–mass spectrometry (GC-MS).

**Figure 13. Flux chamber and wind tunnel during measuring the emissions from a silage pile.**

For measuring the emissions from compost heaps, Osada et al. (2001) used a mobile chamber on wheels. The chamber was made of marine plywood and mounted on a metal frame. The chamber dimensions were 1.6 m tall, 2 m wide and 4 m long. The chamber can be moved and placed over compost heap. The chamber is equipped with a ventilator that allows controlling the air flow rate through the chamber. Therefore, the emission flux and rate can be calculated. Amon et al. (2006) quantified the emissions of $NH_3$, methane and $N_2O$ from dairy and pig slurry storage and after its field application. Emissions were determined for untreated, compost produced from mechanically separated solids, anaerobically digested, straw covered and aerated slurry. Open dynamic chamber that covers an area of 27 $m^2$ was used in the study (Figure 14). The dynamic chamber can move on wooded rails to intermittently (at least twice a week for several hours) measure the emissions from different manure samples. Fourier-transform infrared spectroscopy (FTIR) was used to measure the emissions of different gases. Results showed that most $NH_3$ emissions occurred after field application. Methane emissions represented more than 90% of net total GHG emissions from untreated slurry during slurry storage. Greenhouse gas emissions increased after covering the slurry store with a layer of chopped straw. Nitrous oxide emissions were greater from the storage of aerated slurry than the untreated manure. However, the total GHG emissions from the aerated slurry were lower than that of untreated slurry.

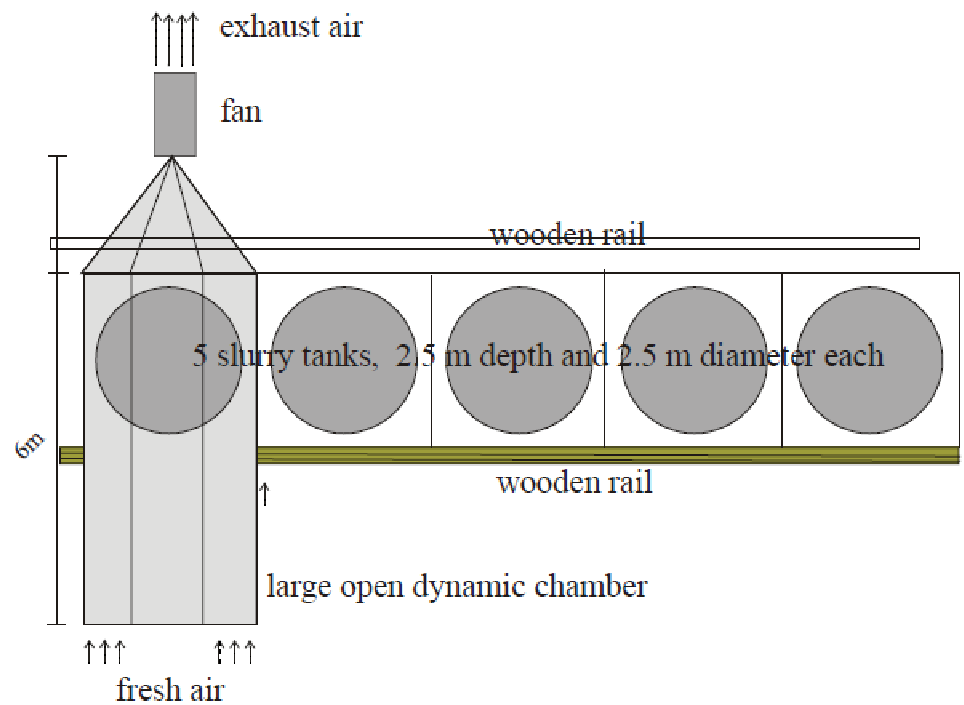


**Figure 14. Open dynamic chamber moving over wooden rails (Amon et al., 2006).**

Ammon et al. (2001) determined the emissions of $NH_3$ and GHG ($N_2O$ and $CH_4$) from farmyard manure using a large open-dynamic-chamber that was made of polycarbonate that does not does not adsorb $NH_3$. Light could penetrate inside the chamber. The open-dynamic-chamber covered an area of 27 $m^2$. The average air velocity inside the chamber could be adjusted between 0.18 and 2.04 m/sec. The emissions were determined from an aerobically (turning was applied seven times during the storage period) composted manure heap and an anaerobically (no turning was applied) stacked heap. A high resolution FTIR spectroscopy to continuously measure the concentrations of different gases. The emissions of $NH_3$ and GHG during the summer were, respectively 552.2 g/ton and 13.8 kg [$CO_2$-eq/ton) for the composted manure; and 205.7 g/ton and 61.5 kg [$CO_2$-eq/ton) for the stacked manure. During the winter, the emissions were, respectively 249.2 g/ton and 36.5 kg [$CO_2$-eq/ton) for the composted manure; and 201.3 g/ton and 39.1 kg [$CO_2$-eq/ton) for the stacked manure.

Ahn et al. (2011) used flux chamber with height of 1.9 m and a square base of 2.1 m to study the effect of pile mixing on the emissions from dairy manure compost. The chamber was equipped with internal and external fans to mix the inside air and to draw air through the chamber. The concentration in the inlet and outlet gases were measured using INNOVA and an oxygen sensor for 80 days. The emissions from mixed and static piles were released 2 and 1.6 kg GHG ($CO_2$e.) for each kg of degraded VS, respectively. Approximately 70% and 90% of $CO_2$ and $CH_4$ emissions, respectively, occurred in the first 23 days of composting. While 80–95% of $N_2O$ emissions occurred after this period.

Heber et al. (2002) developed a floating emission chamber that can be used for measuring the emissions of different gases from manure lagoons (Figure 15, left). The chamber was: equipped with an air supply blower; carried on Styrofoam boards for buoyancy; and covering an area of 0.76 $m^2$ of lagoon surface. The chamber was used to measure odor flux from swine manure lagoons. A simulated wind speed of 1.1 m/s was used to measure odor flux of the stratified lagoon. Air samples were collected, in gas bags, from the inlet and outlet of the chamber. The samples were analyzed using an olfactometer.

Day et al. (2016) used a floating chamber for measuring the emissions at sewage treatment plants. The chamber was made of polyethylene drums cut in two that installed above a circular float (Figure 15, right). To measure methane emissions from rice fields, Day et al. (2016) used a high flux chamber that can accommodate rice plant at its maximum height (1.2 m) before harvest (Figure 16).

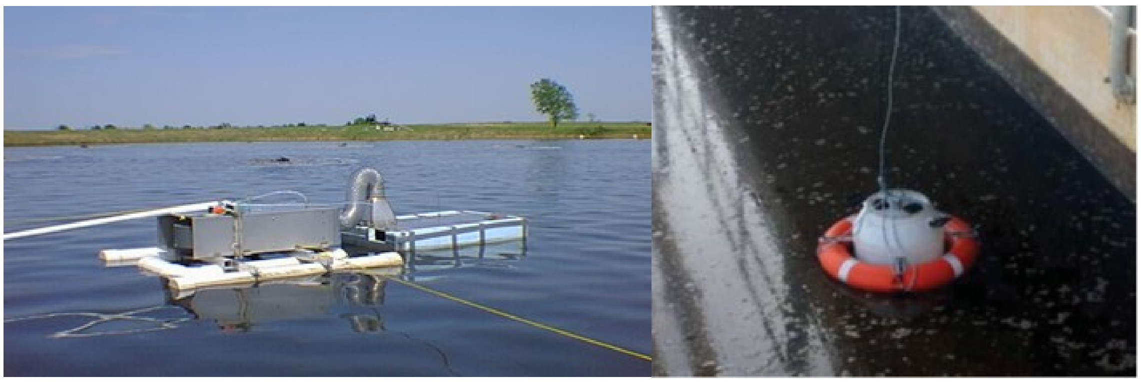

**Figure 15. A floating emission chamber (Heber et al., 2002), left; floating flux chamber used at a sewage treatment plant (Day et al., 2016), right.**

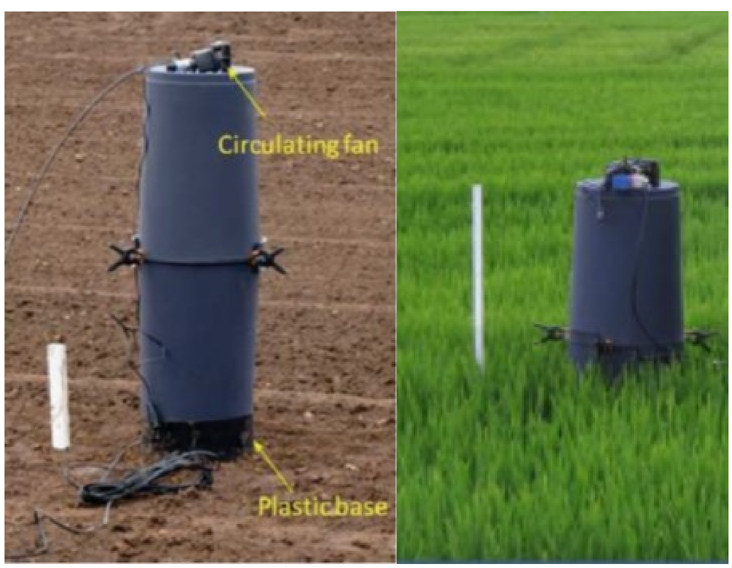


**Figure 16. Flux chamber used at rice fields (Day et al., 2016).**

For measuring the emissions of $NH_3$ from lagoons treating swine manure, Aneja et al. (2001) employed a dynamic chamber system with continuous impeller stirring (100 rpm). Stirring was applied to assure completely mixed atmosphere inside the dynamic chamber. Therefore, the measured concentration of ammonia at the chamber outlet represented ammonia concentration inside the chamber. Tracer experiments were used to determine the goodness of mixing inside the chamber. The results of experiments showed that the dynamic chamber was perfectly mixed with negligible stagnancy or channeling. Ammonia fluxes were continuously determined to develop 24-hour flux profiles. Malkina et al. (2011) measured VOC emission from silage and other feed samples from a commercial dairy using a room-sized environmental chamber at the University of California, Davis

Minato et al. (2013) used a floating dynamic chamber to measure the emissions of GHG and $NH_3$ from stored dairy cattle slurry on a dairy cattle farm in eastern Hokkaido, Japan. Figure 17 shows the floating open chamber placed on the slurry surface. Fresh air was continuously forced into the chamber at a constant flow rate. A photoacoustic multigas monitor (Model 1312; INNOVA) was used to measure the concentration of the gases. The emission rates were determined from the ventilation rate and the concentration difference between the outlet and inlet air samples. Average emission rates of $CH_4$ in summer, fall and spring were 54.8, 54.2 and 34.3 g/m$^2$/day; and $NH_3$ were 0.55, 0.73 and 0.46 g/m$^2$/day, respectively. The emissions of $N_2O$ were very low.

**Figure 17. A floating open chamber on the storage tank surface (Minato et al., 2013).**

Ammon et al. (2001) determined the emission rates of $NH_3$, $N_2O$ and $CH_4$ from composted and anaerobically stacked farmyard manure using a large open-dynamic-chamber that was made of polycarbonate. Light could penetrate inside the chamber. Air speed inside the chamber could be adjusted between 0.18 and 2.04 m/sec. A high-resolution Fourier transform infrared (FTIR) spectroscopy was employed to continuously measure the concentrations of different gases. Anaerobically stacked farmyard manure emitted less $NH_3$ than the composted manure. While the emissions of GHG ($N_2O$ and $CH_4$) were much higher from the anaerobically stacked farmyard manure than from the composted one.

Chadwick (2005) studied the effect of compaction and covering during storage on the emissions from stored farmyard manure from beef cattle. The manure was stored in 14 m$^3$ bunkers. A mobile wind tunnel with a volume of 7 m$^3$ was used to measure the emissions of $NH_3$, $N_2O$, and $CH_4$. The wind tunnel was attached to a steel trolley could be moved over the bunkers. An adjustable speed fan was attached to the outlet end of the wind tunnel. Air samples from the inlet and outlet of the wind tunnel were continuously drawn and then analyzed for $N_2O$ and $CH_4$ using a GC. Ammonia concentrations in air were measured after absorption in orthophsophoric acid flasks. Compaction and covering significantly reduced $NH_3$ and $N_2O$ emissions from manure by over 90% and 30%, respectively during summer storage period. Heavy and persistent rainfall during heap establishment and the following week significantly reduced $NH_3$ emissions due to on-favorable conditions for composting. Methane emissions were sometimes increased by covering and compacting.

Using the open chamber technique in laboratory, Husted (1994) determined the emission of $CH_4$ from stored pig slurry, cattle slurry, pig solid manure, and cattle solid manure during a one-year period. Inlet and outlet gas samples were periodically collected and analyzed using a GC. The presence of a natural surface crust reduced $CH_4$ emission from slurry by a factor of 11 to 12. Annual $CH_4$ emissions from pig slurry, cattle slurry, pig solid manure, and cattle solid manure were estimated at 8.9, 15.5, 27.3, and 5.3 kg/animal/year, respectively.

Using isolation flux chambers and a portable gas chromatograph, Borhan et al. (2011a) quantified the emissions of $CH_4$, $CO_2$, and $N_2O$ at a dairy and a feedyard operation in the Texas Panhandle during the summer. Air samples using were collected from manure lane, bedding area, loafing pen, open lot, settling basin, lagoons, and compost pile within the dairy operation. While for the cattle feedyard, air samples were collected from four corner pens of a large feedlot, runoff holding pond, and compost pile. For the dairy farm, the estimated total emission rates for $CH_4$, $CO_2$, and $N_2O$ were 836, 5573, 3.4 g/head/day, respectively. While for the cattle farmyard, the total emissions rates were 3.8, 1399, 0.68 g/head/day, respectively. The average emission rates of $CH_4$ from the settling basin, primary and secondary lagoons contributed approximately 98% of the total emissions from the dairy farm. The runoff holding pond and pen surface contributed about 99% of the $CH_4$ emissions from the feedyard.

Borhan, et al. (2011b) applied also flux chambers and a GC to determine seasonal GHG emissions from ground-level area sources in a dairy operation in Central Texas. The estimated overall emission rates for $CH_4$, $CO_2$, and $N_2O$ during the summer were 274, 6005, and 7.96 g/head/day, respectively. These emission rates during the winter were 52, 7471, and 3.59 g/head/day, respectively. Methane concentrations measured in the summer from different sources were higher than those measured in the winter. The seasonal variations were likely due to fluctuations in ambient temperature, dairy manure loading rates, and manure microbial activity of different sources on the farm. During the summer, the highest average $CH_4$ concentration was measured from the settling basin, followed by the primary lagoon and loafing pen. While during the winter, the average $CH_4$ concentrations measured from the settling basin and primary lagoon were significantly higher than those in other sources on the dairy.

**Micrometeorological techniques**

Description

In the micrometeorological techniques, the vertical flux density of the gas is measured in the free air above the surface and relate the flux to the source of emission (Harper et al., 2011). There are several micrometeorological techniques, each with advantages and disadvantages (Harper et al., 2011). They include mass balance, Integrated horizontal flux (IHF), flux gradient (FG), eddy covariance (EC) and the dispersion modelling using the backward Lagrangian stochastic method (BLS) (McGinn, 2013). The micrometeorological mass balance method is a simple technique for measuring $CH_4$ emissions. The technique, on the other hand, is sensitive enough to account for diurnal variations in $CH_4$ emissions (Khan et al., 1997).

Inverse dispersion technique employs a mathematical model of gas dispersion that calculate the emission rates as a function of measurements of concentration, wind direction, and turbulence at the farm (Flesch et al., 1995, 2004). The inverse dispersion technique is an economical alternative for measuring emissions. It needs wind direction and velocity and a single concentration measurement at a chosen measurement location. The disadvantage of this technique is that it involves the assumption of idealized wind conditions. However, careful selection of measurement locations could provide accurate calculation of emissions even under non-ideal wind conditions (Flesch et al., 2005a, 2005b).

Application

Harper et al. (2011) reviewed the concepts and applications of different micrometeorological techniques. Khan et al. (1997) applied the micrometeorological mass balance technique to determine the $CH_4$ emissions from stored cattle slurry at Lincoln University (South Island, New Zealand). Wind speed and $CH_4$ concentrations downwind of a dairy slurry pond were measured and used to calculate the horizontal and vertical $CH_4$ flux. Gas samples were periodically taken with syringes at different heights and analyzed using GC. During autumn to late winter, methane emissions ranged from 2 to 100 kg C/ha/day. In the micrometeorological mass balance technique, the vertical $CH_4$ flux from the slurry pond was calculated using the measurements of the gas concentrations and wind speeds at different heights.

Brown et al. (2002) measured $N_2O$ flux from solid manure piles using micrometeorological mass balance technique. A tunable diode laser trace gas analyzer was used to measure the concentration of $N_2O$ in the inlet and outlet of the storage facility. The flux from manure was given by the difference in the horizontal flux at an upwind and downwind position of the heap area. The mean $N_2O$ flux was 0.42 $g/m^2/day^1$.

VanderZaag et al. (2014) applied the backward Lagrangian Stochastic technique to determine the $CH_4$ emissions from two small dairy farms (50-100 lactating cows) in Alberta, Canada. Methane concentrations were measured with open-pathabsorption spectrometers. Manure storage was the main source of methane emission. During the fall, when the manure storage was full, $CH_4$ it represented 60% of the whole farm emission. Emissions from liquid manure ranged from near zero to 673 g $CH_4$/cow/day depending on the season and the amount of manure in storage. VanderZaag et al. (2011) measured the emissions of $CH_4$ from a liquid dairy manure storage tank on a dairy farm (with 80 cows) near Bright, Ontario. Tunable Diode Laser Trace Gas Analyzers was used to measure the concentration of $CH_4$ in air samples that were drawn from four different heights above the storage tank. A non-interfering micrometeorological mass balance method was used to determine the emission rates. Monthly average $CH_4$ flux ranged from 11 $g/m^2/s$ to 153 $g/m^2/s$. The low $CH_4$ flux was determined when the storage was empty.

Baldé et al. (2016) determine $CH_4$ emissions from stored liquid manure for two years on a dairy farm with approximately 146 milking cows and a screw-press solid-liquid separator processing manure prior to storage. Concentrations of $CH_4$ were measured for two years using two open-path lasers. The measured emission rates were compared with modeled $CH_4$ emissions. Methane emission rates were calculated based on inversion dispersion model using the WindTrax. The $CH_4$ emissions were in the range of 146 to 186 kg $CH_4$/head/year. The determined emissions were higher than the estimated emissions using both the IPCC methane conversion factor (0.17) for cool climates (≤10ºC), and the USEPA model.

In the National Air Emissions Monitoring Study (NAEMS) project, Zhao et al. (2010) applied the backwards Lagrangian stochastic (BLS) method and the Vertical Radial Plume Mapping model (VRPM) method (Grant et al., 2008) to determine the emissions from open/area sources on two dairies in California. FTIR analyzer was used to measure VOCs, $NH_3$, and $H_2S$. The TEI Model 55C analyzer was used for measuring the concentration of methane.

Leytem et al. (2017) monitored the emissions of $CH_4$ from six lagoons in south-central Idaho for one year. The emissions estimated by inverse dispersion modeling. The concentration of $CH_4$ in the air was measured using open-path Fourier transform infrared spectrometry. Depending on the dimensions of lagoons, number of cows, and characteristics of manure, average $CH_4$ emissions measured from lagoons ranged from 30 to 126 kg/ ha/d (22–517 kg/d). Greater emissions were observed during the periods with high temperature. Irrespective of temperatures, events such as pumping-out manure contents, rainfall, freeze or thaw of lagoon surfaces, and increased wind significantly increased $CH_4$ emissions. Leytem et al. (2011) estimated the emissions of $NH_3$, $CH_4$, $CO_2$, and $N_2O$ from the three main sources (open lots, wastewater pond, and composting areas) on a commercial dairy (with 10,000 milking cows) located in southern Idaho. At temperatures above 5°C, the concentrations of the gases were measured continuously using a photoacoustic field gas monitor (INNOVA 1412). The measured emissions of $NH_3$ were compared with those measured with open-path, ultraviolet-differential optical absorption spectrometer (UV-DOAS) in selected months. The differences between both devices was less than 5%. The emissions rates were estimated by applying combines the backward Lagrangian stochastic inverse-dispersion technique in WindTrax software. The average emission rates of $NH_3$, $CH_4$, $CO_2$, and $N_2O$ from the open lots were 0.13, 0.49, 28.1, and 0.01 kg/cow/day, respectively. The emissions of these gases from the wastewater ponds were 2.0, 103, 637, and 0.49 g/m$^2$/day, respectively. The emissions of these gases from the compost facility were 1.6, 13.5, 561, and 0.90 g/m$^2$/day, respectively. The combined emissions from the three sources were 0.15, 1.4, 30.0, and 0.02 kg/cow/day, respectively. Methane emissions were greatest from the open lots in the spring and while the wastewater pond was the largest source of emissions for the remainder of the year.

Leytem et al. (2013) estimated the emissions of $NH_3$, $CH_4$, and $N_2O$ from a commercial dairy (with 10,000 milking cows) located in southern Idaho. The concentrations of the gases and wind statistics were measured in the open-freestall and wastewater pond source areas. The inverse dispersion model was applied to calculate the emission rates. The average emission rates of $NH_3$, $CH_4$, and $N_2O$ from the open-freestall source area were 0.08, 0.41, and 0.02 kg/ cow/ day, respectively. While, from the wastewater ponds, they were 6.8, 22, and 0.2 g/m$^2$/day, respectively. During spring and summer, the wastewater ponds were the greatest source of total farm $NH_3$ emissions. While the emissions of $CH_4$ were approximately equal from the two source areas. The combined emissions of $NH_3$ and $CH_4$ from both sources were 0.20 and 0.75 kg/ cow/ day, respectively. Bjorneberg et al. (2009) measured the emissions of $NH_3$, $CH_4$, and $N_2O$ from a commercial dairy (700 milking cows and 80 dry cows) in a rural location in southern Idaho. The concentrations of the three gases were measured in three locations (pens, storage pond, and compost area) using an open-path Fourier transform infrared spectrometry in January, March, June, and September. The emission rates of $NH_3$ and methane were calculated using a backward Lagrangian stochastic inverse-dispersion technique using WindTrax. The emission rates of nitrous dioxide were not determined because the measured concentrations differed little from background concentrations. The highest concentrations of methane were measured from the pens followed by the storage pond. Compost area had the lowest concentrations of methane. Both animal activity and greater area of the pens were the reasons for their high emissions. Combined $CH_4$ emissions from the pens and storage pond were 0.34, 0.55, 0.21, and 0.20 kg/cow/day for January, March, June, and September, respectively. While the emissions of $NH_3$ were 0.04, 0.25, 0.19, and 0.15 kg/cow/day, respectively.

Todd et al. (2011) determined the $CH_4$ emissions for eight summer days from three lagoons on a commercial dairy farm located in Curry County, New Mexico. Methane concentration at the lagoons surface was measured using an open path tuned diode laser. Methane emissions quantified using an inverse dispersion model using WindTrax software. Methane concentration over the lagoon ranged from 3 to 12 ppm. The highest concentrations (>10 ppm) were measured either near sunrise or during the night. Mean daily $CH_4$ was 0.21 kg/ head/day. Grant et al. (2015) measured the emissions of $CH_4$ and $CO_2$ around an anaerobic waste lagoon at an Indiana freestall dairy and around two waste basins at a Wisconsin freestall dairy. Gas concentrations were measured using open-path ultraviolet differential optical absorption spectrometer. The emission rates were determined using the backward Lagrangian Stochastic model in WindTrax. Mean daily $CH_4$ emissions during the fall (October) from the WI basins and IN lagoon were 295 and 47 kg/ head/day, respectively. Mean $CO_2$ emissions during the fall were 575 and 107 kg/ head/day from the WI basins from the IN lagoon, respectively. Mean $CO_2$ emissions during the fall were 575 and 107 kg/ head/day, respectively. Lower emission rates were determined during cooler weather conditions.

## Tracer ratio method

Description

In the tracer ratio method, a tracer gas is mixed well with emitted gases. Then the emitted gases and tracer concentrations upwind and downwind of the source are measured. The ratio of the emission rates of the tracer and the emitted gas are the same as the ratio of the rise in concentrations of the tracer and emitted gas. The emission of the emitted gas can be calculated because the tracer release rate is controlled (Sneath et al., 2006).

Application

Lamb et al. (1995) developed a tracer ratio method to measure methane emissions from natural gas transmission and distribution facilities and urban areas. Sulfur hexafluoride was used as a tracer gas. Methane concentrations along downwind sampling paths were measured using a mobile methane monitor that is based on the absorption of infrared radiation. Tracer Gas Analyzer was used to measure the concentration of sulfur hexafluoride. Using this method, Sneath et al. (2006) measured the emissions of GHG from covered and uncovered slurry stores and farmyard manure (FYM) heaps over one year on conventional and organic farms. Sulphur hexafluoride (SF6) was used as a tracer gas for the emission measurements. Average emission rates of methane from the uncovered slurry stores was 35 and 26 g $C/m^3$/day from on the conventional farm and the organic farm, respectively. On both farms, $N_2O$ emissions were close to zero. Methane emissions from the indoor organic FYM in summer were 17.1 g $C/m^3$/day and the $N_2O$ emission was 411 mg $N/m^3$/day.

Marik and Levin (1996) experimentally estimated the $CH_4$ and $CO_2$ emissions from a dairy cow shed in Germany using sulfur hexafluoride (SF6) as a tracer. Air samples were taken for the analysis of $CH_4$ and $CO_2$ concentrations using a GC equipped with a flame ionization detector. SF6 concentration was measured by a GC equipped with an electron capture detector. The respective ratio between $CH_4$ or $CO_2$ and SF6 concentration together with the known SF6 release rate were used to calculate the emission rates of both gases. The total daily mean $CH_4$ emissions from the cows and manure was ranged from 521-530 L/ cow. The emission from manure amounted for 12%-30% of the direct methane release of a dairy cow during rumination. Grainger et al. (2007) compared the tracer gas (SF6) technique with the chamber technique for measuring total enteric $CH_4$ emissions from lactating dairy cows. In each chamber, the cow was fitted with the SF6 tracer apparatus to measure total $CH_4$ emissions. The $CH_4$ emissions measured using the SF6 tracer technique were similar to those using the chamber technique: 331 vs. 322 g /cow/day

**Task 2b: Selection of study sites and development and recommendation of measurement plans.**

Six California dairies were selected for the emission measurements. The sites (using military alphabet code) were as follows:

1) Alpha, Lodi
2) Bravo, Tulare
3) Charlie, Visalia
4) Delta, Turlock
5) Echo, Gustine
6) Foxtrot, Ballico

**Alpha Dairy: Description and manure management**

Alpha dairy was located in Lodi, California. The dairy had 1600 milking cows, 250 dry cows, and 1200 heifers and calves, farmed about 1000 acres to grow oats and corn silage. The cows where housed in freestall barns. The average milk yield was 98 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 gravity flowed to a sand settling lane where sand separated from manure by gravity. Sand land effluent flowed by gravity to two settling basins that where estimated to be 69 ft (21 m) wide and 584 ft (178 m) long each using. It should be mentioned that the dimensions of the settling basins and lagoons for all the studied dairies were estimated using the 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 125x689 ft (38 m x 210 m) lagoon. Lagoon water was usually stored until used for irrigation or barns flushing. The solids removed from the settling basin were sun dried and used as stall bedding and soil amendment. Figure 18 shows a single-line flow diagram for the farm's manure management system. Usually, approximately 600 acres received manure solids, 200 acres received lagoon water, and the other 200 acres received commercial fertilizer. Samples were collected at points 1, 2, and 3. No information was available on the date of the last time the lagoon was cleaned.

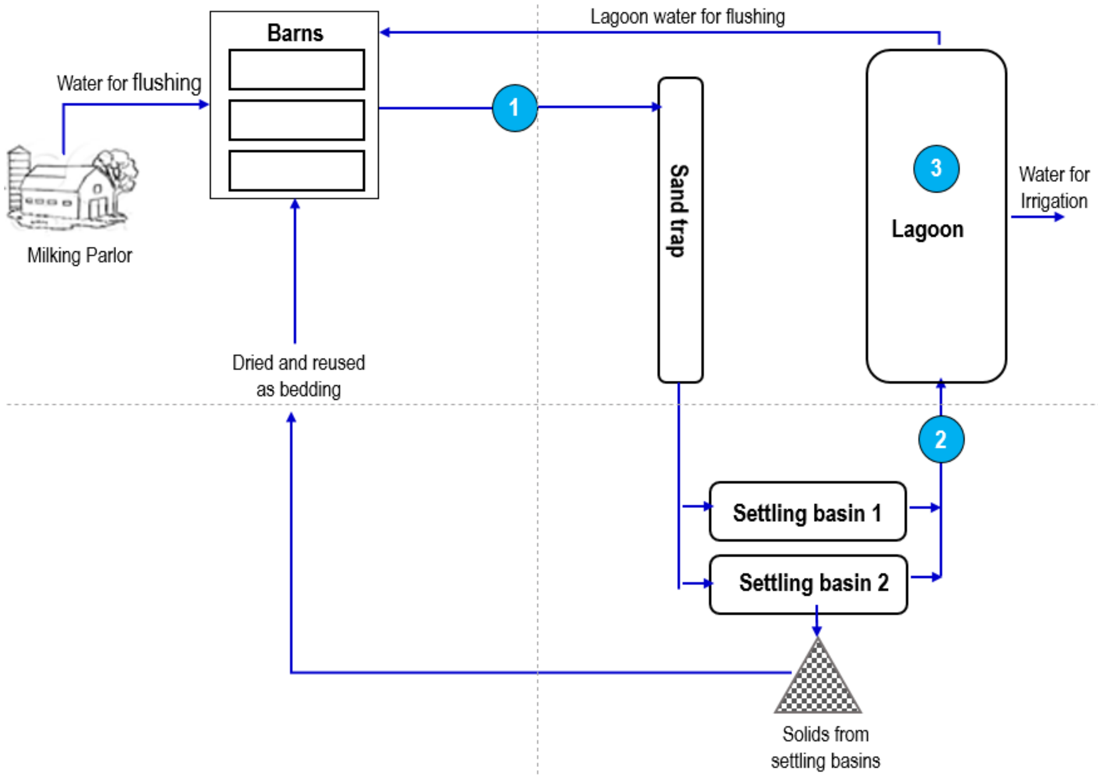


**Figure 18. Single-line flow diagram for the manure management system on Alpha dairy.**

## Bravo Dairy: Description and manure management

Bravo dairy was located in Tulare, California. The dairy had 850 milking cows, 60 dry cows, and 750 calves. The cows were housed in freestall barns. The average milk yield was 80 lb/cow/day. Cow barns were flushed using milk center wastewater and fresh water three times a day; effluent flowed to two settling basins. The first settling basin had the width and length of 49x150 ft (15 and 46 m), respectively. The second settling basin had the width and length of 49 and 135 ft (15 and 41 m), respectively. The settling basins were used alternately: a settling basin used until filled then effluent was allowed to flow to the second one. Each settling basin was used for six months. Settling basin effluent flowed to the lagoon that had an estimated width and length of 55 and 185 m, respectively. Lagoon water was stored until used to irrigate available cropland cultivated with winter wheat (115 acres), corn (70 acres), and sorghum (45 acres). 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 19 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

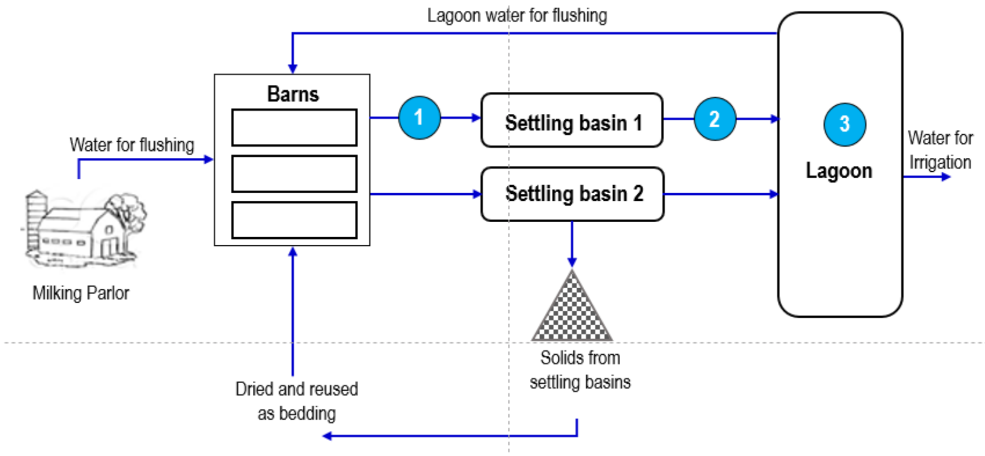


**Figure 19. Single-line flow diagram for the manure management system on Bravo dairy.**

## Charlie Dairy: Description and manure management

Charlie dairy was located in Visalia, California. The dairy had 1800 milking cows, 250 dry cows, and 900 heifers. The cows were housed in open corral with shades. The average milk yield was 78.5 lbs/cow/day. Corral feed lanes were flushed using milking center wastewater twice daily, and effluent was pumped to a lagoon that had an estimated width and length of 150 and 900 ft (46 and 275 m), respectively. Lagoon water was stored until used for cropland irrigation. The dairy had 600 acres that were cultivated with wheat and corn. No information was available on the frequency of lagoon settled solids removal. Prior to using lagoon water for irrigation, it was pumped over a single stage screen separator to remove the solids. The solid removed were sun dried and used as bedding material. Figure 20 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

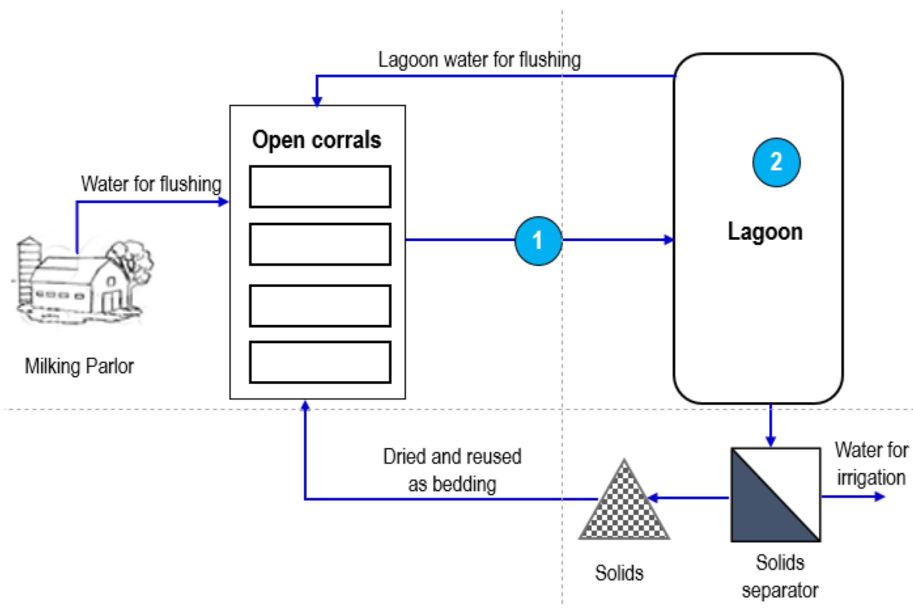


**Figure 20. Single-line flow diagram for the manure management system on Charlie dairy.**

**Delta Dairy: Description and manure management**

Delta dairy was located in Turlock, California. The Dairy had 2000 milking cows, 700 dry cows, 460 heifers, and 360 calves. The cows were housed in freestall barns flushed twice a day. 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 (75%) was used for flushing. Barn effluent was pumped to two settling basins. The first settling basin had a width and length of 144x1109 ft (44 and 338 m) and the second was 46 by 338 m, respectively. The settling basins were used alternately: A settling basin used until filled then barn effluent was directed to the second one. Each settling basin had a storage capacity of six months. Settling basin effluent flowed to the lagoon that had an estimated width and length of 43 and 309 m, respectively. Lagoon water was stored until used for cropland irrigation. Solids collected in the settling basins were sun dried and used as bedding and fertilizer. The dairy had 600 acres irrigated with lagoon water and 1800 acres fertilized with dry manure solids. The available land was cultivated with winter wheat and oats. The dairy manager mentioned that he was not aware that settled solids had been removed from the lagoon anytime during the recent years. Figure 21 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

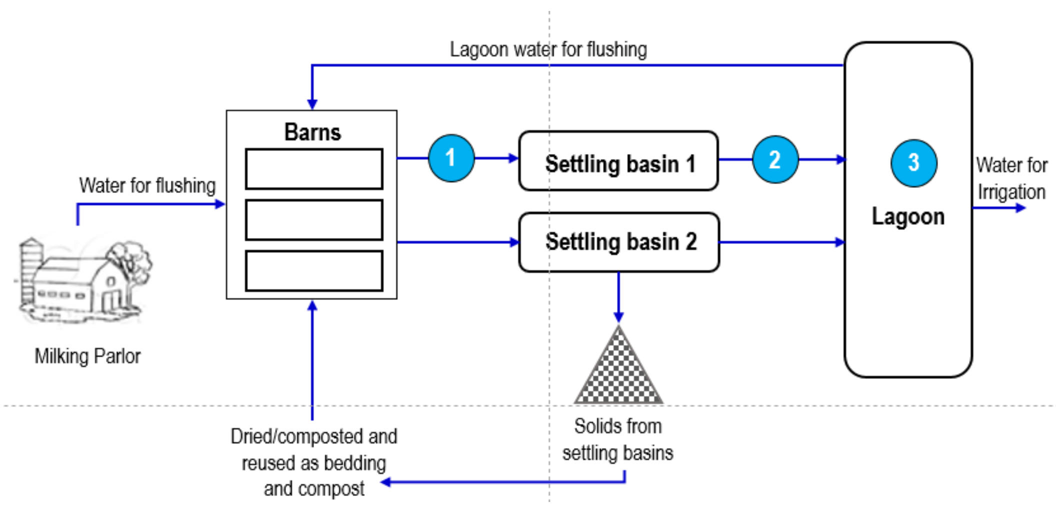


**Figure 21. Single-line flow diagram for the manure management system on Delta dairy.**

**Echo Dairy: Description and manure management**

Echo dairy was located in Gustin, California. The dairy had 1250 milking cows, 168 dry cows, and 1500 heifers and calves. The cows were housed in freestall barns. The average milk yield was 67.4 lbs/cow/day Milking center wastewater and lagoon water were used during the time of non-irrigation to flush the barns. Barns were flushed four time per day; barn effluent was pumped to a sand lane to remove sand. Sand lane effluent was pumped to a settling basin that had a width and length of 56 and 1190 ft (17 and 363 m), respectively.  Manure solids was excavated out of the settling basin four times per year and then windrowed to produce compost that was used as bedding and soil amendment. Settling basin liquid effluent flowed to the lagoon that had a width and length of 400 and 1190 ft (122 and 359 m), respectively. Lagoon water was stored until used for irrigation. The dairy had 307 acres that were cultivated with winter forage, Sudan grass, and corn. During the irrigation season, fresh water was pumped to the lagoon, and the mixture was used for irrigation. Solids removed from the settling basin were sun dried prior to use as stall bedding. Figure 22 shows a single-line flow diagram for the manure management system on Echo dairy. Samples were collected at points 1, 2, and 3.

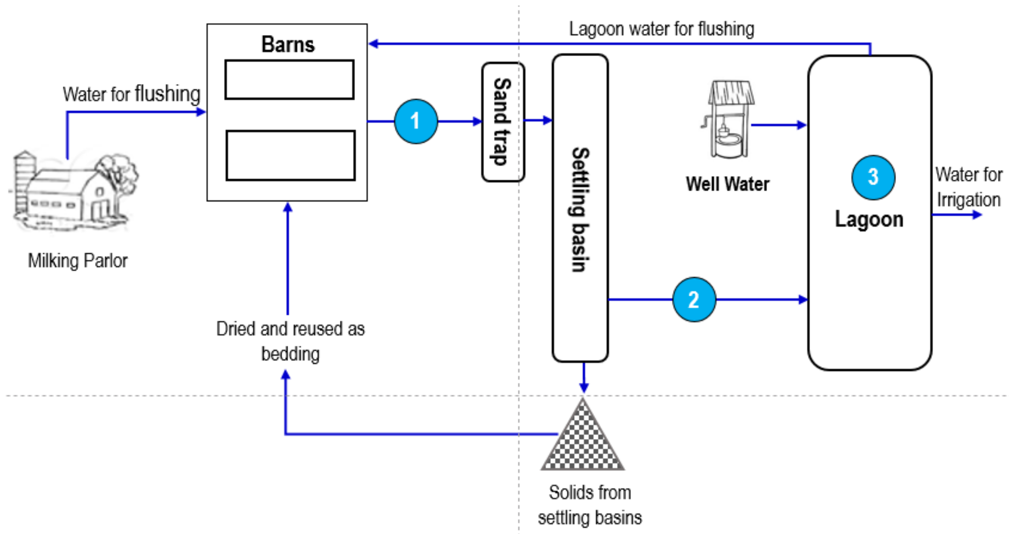


**Figure 22. Single-line flow diagram for the manure management system on Echo dairy.**

### Foxtrot Dairy: Description and manure management

Echo dairy was located in Ballico, California. The dairy had 660 milking cows, 720 heifers, and 1458 calves. The cows where housed in freestall barns. At least half of the time in summer, the cows were on pasture. The average milk yield was 66.5 lbs/cow/day. Milking center wastewater and lagoon water were used to flush the barns three times a day in the summer and two times a day in the winter (October to March). Barn effluent was pumped to settling basin that had a width and length of 49x646 ft (15 and 197 m), respectively. Solids were removed from the settling basins every six months and were composted for bedding and soil amendment. After the settling basin, manure was flowed to the lagoon that had an estimated width and length of 131 and 436 ft (40 and 133 m), respectively. Lagoon water was stored until used to irrigate 200 acres. Most of the available land is used as pasture. During the irrigation season, fresh water was pumped to the lagoon to help meet the pasture's irrigation water demand. The solids removed from the settling basin were sun dried and then used as bedding material. Figure 23 shows a single-line flow diagram for the farm's manure management system. Samples were collected at points 1, 2, and 3.

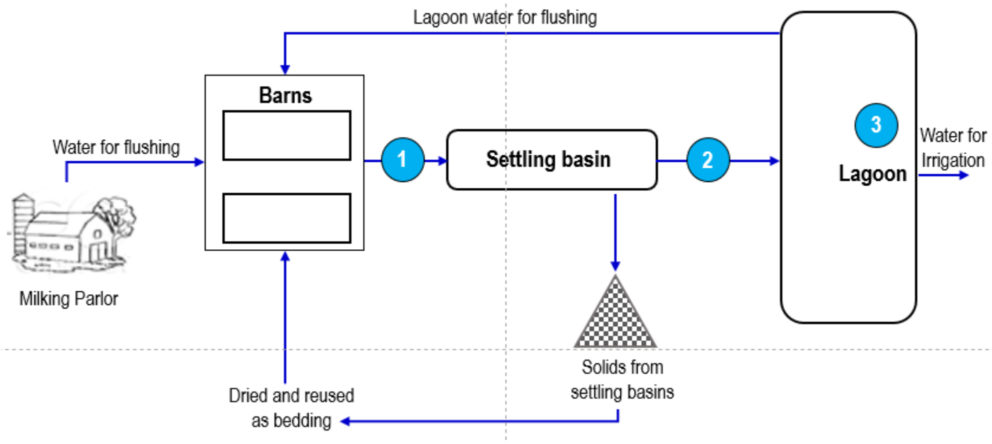


**Figure 23. Single-line flow diagram for the manure management system on Foxtrot dairy.**

## Task 2c: Measurement of pre-project emissions from study dairies

### Mobile Air Quality Laboratory (MAQ Lab) and equipment

Measurements and sampling plans were developed. The concentrations of $CH_4$, $N_2O$, $NH_3$, $H_2S$, and ethanol were measured using state-of-art devices such as 55i methane analyzer, INNOVA 1412 analyzer, and a TEI 17i NH3 analyzer. These devices were housed on the Mobile Air Quality Laboratory (MAQ Lab) of UC Davis. In addition to these state-of-art emission analyzers, the MAQ Lab had other supporting equipment and software that are required to measure and record the emissions on different dairies. The devices on the MAQ Lab can be remotely monitored and controlled. The MAQ Lab and other equipment were prepared and moved to the selected dairies one after another. The on-farm measurements on the emissions from the lagoons and settling basins were carried out according to the schedule shown in Table 7. After moving the MAQ Lab to the intended site, the set-up of the measurements was carried out including, connecting the required gas cylinder for operating different measurement devices, calibration of the measurement devices, preparing and floating the wind tunnel. The analyzers and other equipment were powered with 120/240 Volts alternative current. An electricity generator, rented from a rental company located in Sacramento, was used to provide the required electricity for the research analyzers and equipment. Figure 24 shows the MAQ Lab and electricity generator. Figure 25 shows different analyzers and equipment onboard the MAQ Lab.

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

| Site ID | Monitored sources | Schedule and work status |
|---|---|---|
| Alpha | Settling basin and lagoon | • The MAQ Lab and other equipment moved to the Alpha dairy on 9/7/2018<br>• The measurements system was set up on 9/9/2018<br>• The emissions from the lagoon were measured from 9/11/2018 to 9/12/2018.<br>• The emissions from the settling basin were measured on 9/13/2018.<br>• The MAQ Lab and other equipment were demobilized on 9/14/2018 |
| Brovo | Settling basin and lagoon | • The MAQ Lab and other equipment moved to the Brovo dairy on 9/14/2018<br>• The measurements system was set up on 9/15/2018<br>• The emissions from the lagoon were measured from 9/15/2018 to 9/18/2018.<br>• The emissions from the settling basin were measured on 9/19/2018.<br>• The MAQ Lab and other equipment were demobilized on 9/20/2018 |
| Charlie | Lagoon | • The MAQ Lab and other equipment moved to the Charlie dairy on 9/20/2018<br>• The measurements system was set up on 9/22/2018<br>• The emissions from the lagoon were measured from 9/22/2018 to 9/26/2018<br>• The MAQ Lab and other equipment were demobilized on 9/26/2018 |
| Delta | Settling basin and lagoon | • The MAQ Lab and other equipment moved to Delta dairy on 9/26/2018<br>• The measurements system was set up on 9/29/2018<br>• The emissions from the lagoon were measured from 9/29/2018 to 10/2/2018<br>• The emissions from the settling basin were measured on 10/2/2018.<br>• The MAQ Lab and other equipment were demobilized on 10/3/2018 |
| Echo | Lagoon and settling basin | • The MAQ Lab and other equipment were moved 10/3/2018<br>• The measurements system was set up on 10/6/2018<br>• The emissions from the lagoon were measured from 10/6/2018 to 10/8/2018<br>• The emissions from the settling basin were measured on 10/9/2018.<br>• The MAQ Lab and other equipment were demobilized on 10/10/2018 |
| Foxtrot | Lagoon and settling basin | • The MAQ Lab and other equipment were set up on 10/13/2018<br>• The emissions from the lagoon were measured from 10/13/2018 to 10/15/2018<br>• The emissions from the settling basin were measured on 10/16/2018.<br>• The MAQ Lab and other equipment were demobilized on 10/17/2018 and moved to the UC Davis |

**Figure 24. The Mobile Air Quality Laboratory (MAQ Lab) and engine-generator set.**

**Figure 25. Different analyzers and supporting equipment onboard of the MAQ Lab.**

**Wind Tunnel measurements**

A wind tunnel equipped with a floatation was used to collect air samples from the surface of lagoons and settling basins. The float raft was made of two 4” diameter PVC pipes. The main parts and dimensions of the wind tunnel are shown in Figure 26.

The wind tunnel was made of stainless steel. The bottom portion covered 0.32 $m^2$ of emitting surface area of manure. 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.

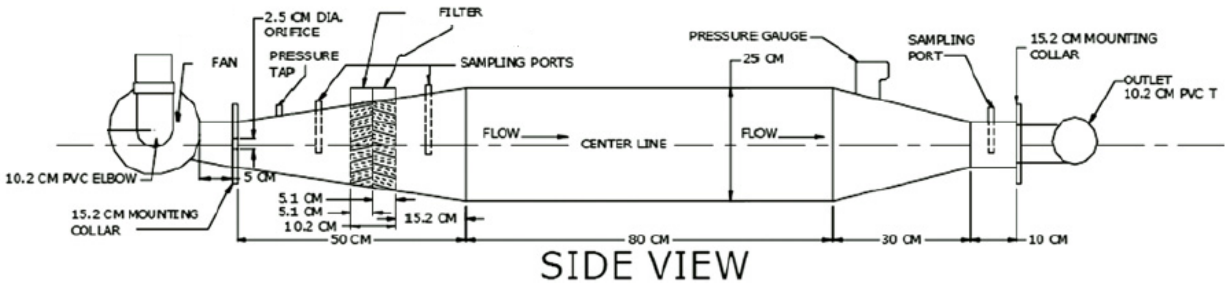


**Figure 26. Main parts and dimensions of the wind tunnel (adapted from Kumar et al., 2011).**

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 drew 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 the blown air 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 location was determined by the possibility to move the wind tunnel in the lagoons while maintaining comparable distances from their banks. 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 an entire day before moving to another spot on the next day. For the emissions measurements from the settling basins, the wind tunnel was set up on one location. If needed, when floated solids accumulated on the settling basin surfaces, the dairy mangers helped the research team to remove the solids so that the wind tunnel edges could be submersed under the liquid surface.

The air flow rate inside the wind tunnel was calculated after measuring the air velocity in 4” 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 about 200 ft. distance from the MAQ Lab and at approximately 75 ft. from the lagoon banks. Due to the presence of floating solids on the settling basins, it was hard to locate the wind tunnel far from their banks. Figures 27-30 show the wind tunnel during the emission measurements from lagoons and settling basins on selected dairies that were monitored in this study.

**Figure 27. The wind tunnel during the emission measurements from the lagoons on the Bravo (top left), Charlie (top right), and Delta (bottom) dairies.**

**Figure 28. The wind tunnel during the emission measurements from the settling basins on the Alpha dairy (top left), Bravo (top right), and Delta (bottom) dairies.**

**Figure 29. The wind tunnel during the emission measurements from the lagoon (left) and the settling basin (right) on Echo dairy.**

**Figure 30. The wind tunnel during the emission measurements from the lagoon (left) and the settling basin (right) on Foxtrot dairy.**

### Calculation of emission flux

The emission flux rate was calculated using the equation:

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

where:

E = Gas emission rate from the chamber, $g/m^2/hr$
Q = Ventilation rate of the wind tunnel at 20ºC and 1 atm, $m^3/hr$

$C_{out}$ = Mass concentration in the wind tunnel exhaust air, $g\ m^{-3}$
$C_{in}$ = Mass concentration in the wind tunnel inlet air, $g/m^3$

A = Area of the emission surface covered by the wind tunnel, $m^2$

### Sampling

During emissions measurements on each site, samples were collected on two days from the inlet of the settling basin, inlet of lagoons, and lagoon surface (10 -15 inches depth (25.4-38 cm)). For each sampling day, at least two samples (each with a volume of 500 ml) were collected at each sampling point (Figures 18-23). For each sampling day, composite samples were produced from each sampling point. The composite samples 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). Another comprehensive sampling event was carried out during January and February of 2019. During this sampling event, each dairy was visited and several samples were collected, at different time intervals, at each sampling point. Composite samples were also produced from each sampling points. The composite samples were also analyzed for TS, VS, pH, $NH^+_4$, TKN, VFAs, DOC, OC, and TC.

The TS, VS, and pH of manure samples were measured in duplicates according to the standard methods (APHA, 1998). The VFAs were analyzed using a gas chromatography equipped with a flame ionization detector as described by El-Mashad and Zhang (2007). DOC, OC, TC, and $NH_4$ were measured in composite samples by the Midwest Labs (www://midwestlabs.com).

### Survey for dairies information and activity data

A survey 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 storage, and bedding material type and applied amount. A copy of the survey questions in enclosed in the Appendix.

### Modeling of methane emissions from manure storage (lagoons and settling basins)

For the five dairies that had settling basins and lagoons, the emissions of methane from the settling basins and lagoons were modeled using the CARB/ICPP model.

Although the DairyGEM can be used to model the emissions of $CH_4$ from manure storage, the model was not used for Alpha, Bravo, Delta, Echo, and Foxtrot dairies because it was not possible to calculate the emissions from the settling basins and lagoons separately. Moreover, the DairGEM model manure handling on the dairies as two parallel (primary and secondary handling) systems. This approach may not completely applicable for the settling basins and lagoons that are operated in series. For Charlie dairy that did not have a settling basin, the emissions from the lagoon was modeled using the CARB/IPCC model, DairyGEM, and Manure-DNDC.

*Input parameters to the models*

The inputs for the CARB/ICPP model were obtained from the conducted surveys. In case, the dairymen have not provided answers to survey questions, values for the model input were obtained from the literatures.

The amount of TS removed by the settling basin for all the dairies that have settling basins was calculated to be 33.5% of the influent TS and the remaining (66.5%) was stored in the lagoons. This value was an average of those reported by Sweeten and Wolfe (1994) and Chastain et al. (2001). Based on the data collected from the surveys, the storage time in settling basins was 6 months in most of the studied dairies except Foxtrot dairy wherein the settling basin was excavated every 3 months. It was not clear how well the Foxtrot dairy settling basin was cleaned out. Therefore, for the model calculations, a filling time of six months was assumed for all the studied settling basins starting on April 1$^{st}$ and October 1$^{st}$, 2018.

The CARB/ICPP model depends on the accumulation and degradation of VS. Mostly the values of VS destruction and methane yields are taken from anaerobic digesters. There are a few literature values for the VS destruction and methane yields from dairy lagoons (Lory et al., 2010). In the current study, a maximum methane yield of 240 L/kg VS added was used. Using a VS destructions in settling basin and lagoon of 44%, and 57% (Chastain, 2006), a methane yield of 545 and 421 L/kg VS [destructed] could be determine and used in the models of the settling basins and lagoons, respectively.

The studied dairies did not have records for the quantify of bedding materials used. Therefore, for this modeling work, the mass of VS in bedding materials used was 1.36 kg/milking cow/day was used based on the values (2.5 to 3.5 kg VS per head per day) reported by Arndt et al., (2018). The book values of weights of milking cows, dry cows, heifers, and calves were 680, 684, 407, and 118 kg, respectively. The average VS daily amounts for animals in these management groups were11.41, 5.56, 8.44, and 7.7 kg/ 1000kg mass/day, respectively. Weather data required for conducting the model calculations were obtained from weather stations that are close by the studied dairies (http://www.wunderground.com). Based on the surveys, the amount of manure that flushed to the settling basin or lagoons were 100%, 80%, 60%, 80%, 80%, and 60% for Alpha, Bravo, Charlie, Delta, Echo, and Foxtrot dairies, respectively.

The Dairy Gem input parameters included the amount and type of feed. The amount of feed used on Charlie dairy was obtained from the dairy records and is shown in Table 8. Cotton seed meal, dried Distillers Grains (DDG), and grains were used as inputs for the crude protein supplements, less degradable protein supplements, and energy supplements, respectively.

**Table 8. Type, amount and composition of each feed used on the Charlie dairy.**

| Feed type | Composition | | | | | | |
|---|---|---|---|---|---|---|---|
| | Annual amount, short dry ton | Dry matter (DM), % | Crude protein, %DM | Degradable protein, %CP | Acid detergent insoluble protein, %CP | Net energy of lactation, Mcal/lb DM | Neutral detergent fiber, %DM |
| High quality silage | 1231.2 | 33.3 | 12.0 | 70.0 | 1.0 | 0.5 | 59.9 |
| High quality hay | 1211.6 | 88.0 | 20.2 | 60.0 | 1.6 | 0.6 | 39.6 |
| Low quality hay | 652.0 | 88.0 | 20.2 | 60.0 | 1.6 | 0.6 | 39.6 |
| Corn silage | 5508.2 | 39.0 | 8.4 | 65.0 | 5.9 | 0.6 | 47.0 |
| High moisture grain | 9742.8 | 88.9 | 25.5 | 52.8 | 5.4 | 0.9 | 22.8 |
| Dry grain | 10,016 | 89.5 | 13.2 | 53.2 | 2.5 | 1.0 | 28.5 |

## Results

### Results of on-dairies measurements of emissions

### Emissions from the settling basin on the Alpha dairy

The emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ from the Alpha dairy settling basin are shown in Figures 31, 32, 33, and 34, respectively. Relatively higher emission rates of $CH_4$ and $H_2S$ were observed during the daytime than during night times. The emission rates of $NH_3$ were relatively constant during the monitoring period. A peak of $N_2O$ with approximately 60 mg/m$^2$/hr was determined for a few hours, but no emission was measured for the remainder of the day since the concentration of $N_2O$ in the wind tunnel outlet was similar to that of the wind tunnel inlet. The emission rates of $CH_4$, and $NH_3$ ranged from 7.36 to 54.55 and from 0.02 to 0.12 g/m$^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 57.57, and from 9.04 to 52.11 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 29.79 and 0.05 g/m$^2$/hr, respectively (Table 9). While they were 7.41 and 26.20 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 1207, 2.17, 0.30, and 1.06 g/ milking cow equivalent/day, respectively (Table 10).

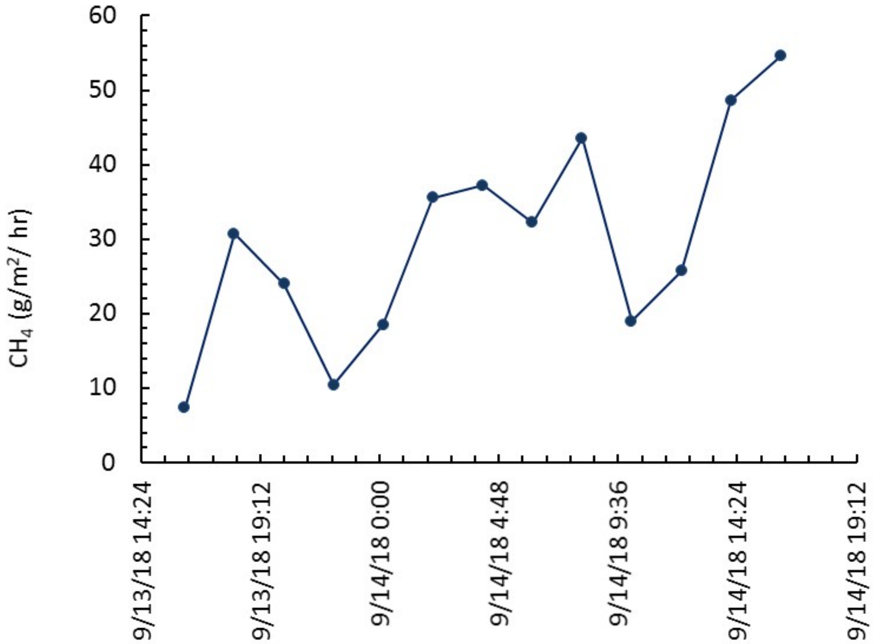


**Figure 31. Emission rates of $CH_4$ from the settling basin on the Alpha dairy.**

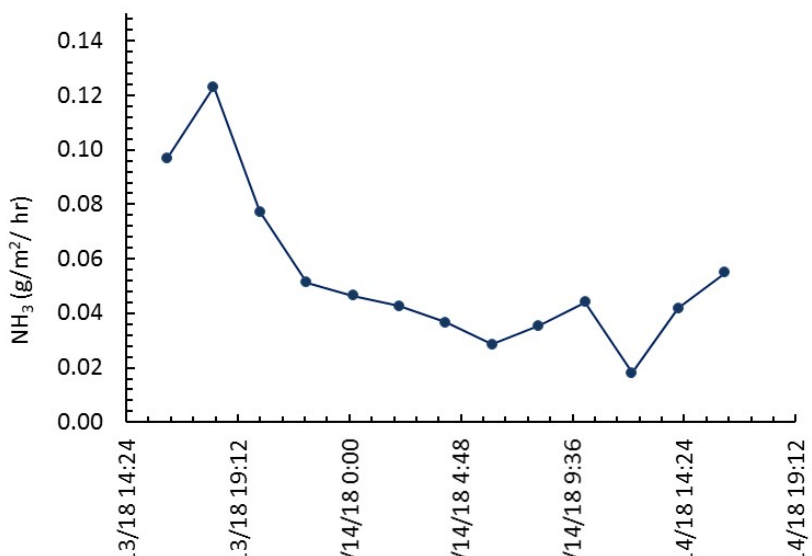


**Figure 32. Emission rates of $NH_3$ from the settling basin on the Alpha dairy.**

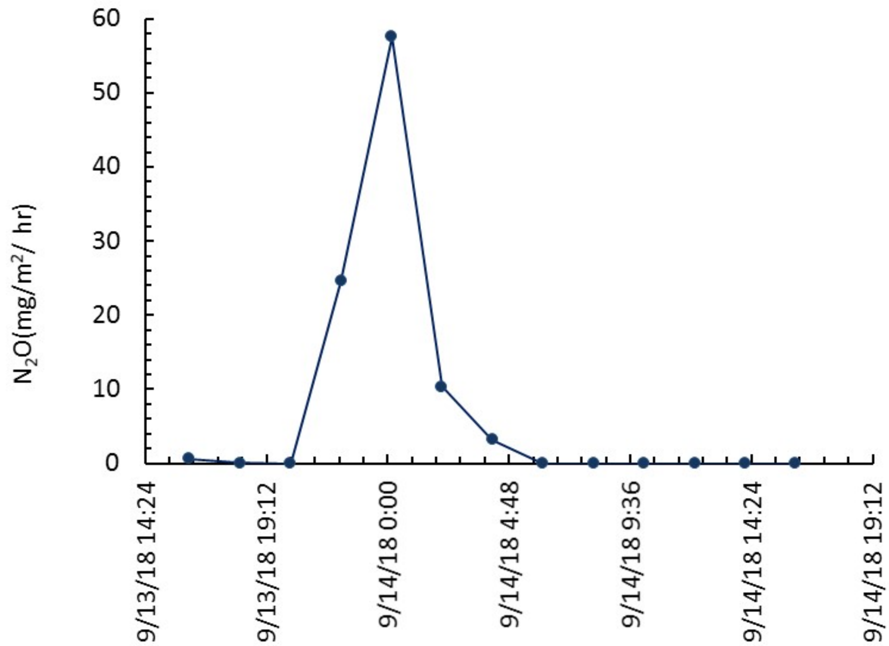


**Figure 33. Emission rates of $N_2O$ from the settling basin on the Alpha dairy.**

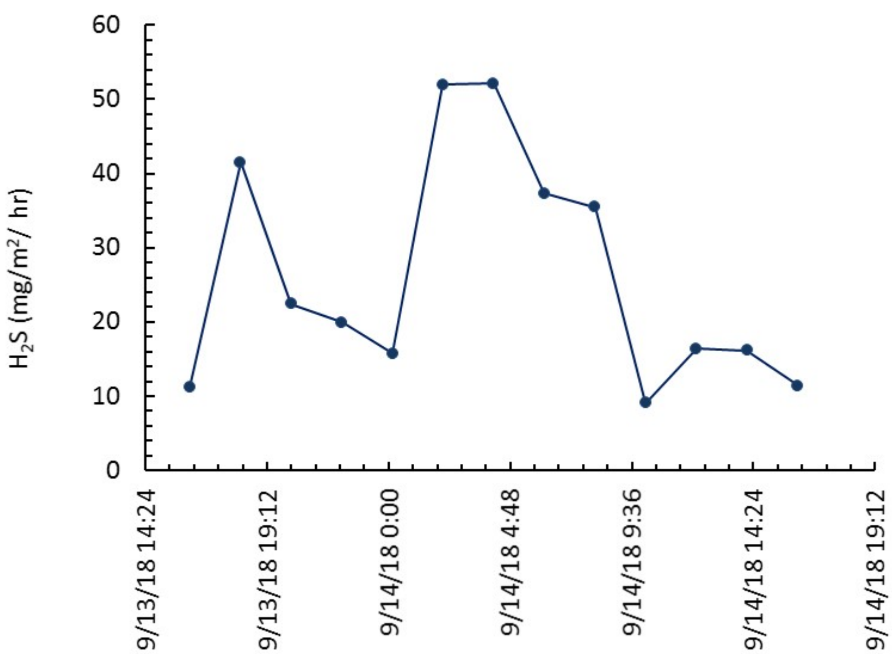


**Figure 34. Emission rates of $H_2S$ from the settling basin on the Alpha dairy.**

**Emissions from the lagoon on the Alpha dairy**

The Alpha dairy lagoon emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 35, 36, 37, and 38, respectively. Relatively higher emission rates were calculated during the daytimes than the night times. The emission rates of $CH_4$, and $NH_3$ ranged from 1.28 to 23.99, and from 0.04 to 0.19 g/m$^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 6.51, and from 0.13 to 0.58 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 10.23 and 0.08 g/m$^2$/hr, respectively, while they were 1.20 and 0.26 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 873.00, 7.00, 0.10, and 0.02 g/ milking cow equivalent/day, respectively (Table 10).Comparing the emissions rates from the lagoon and the settling basin indicated that the lagoon had relatively lower emission rate of $CH_4$, $N_2O$, and $H_2S$ and higher emission rates of $NH_3$ than the settling basin.

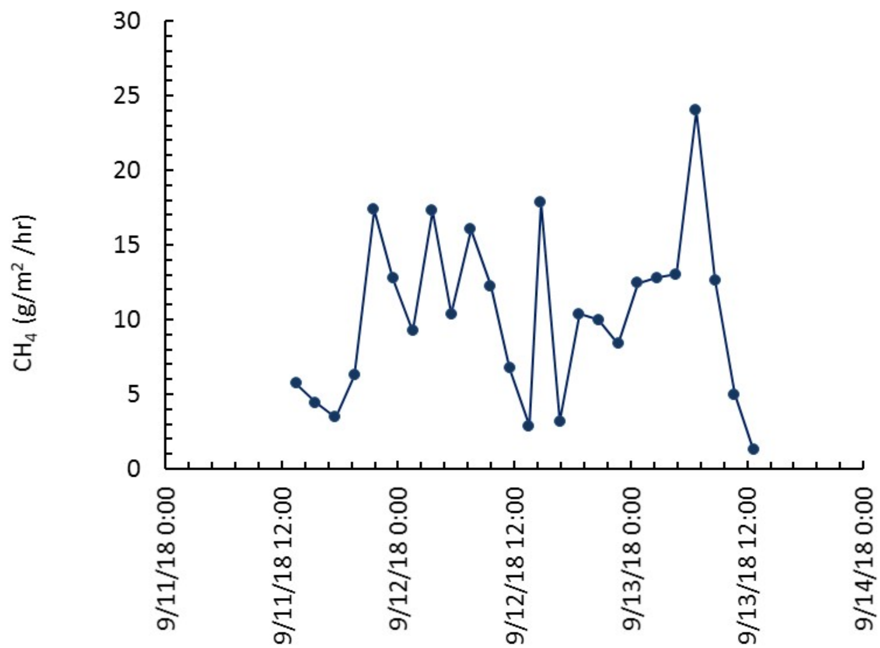


**Figure 35. Emission rates of $CH_4$ from the lagoon on the Alpha dairy.**

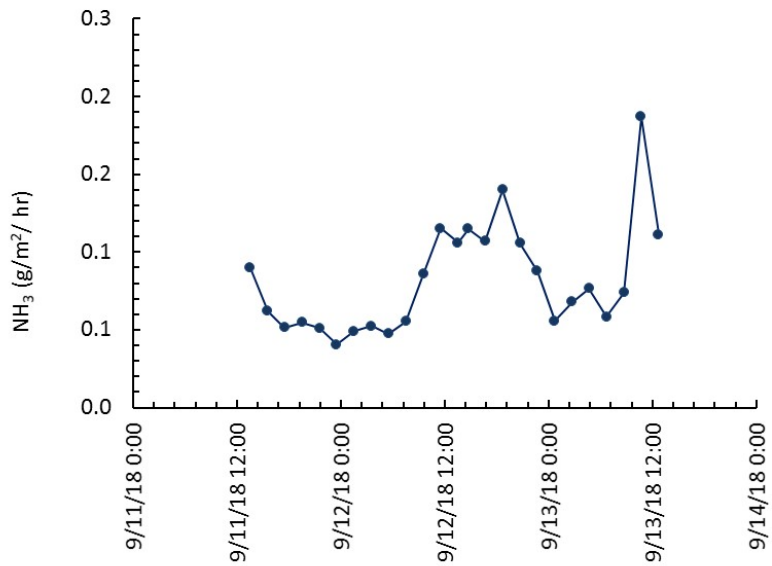


**Figure 36. Emission rates of $NH_3$ from the lagoon on the Alpha dairy.**

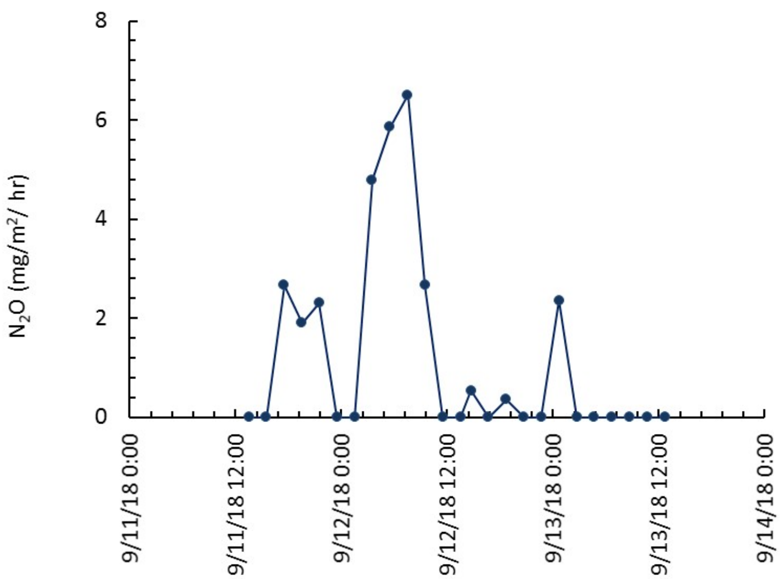


**Figure 37. Emission rates of $N_2O$ from the lagoon on the Alpha dairy.**

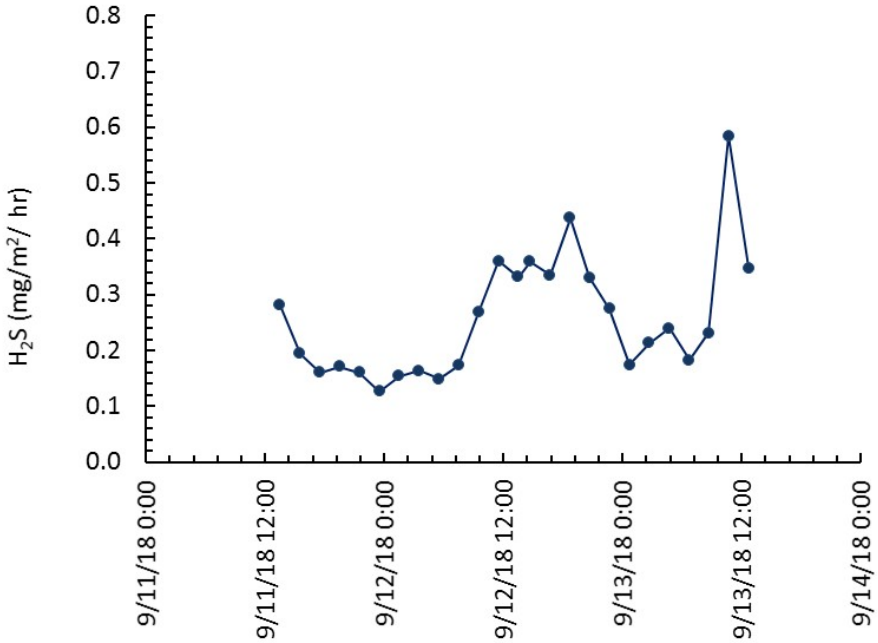


**Figure 38. Emission rates of $H_2S$ from the lagoon on the Alpha dairy.**

## Emissions from the settling basin on the Bravo dairy

The emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ from the settling basin in Bravo dairy are shown in Figures 39, 40, 41, and 42, respectively. Relatively constant emission rates of $CH_4$, $NH_3$, and $H_2S$, except a few peaks, were calculated during the monitoring period. Some peaks of emissions were calculated for $N_2O$. The emission rates of $CH_4$, and $NH_3$ ranged from 5.09 to 24.69, and from 0.03 to 0.19 g/m$^2$/hr, respectively. The ranges of the emission rates were from 0.00 to 9.81, and from 3.40 to 18.89 mg/m$^2$/hr, respectively for $N_2O$ and $H_2S$. The average emission rates of $CH_4$ and $NH_3$ were 11.20 and 0.09 g/m$^2$/hr, respectively (Table 9). While they were 1.99 and 9.36 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 194.90, 1.55,0.04, and 0.16 g/ milking cow equivalent/day, respectively (Table 10).

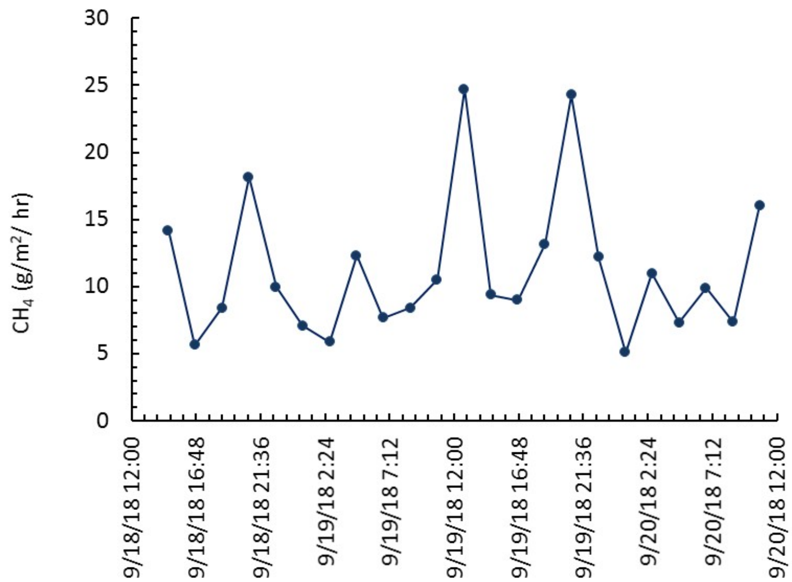


**Figure 39. Emission rates of $CH_4$ from the settling basin on the Bravo dairy.**

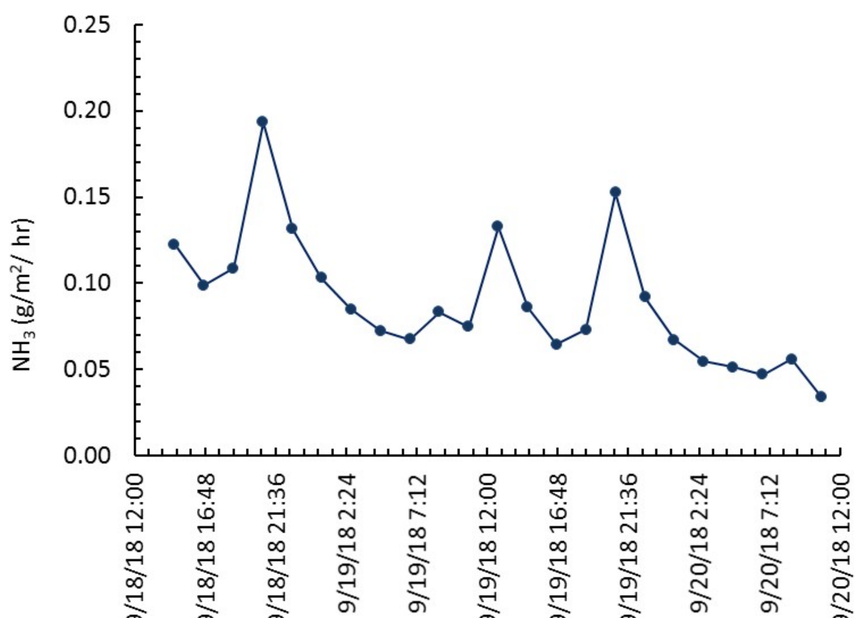


**Figure 40. Emission rates of $NH_3$ from the settling basin on the Bravo dairy.**

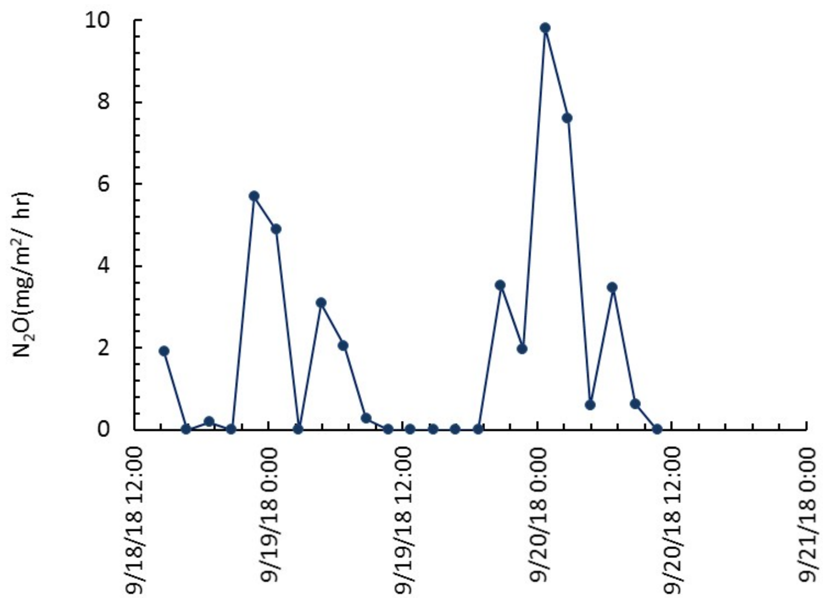


**Figure 41. Emission rates of $N_2O$ from the settling basin on the Bravo dairy.**

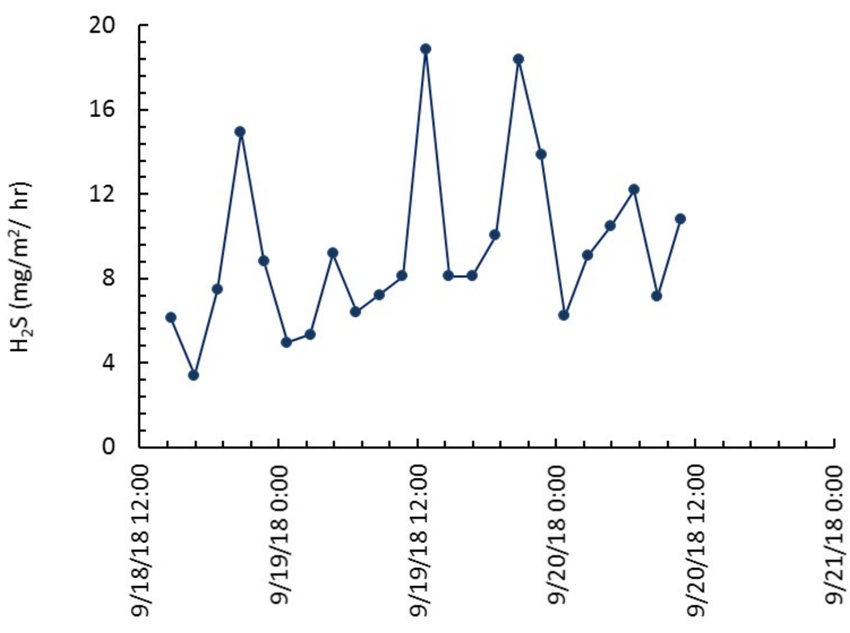


**Figure 42. Emission rates of $H_2S$ from the settling basin on the Bravo dairy.**

**Emissions from the lagoon in the Bravo dairy**

The Bravo dairy lagoon emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 43, 44, 45, and 46, respectively. The emission rates of $CH_4$, and $NH_3$ ranged from 0.76 to 6.95 and from 0.09 to 0.19 g/m$^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 52.65, and from 0.00 to 1.96 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 2.63 and 0.12 g/m$^2$/hr, respectively (Table 9). While they were 5.92 and 0.41 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 662.5, 31.13, 1.49, and 0.10 g/ milking cow equivalent/day, respectively (Table 10). Comparing the emissions rates from the lagoon and the settling basin indicated that the lagoon had relatively lower emission rate of $CH_4$ and $H_2S$ and higher emission rates of $NH_3$ and $N_2O$ than the settling basin.

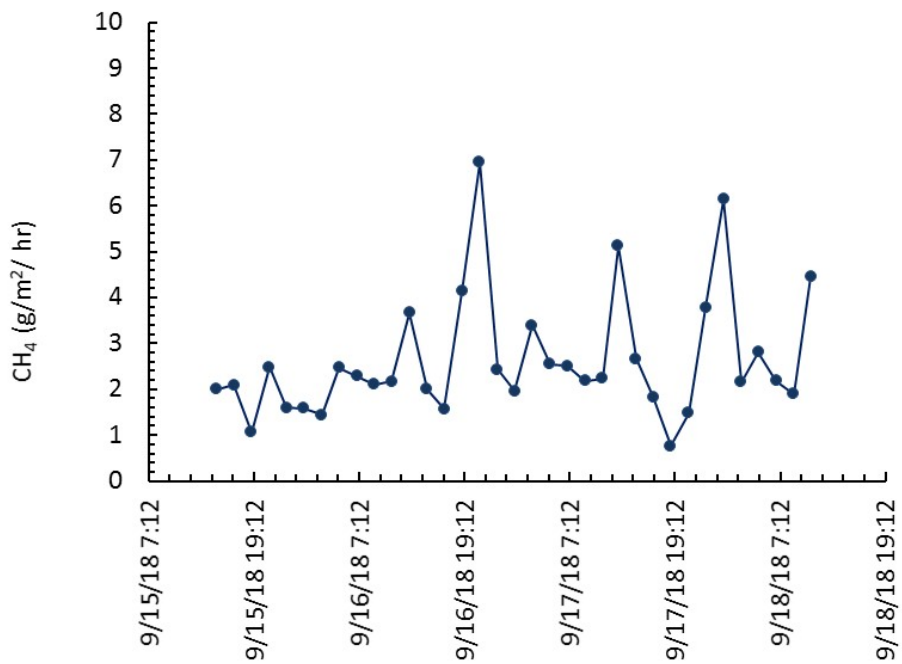


**Figure 43. Emission rates of $CH_4$ from the lagoon on the Bravo dairy.**

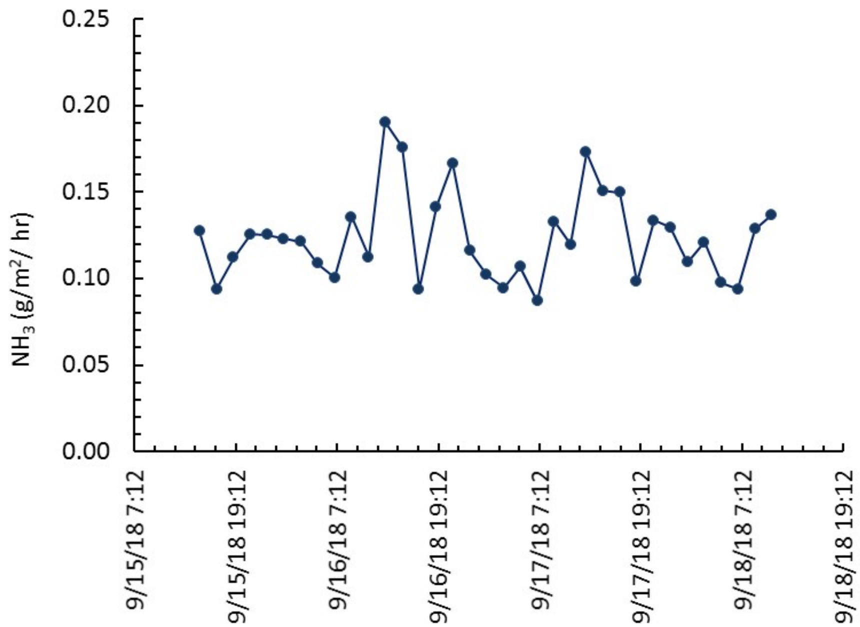


**Figure 44. Emission rates of $NH_3$ from the lagoon on the Bravo dairy.**

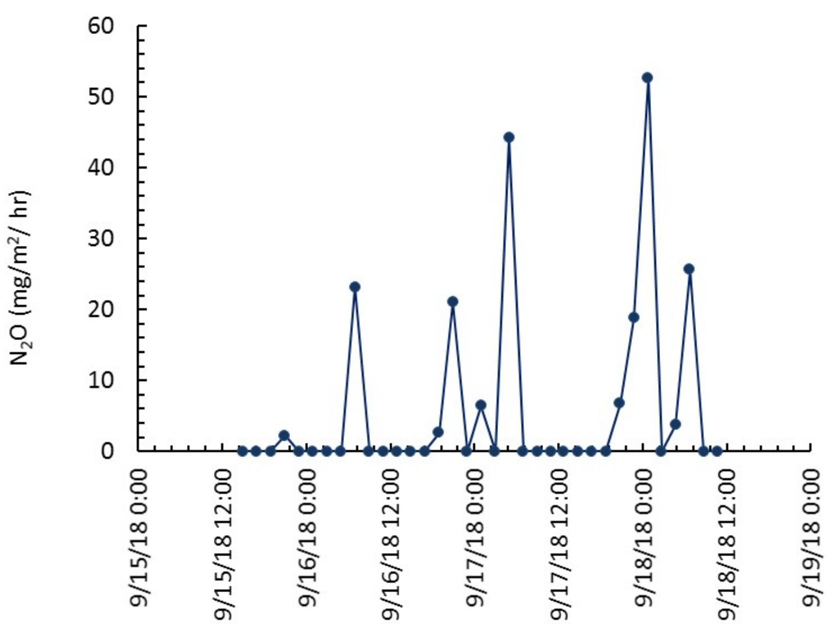


**Figure 45. Emission rates of $N_2O$ from the lagoon on the Bravo dairy.**

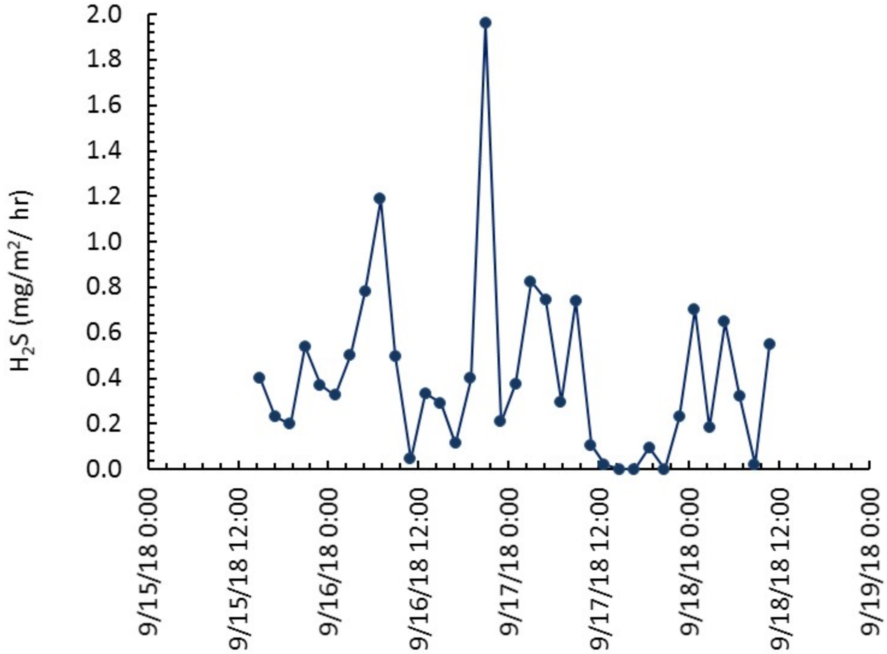


**Figure 46. Emission rates of $H_2S$ from the lagoon on the Bravo dairy.**

**Emissions from the lagoon on Charlie dairy**

The Charlie dairy lagoon emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 47, 48, 49, and 50, respectively. High emission rates of $CH_4$ were calculated during the first two days of monitoring. They were also higher during the daytime than night times. Higher emission rates of $NH_3$ were calculated during the third day of measurements than other days. Low emission rates of $H_2S$ were measured during the monitoring period. Some emission peaks were calculated for $N_2O$.

The emission rates of $CH_4$, and $NH_3$ ranged from 3.00 to 28.90, and from 0.03 to 0.25 g/m$^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from0.00 to 13.48, and from 0.00 to 0.22 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 11.27 and 0.11 g/m$^2$/hr, respectively (Table 9). While they were 1.24 and 0.05 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 1461.47, 13.76, 0.161, 0.01 g/ milking cow equivalent/day, respectively (Table 10).

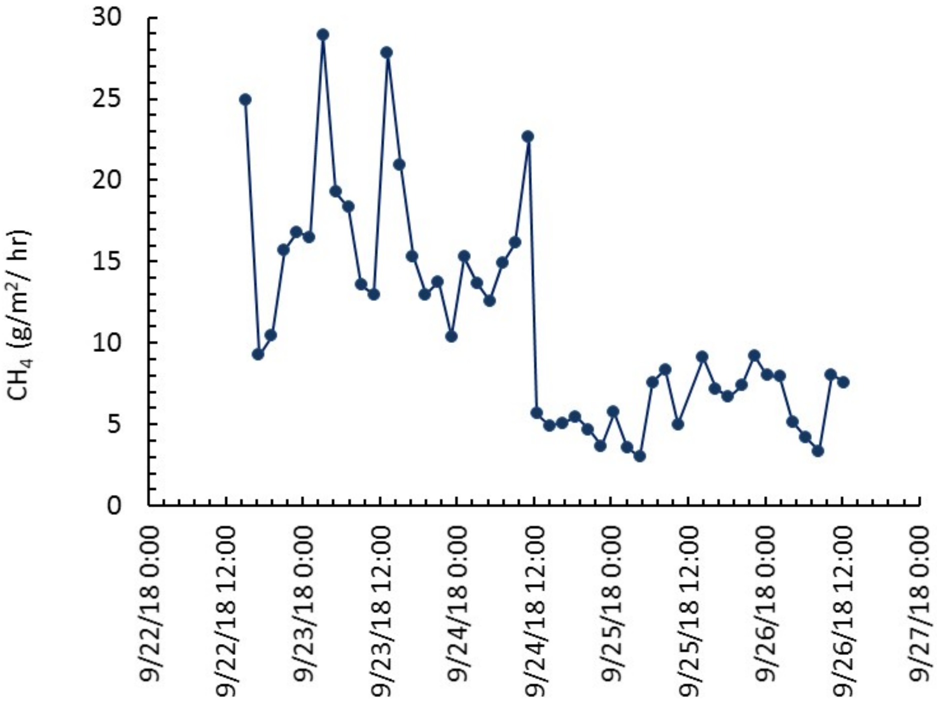


**Figure 47. Emission rates of $CH_4$ from the lagoon on the Charlie dairy.**

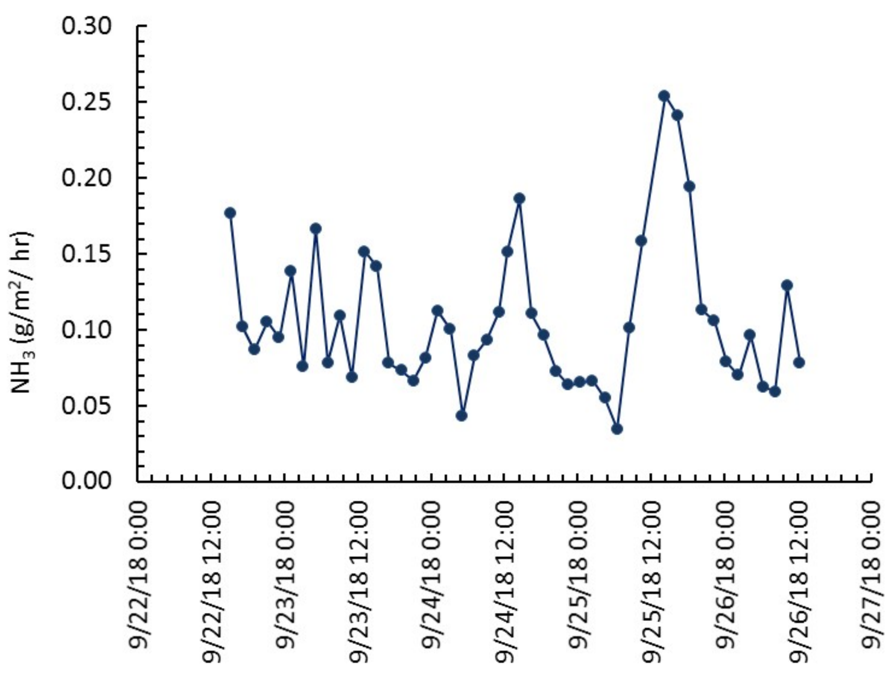


**Figure 48. Emission rates of $NH_3$ from the lagoon on the Charlie dairy.**

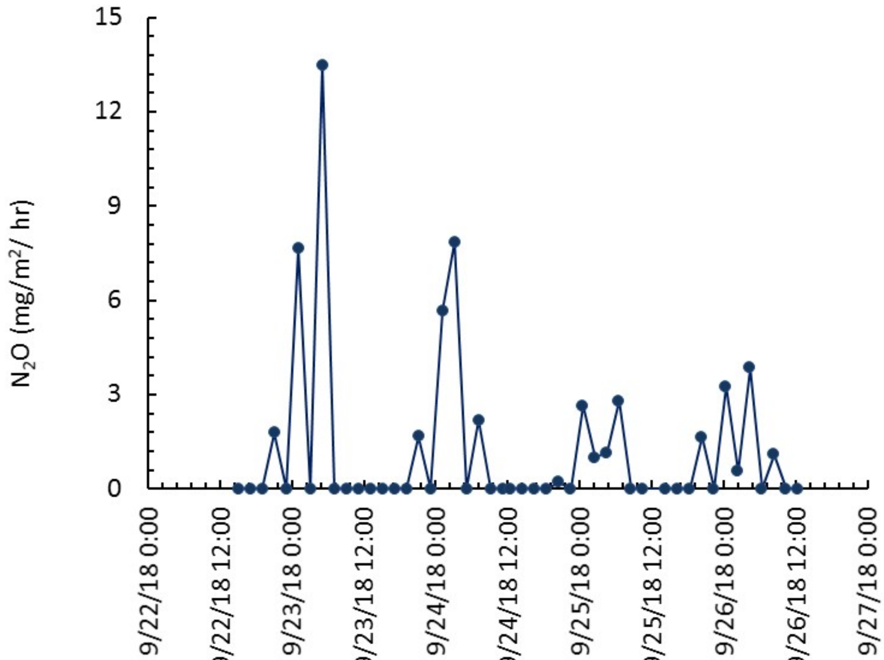


**Figure 49. Emission rates of $N_2O$ from the lagoon on the Charlie dairy.**

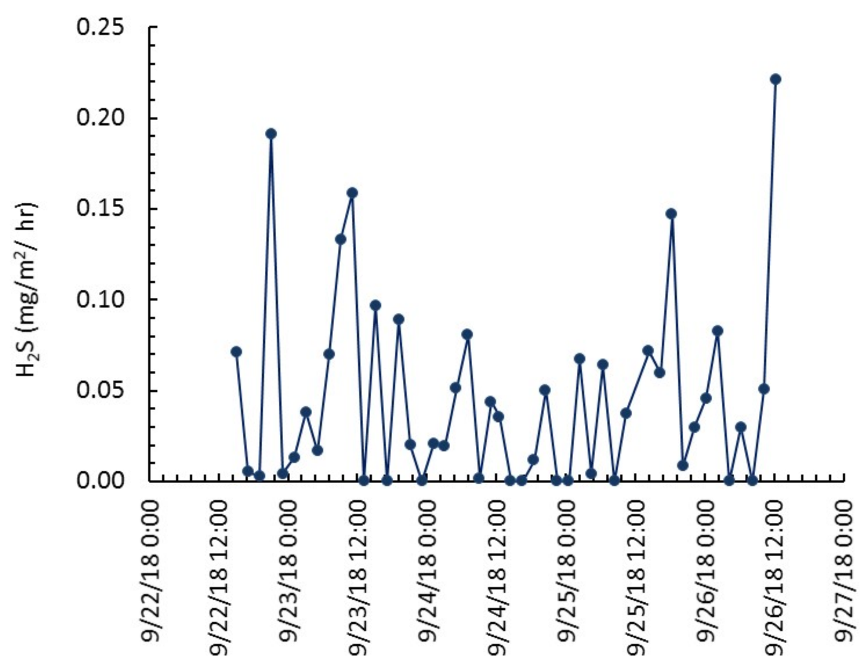


**Figure 50. Emission rates of $H_2S$ from the lagoon on the Charlie dairy.**

**Emissions from the settling basin on the Delta dairy**

The Delta dairy settling basin emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 51, 52, 53, and 54, respectively. Relatively constant emission rates of CH4, except a few peaks, were calculated during the monitoring period. Ammonia emissions decreased during the monitoring period. A peak of $N_2O$ with approximately 47 mg/m$^2$/hr was determined for a few hours. Then no emission was calculated for the remaining of the monitored day since the concentration of $N_2O$ in the wind tunnel outlet was almost similar to that of the wind tunnel inlet. Almost constant emission rates of $H_2S$ were calculated for most of the monitored time.

The emission rates of $CH_4$, and $NH_3$ ranged from 3.24 to 14.52, 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 0.00 to 46.66, and from 0.00 to 0.59 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 6.64 and 0.19 g/m$^2$/hr, respectively (Table 9). While they were 5.34 and 0.16 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 921.00, 25.82, 0.74, and 0.02 g/ milking cow equivalent/day, respectively (Table 10).

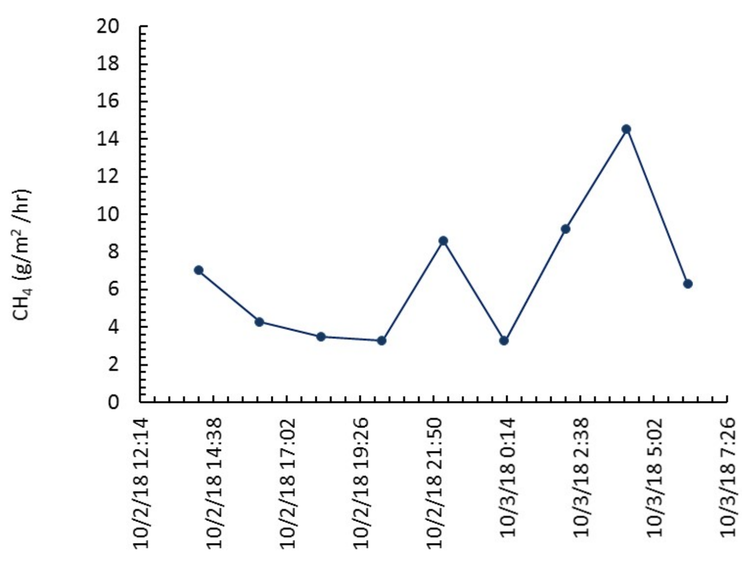


**Figure 51. Emission rates of $CH_4$ from the settling basin in the Delta dairy.**

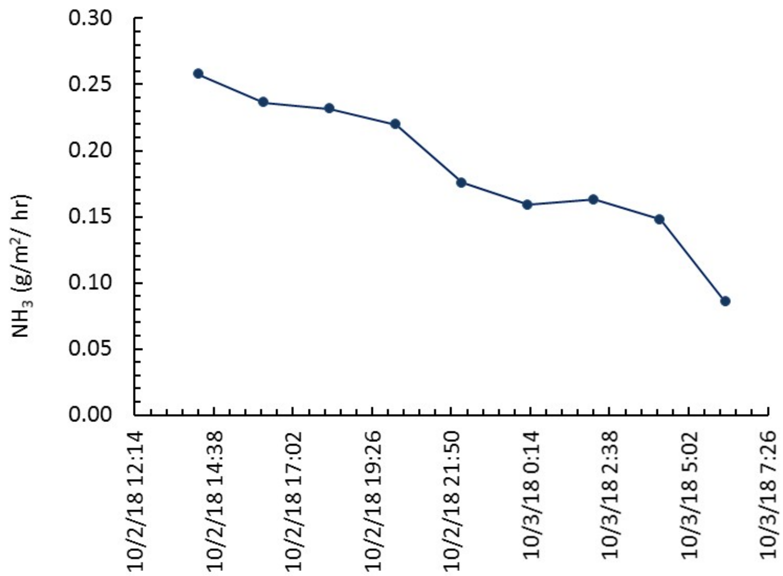


**Figure 52. Emission rates of $NH_3$ from the settling basin on the Delta dairy.**

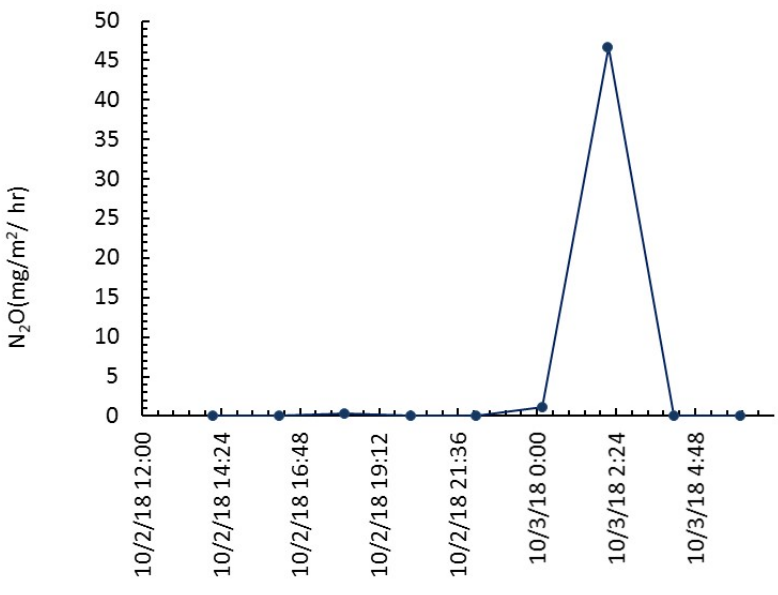


**Figure 53. Emission rates of $N_2O$ from the settling basin on the Delta dairy**

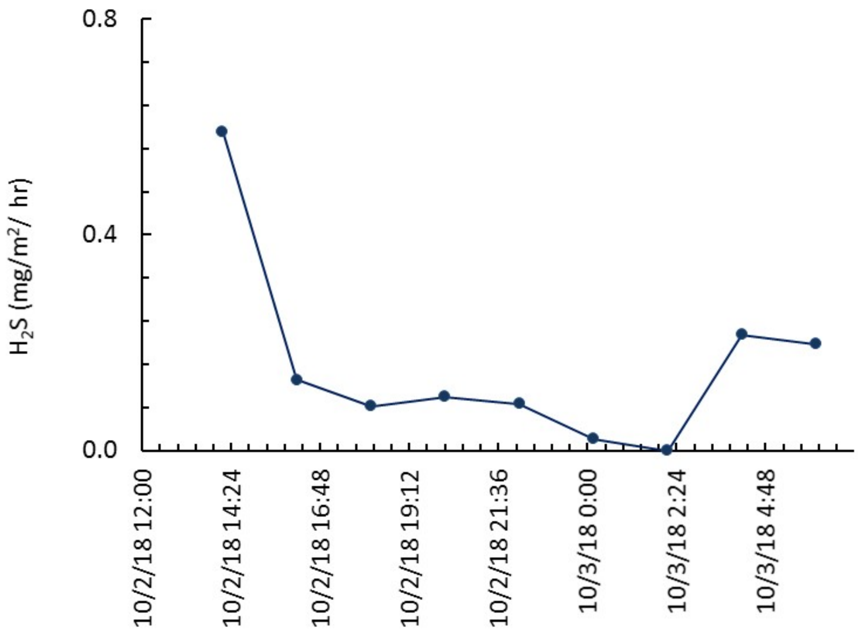


**Figure 54. Emission rates of $H_2S$ from the settling basin on the Delta dairy.**

## Emissions from the lagoon on the Delta dairy

The Delta dairy lagoon emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 55, 56, 57, and 58, respectively. Almost constant emission rates of $CH_4$, except a few peaks, were calculated during the monitoring period. Relatively higher emission rates of $NH_3$ were calculated during the day times than night times. For $N_2O$, only one peak of emission rate of approximately 241 mg/m$^2$/hr was determined on the third day of monitoring. A few peaks of the emissions of H2S were calculated.

The emission rates of $CH_4$, and $NH_3$ ranged from 1.33 to 21.49, and from 0.13 to 0.34 g/m$^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 241.38 and from 0.00 to 0.95 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 4.48 and 0.22 g/m$^2$/hr, respectively (Table 9). While they were 10.35 and 0.13 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 548.53, 27.18, 1.27, and 0.02 g/ milking cow equivalent/day, respectively (Table 10). The lagoon had relatively lower emission rate of $CH_4$ and $H_2S$ and higher emission rates of $NH_3$ and $N_2O$ than the settling basin.

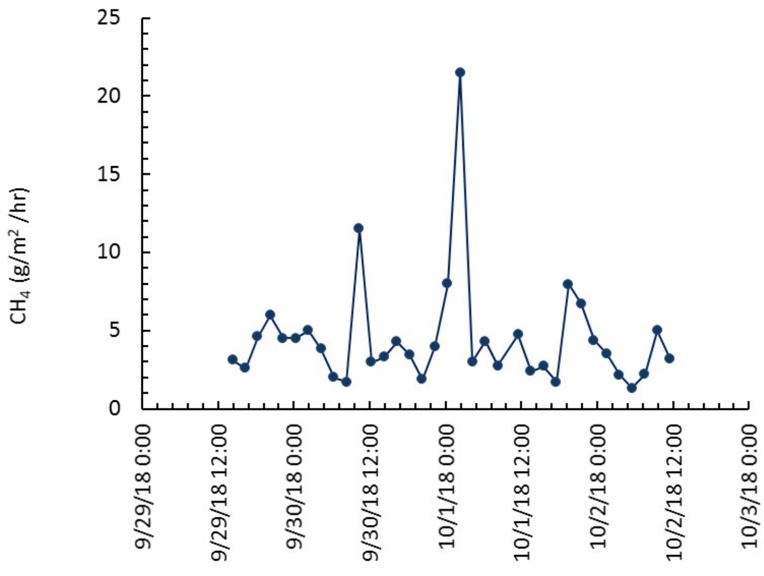


**Figure 55. Emission rates of $CH_4$ from the lagoon on the Delta dairy.**

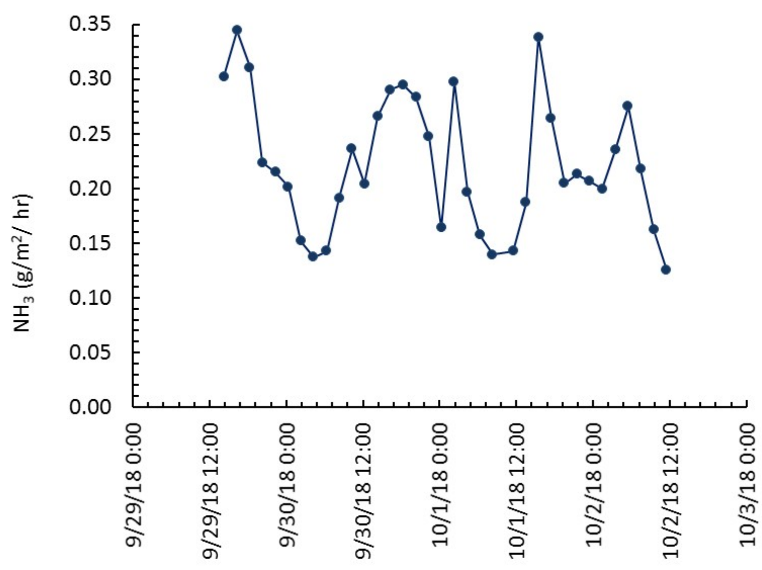


**Figure 56. Emission rates of $NH_3$ from the lagoon on the Delta dairy.**

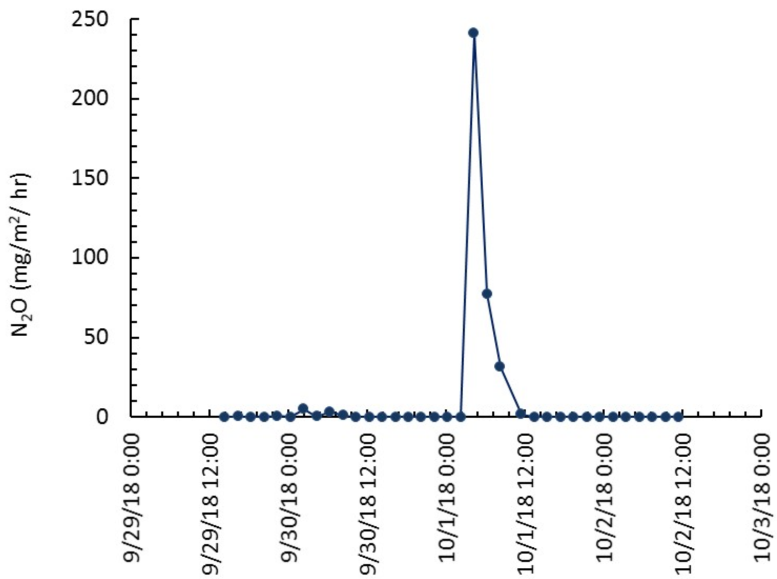


**Figure 57. Emission rates of $N_2O$ from the lagoon on the Delta dairy.**

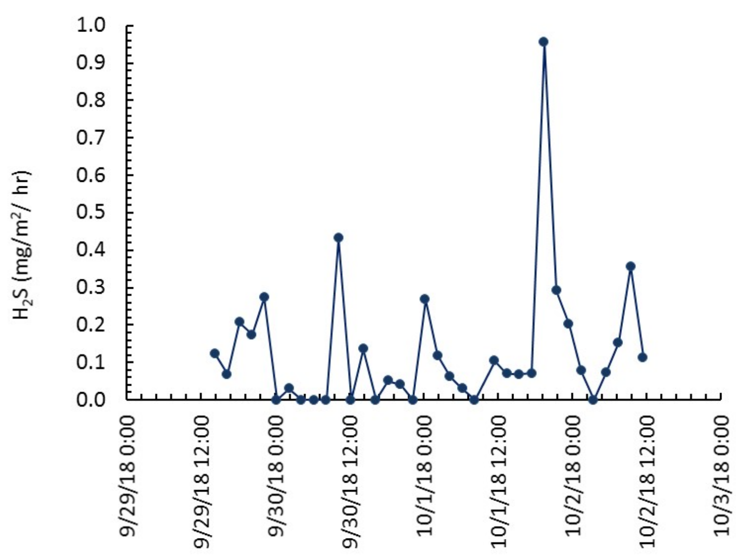


**Figure 58. Emission rates of $H_2S$ from the lagoon on the Delta dairy.**

## Emissions from the settling basin on the Echo dairy

The Echo dairy settling basin emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 59, 60, 61, and 62, respectively. Low emission rate of $CH_4$ were calculated over the monitoring period. Almost constant emission rates of $NH_3$ were calculated during the two day of monitoring. Then, a peak of emission was determined. Two peaks of $N_2O$ with approximately 0.2

and 0.6 $mg/m^2/hr$ were determined for a few hours. Then no emissions were calculated for the remaining of the monitoring period since the concentration of $N_2O$ in the wind tunnel outlet was almost similar to that of the wind tunnel inlet.

The emission rates of $CH_4$, and $NH_3$ ranged from 0.09 to 1.38, and from0.12 to 0.24g/$m^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 0.58, and from 0.00 to 0.13 $mg/m^2/hr$, respectively. The average emission rates of $CH_4$ and $NH_3$ were 0.60 and 0.15 $g/m^2/hr$, respectively (Table 9). While they were 0.07 and 0.02 $mg/m^2/hr$, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 43.32, 10.76, 0.01, and 0.00 g/ milking cow equivalent/day, respectively (Table 10).

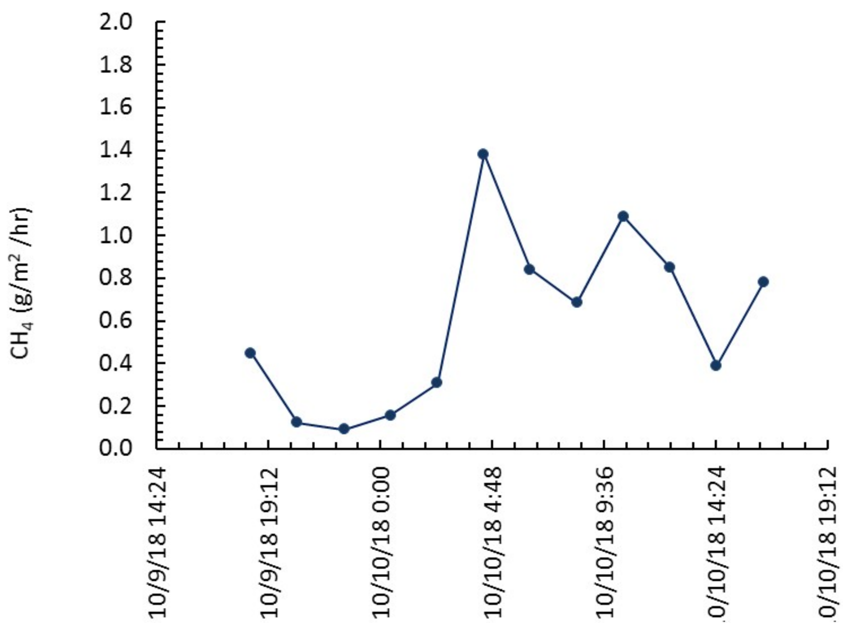


**Figure 59. Emission rates of $CH_4$ from the settling basin on the Echo dairy.**

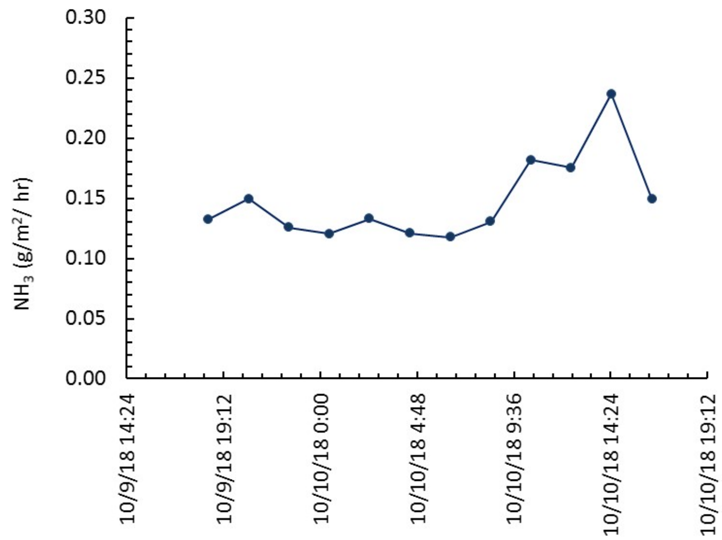


**Figure 60. Emission rates of $NH_3$ from the settling basin on the Echo dairy.**

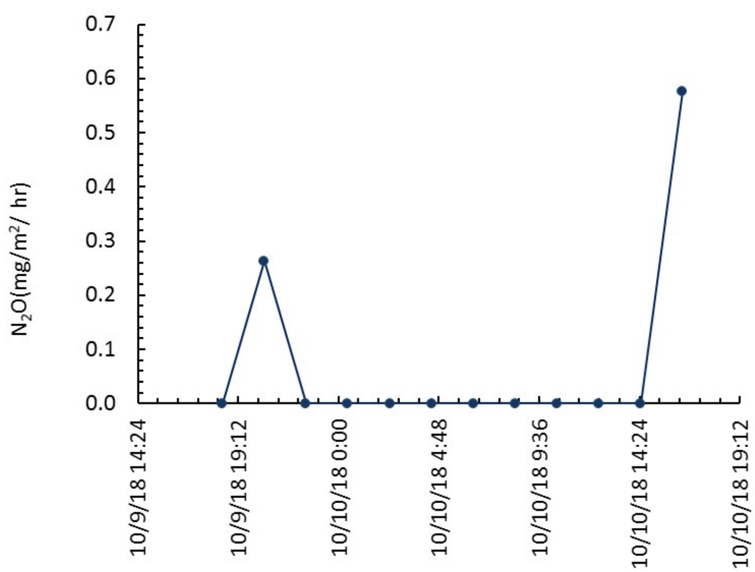


**Figure 61. Emission rates of $N_2O$ from the settling basin on the Echo dairy.**

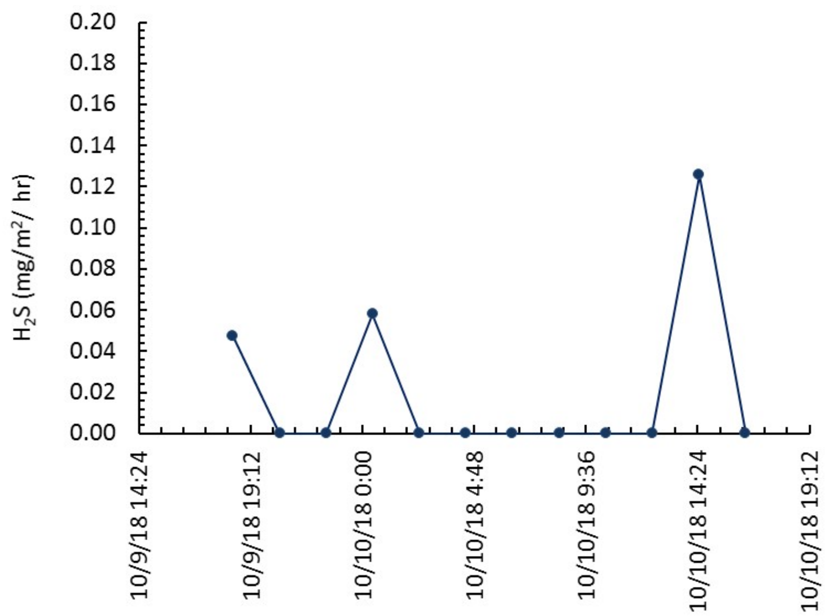


**Figure 62. Emission rates of $H_2S$ from the settling basin on the Echo dairy.**

**Emissions from the lagoon on the Echo dairy**

The Echo dairy lagoon emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 63, 64, 65, and 66, respectively. Almost constant emission rates of $CH_4$ and $H_2S$ were determined during the emission period. The emission rates of $NH_3$ were also relatively constant on the first day of monitoring. A few peaks of emission rates were calculated for $N_2O$.

The emission rates of $CH_4$, and $NH_3$ ranged from 0.01 to 2.33, and from 0.02 to 0.14 g/m$^2$/hr, respectively. The ranges of the emission rates $N_2O$ and $H_2S$ were from 0.00 to 51.33, and from 0.00 to 0.14 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 0.84 and 0.07 g/m$^2$/hr, respectively (Table 9). While they were 5.62 and 0.02 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 441.44, 33.97, 2.96, and 0.01 g/ milking cow equivalent/day, respectively (Table 10). The lagoon had relatively lower emission rate of $NH_3$ and higher emission rates of other gases than the settling basin.

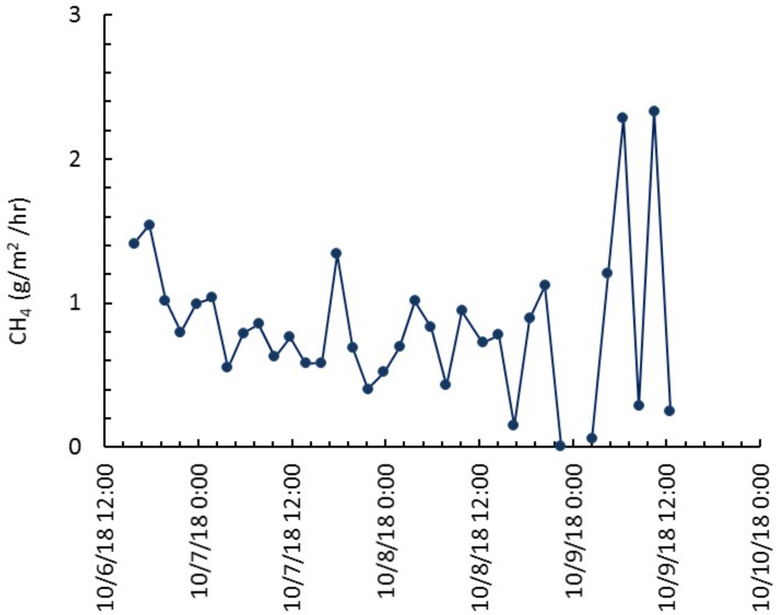


**Figure 63. Emission rates of $CH_4$ from the lagoon on the Echo dairy.**

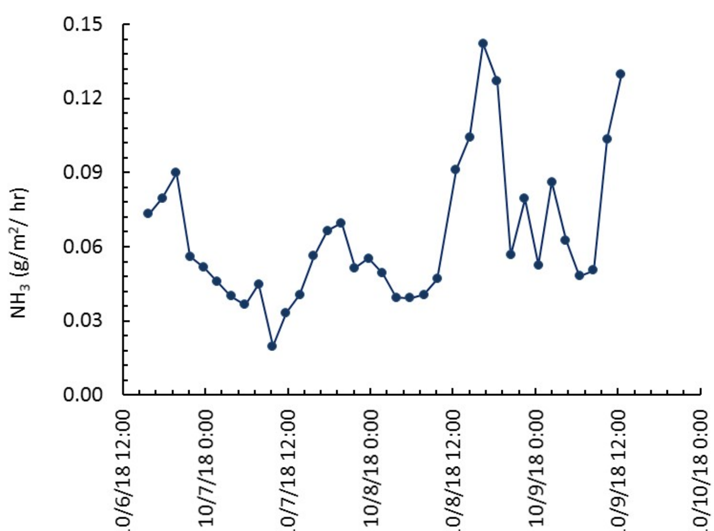


**Figure 64. Emission rates of $NH_3$ from the lagoon on the Echo dairy.**

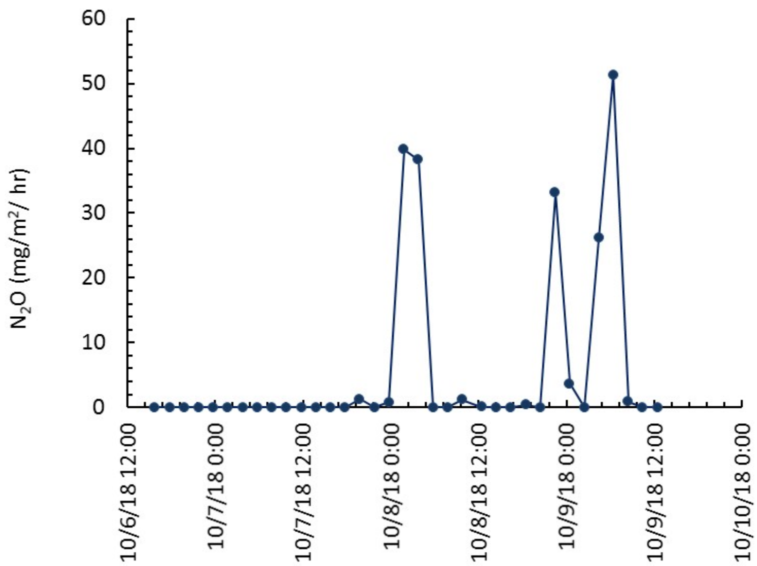


**Figure 65. Emission rates of $N_2O$ from the lagoon on the Echo dairy.**

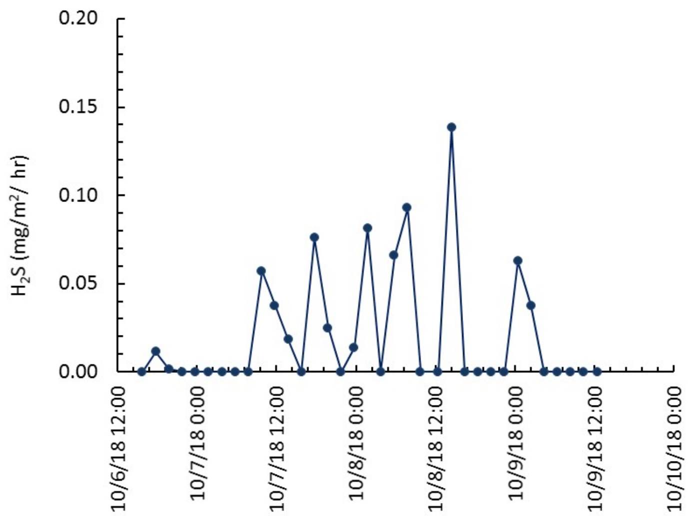


**Figure 66. Emission rates of $H_2S$ from the lagoon on the Echo dairy.**

**Emissions from the settling basin on the Foxtrot dairy**

The Foxtrot dairy settling basin emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 67, 68, 69, and 70, respectively. Methane emission rate was relatively constant during the first two days of monitoring with a peak of approximately 65 g/m$^2$/hr. Ammonia emission was relatively constant with a few peaks in the middle and end of the monitoring days. Two pronounced peaks of emissions were determined for $N_2O$. 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 0.59 to 64.68 and from 0.05 to 0.30 g/m$^2$/hr, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 65.65, and from 0.00 to 0.78 mg/m$^2$/hr, respectively. The average emission rates of $CH_4$ and $NH_3$ were 12.93 and 0.15 g/m$^2$/hr, respectively (Table 9). While they were 11.59 and 0.18 mg/m$^2$/hr, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 808.69, 9.47, 0.73, and 0.01 g/ milking cow equivalent/day, respectively (Table 10).

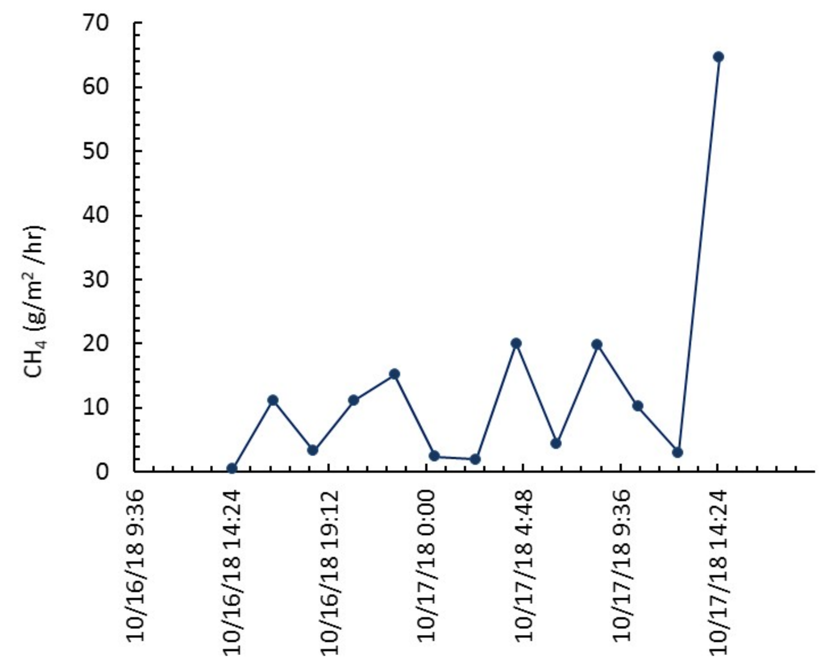


**Figure 67. Emission rates of $CH_4$ from the settling basin on the Foxtrot dairy.**

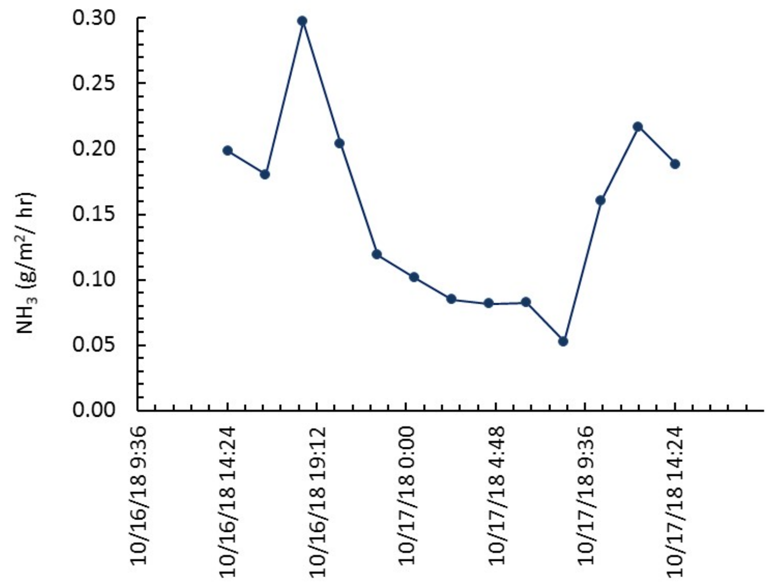


**Figure 68. Emission rates of $NH_3$ from the settling basin on Foxtrot dairy.**

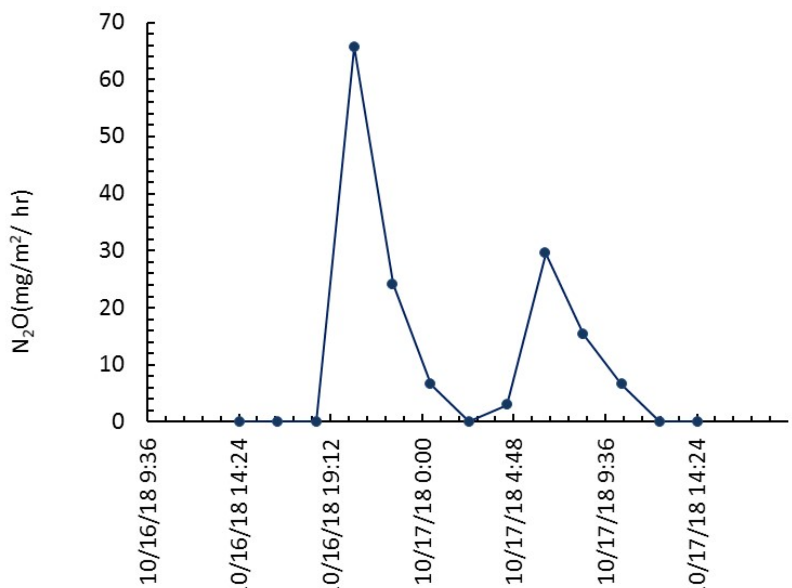


**Figure 69. Emission rates of $N_2O$ from the settling basin on the Foxtrot dairy.**

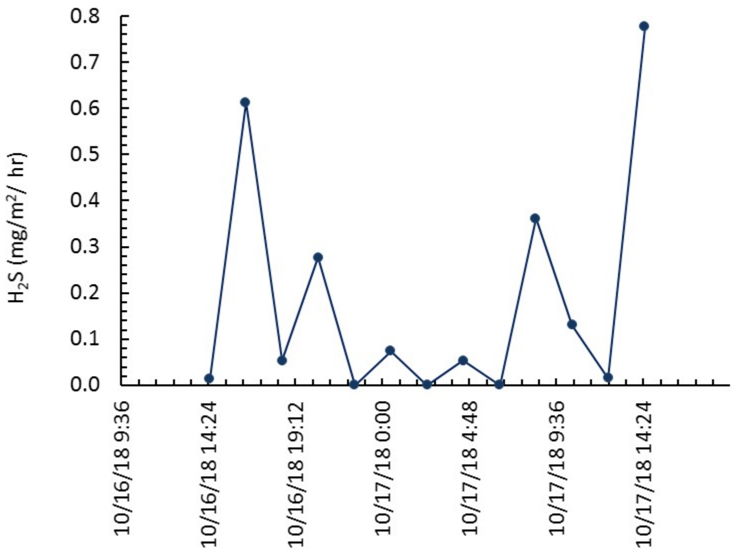


**Figure 70. Emission rates of $H_2S$ from the settling basin on the Foxtrot dairy.**

### Emissions from the lagoon on the Foxtrot dairy

The Foxtrot dairy lagoon emission rates of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ are shown in Figures 71, 72, 73, and 74, respectively. Relatively constant emission rates of $CH_4$ were determine for most of the time during the monitoring period. Some peaks of emissions were determined for other gases.

The emission rates of $CH_4$, and $NH_3$ ranged from 0.80 to 15.98, and from 0.08 to 0.24 $g/m^2/hr$, respectively. The ranges of the emission rates of $N_2O$ and $H_2S$ were from 0.00 to 422.20, and from 0.00 to 0.71 $mg/m^2/hr$, respectively. The average emission rates of $CH_4$ and $NH_3$ were 3.82 and 0.14 $g/m^2/hr$, respectively (Table 9). While they were 40.25 and 0.096 $mg/m^2/hr$, for $N_2O$ and $H_2S$, respectively. The daily emission of $CH_4$, $NH_3$, $N_2O$, and $H_2S$ were 418.94, 15.00, 4.42, and 0.01 g/ milking cow equivalent/day, respectively (Table 10). Comparing the emissions rates from the lagoon and the settling basin indicated that the lagoon had relatively lower emission rate of $CH_4$, $NH_3$, and $H_2S$ and higher emission rates of $N_2O$ than the settling basin.

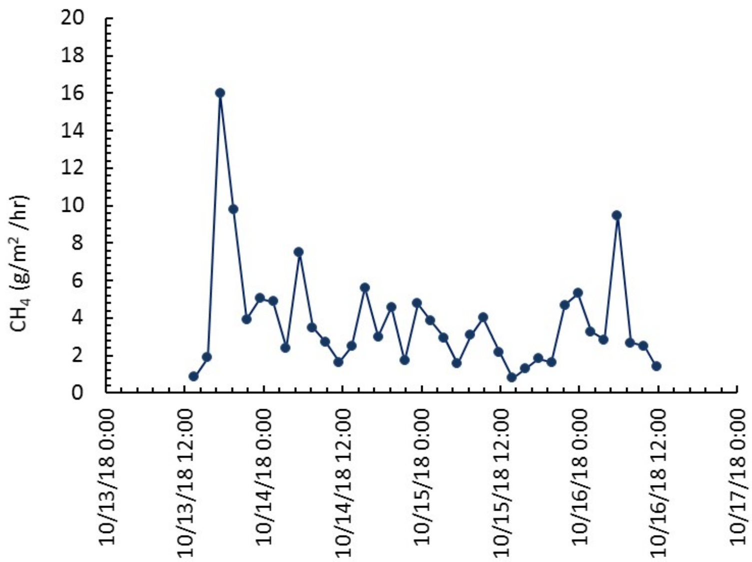


**Figure 71. Emission rates of $CH_4$ from the lagoon in the Foxtrot dairy.**

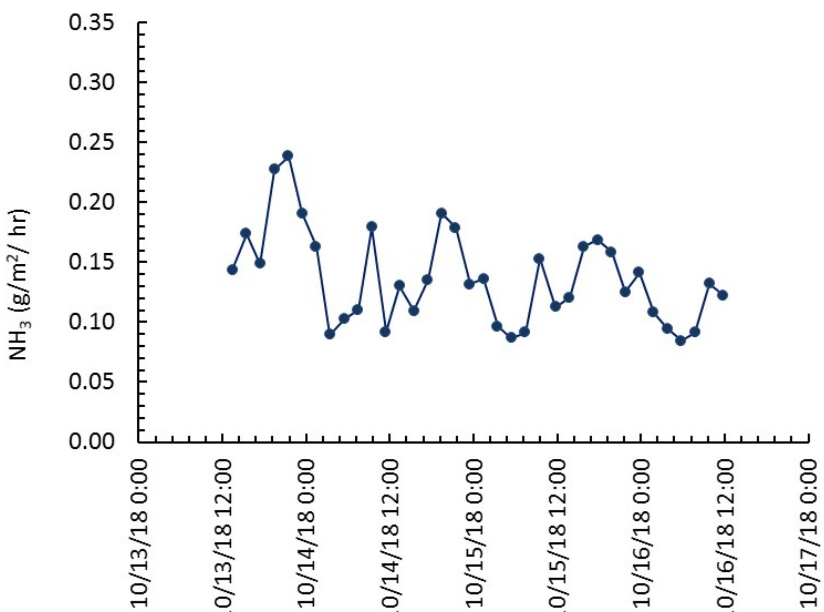


**Figure 72. Emission rates of $NH_3$ from the lagoon in the Foxtrot dairy.**

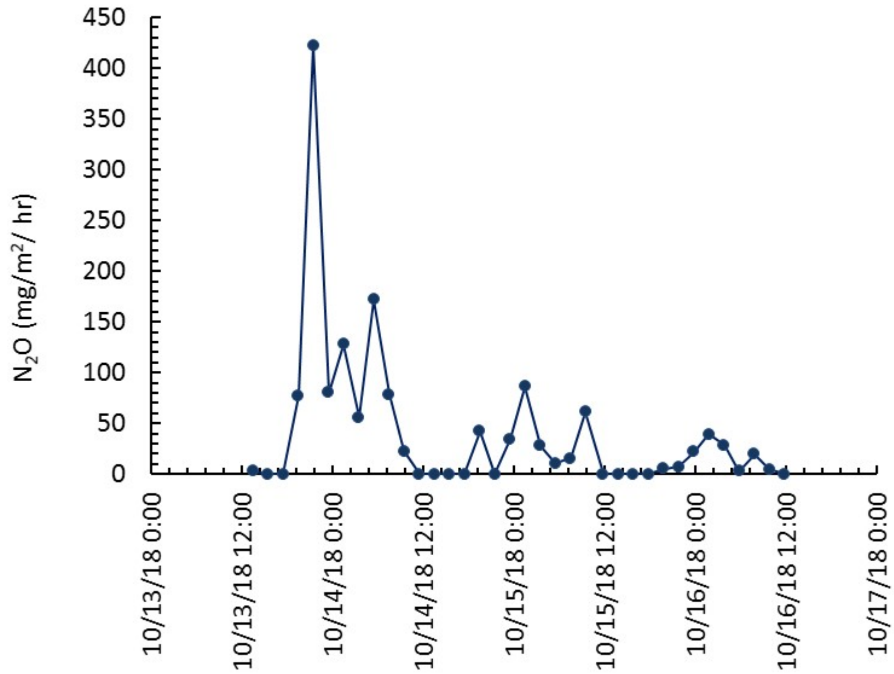


**Figure 73. Emission rates of $N_2O$ from the lagoon in the Foxtrot dairy.**

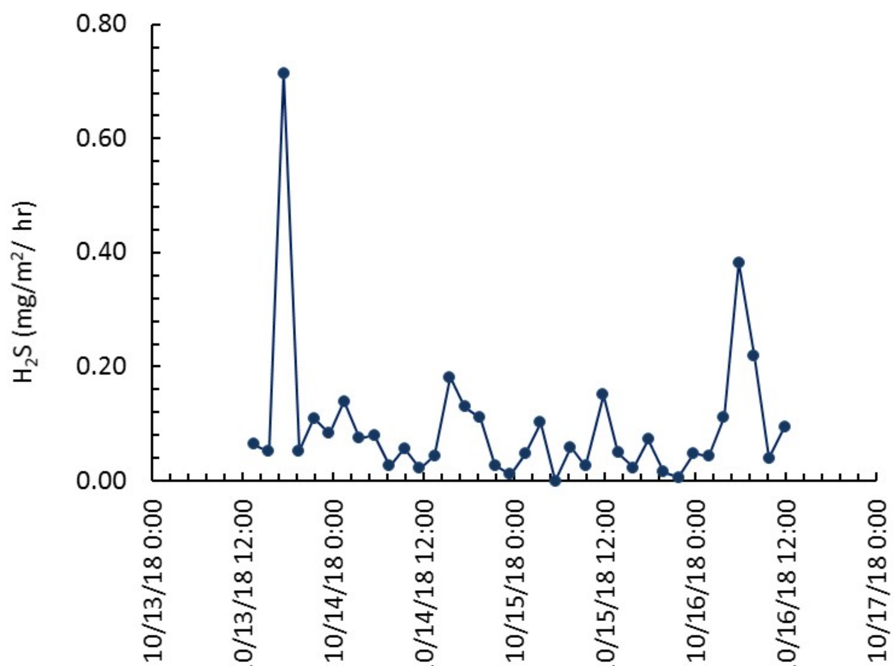


**Figure 74. Emission rates of $H_2S$ from the lagoon in the Foxtrot dairy.**

**Table 9. Average, Minimum, and Maximum emission rates of different gases.**

| 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 | 10.23 | 29.79 | 0.08 | 0.05 | 1.20 | 7.41 | 0.26 | 26.20 |
| | Minimum | 1.28 | 7.36 | 0.04 | 0.02 | 0.00 | 0.00 | 0.13 | 9.04 |
| | Maximum | 23.99 | 54.55 | 0.19 | 0.12 | 6.51 | 57.57 | 0.58 | 52.11 |
| Bravo | Average | 2.63 | 11.20 | 0.12 | 0.09 | 5.92 | 1.99 | 0.41 | 9.36 |
| | Minimum | 0.76 | 5.09 | 0.09 | 0.03 | 0.00 | 0.00 | 0.00 | 3.40 |
| | Maximum | 6.95 | 24.69 | 0.19 | 0.19 | 52.65 | 9.81 | 1.96 | 18.89 |
| Charlie | Average | 11.27 | | 0.11 | | 1.24 | | 0.05 | |
| | Minimum | 3.00 | | 0.03 | | 0.00 | | 0.00 | |
| | Maximum | 28.90 | | 0.25 | | 13.48 | | 0.22 | |
| Delta | Average | 4.48 | 6.64 | 0.22 | 0.19 | 10.35 | 5.34 | 0.13 | 0.160 |
| | Minimum | 1.33 | 3.24 | 0.13 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 21.49 | 14.52 | 0.34 | 0.26 | 241.38 | 46.66 | 0.95 | 0.59 |
| Echo | Average | 0.838 | 0.595 | 0.065 | 0.148 | 5.620 | 0.0700 | 0.021 | 0.019 |
| | Minimum | 0.005 | 0.090 | 0.019 | 0.117 | 0.000 | 0.000 | 0.00 | 0.000 |
| | Maximum | 2.332 | 1.380 | 0.142 | 0.236 | 51.330 | 0.577 | 0.138 | 0.126 |
| Foxtrot | Average | 3.819 | 12.93 | 0.137 | 0.15 | 40.245 | 11.59 | 0.096 | 0.18 |
| | Minimum | 0.797 | 0.59 | 0.084 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Maximum | 15.980 | 64.68 | 0.239 | 0.30 | 422.196 | 65.65 | 0.714 | 0.78 |

**Table 10. Average emission rate (g/milking cow equivalent/day) of different gases*.**

| Dairy | Number of milking cow equivalents** | $CH_4$ | | $NH_3$ | | $N_2O$ | | $H_2S$ | |
|---|---|---|---|---|---|---|---|---|---|
| | | Lagoon | Settling basin | Lagoon | Settling basin | Lagoon | Settling basin | Lagoon | Settling basin |
| Alpha | 2,254 | 872.98 | 1207.03 | 6.99 | 2.17 | 0.10 | 0.30 | 0.022 | 1.06 |
| Bravo | 967 | 662.50 | 194.90 | 31.13 | 1.55 | 1.49 | 0.04 | 0.10 | 0.16 |
| Charlie | 2,321 | 1461.47 | | 13.76 | | 0.16 | | 0.01 | |
| Delta | 2,589 | 548.53 | 920.99 | 27.18 | 25.82 | 1.27 | 0.74 | 0.02 | 0.02 |
| Echo | 1,996 | 441.44 | 43.32 | 33.97 | 10.76 | 2.96 | 0.01 | 0.01 | 0.00 |
| Foxtrot | 1,150 | 418.94 | 808.69 | 15.00 | 9.47 | 4.42 | 0.73 | 0.01 | 0.01 |

* the average daily emissions were calculated based on the average hourly concentration of different gases (number of data points varied Figures 31-74) *Calculated based on the total weights of the animal available on a dairy divided by the book value weight of a milking cow

## Characteristics of samples in late summer/early fall

For all the studied dairies except Charlie dairy, the lagoons receive manure from the settling basins; the. Charlie dairy lagoon received influent directly from the barn flush lanes. Table 11 shows the average pH, and the concentration of TS and VS in manure samples collected in the late summer/early fall. The pH for the inlet of settling basins and lagoons were in the ranges 6.97-7.46, and 6.61-7.34, respectively. The pH of the surface of the lagoons were in the range of 7.16-7.53. The TS content (% wet basis) of the settling basin and lagoons inlets were in the ranges of 0.32%-1.03%, and 0.35%-1.24%, respectively. Compared all the dairies, the Delta dairy had the highest TS contents in the settling basin inlet and lagoon surface as shown in Table 11. The high TS in the lagoon surface might be attributed to the presence of floating solids accumulation present during sampling. The VS/TS contents of the settling basin and lagoons inlets were in the ranges of 49.32%-69.91%, and 42.57%-76.87%, respectively. The TS and VS contents of the lagoon surfaces were in the ranges of 0.22%-0.57%, and 37.30%-65.25%, respectively. Among all the studied dairies, the Charlie dairy lagoon inlet had the highest VS/TS contents. For each studied dairy, the samples collected from lagoon surfaces had the lowest VS/TS concentrations. Although some of the measured TS and VS concentrations are typical for the flushed manure in California, others are lower than expected concentrations.

Table 12 shows the concentration of dissolved organic carbon (DOC), nitrogen and VFAs in manure samples collected in the late summer/early fall. The highest dissolved organic carbon (DOC) contents (0.09 g/gTS) in the settling basin inlet were determined on Alpha and Echo dairies while the lowest were determined on Foxtrot dairy. The DOC in the lagoon inlet was almost the same for all dairies except Charlie dairy where it had the lowest concentration of 0.04 g/g TS. For the settling basin inlets, the highest organic nitrogen content (0.037 g/g TS) was determined on Alpha dairy and the lowest (0.023 g/ gTS) was determined in Foxtrot dairy. Although the lagoon in Charlie dairy directly received the flushed manure, it had the lowest organic nitrogen contents. For all the studied dairies, lagoon surface had the highest ammonium concentrations than the settling basin and lagoon inlets. This probably due to the mineralization of the organic nitrogen and the solubility nature of ammonium. For most of the studied dairies the highest total nitrogen contents was determined in lagoon surfaces. For Bravo, Charlie, Echo, and Foxtrot dairies, the highest VFAs contents were determined in the fresh manure (the inlets of the settling basins and the lagoon on Charlie dairy)). Relatively higher VFAs contents was determined in the lagoon inlet on Alpha dairy and the lagoon surface on Delta dairy.

**Characteristics of Samples in late Winter/early Spring**

Table 13 shows the average pH, and the contents of TS and VS in manure samples collected late winter/early Spring. The pH for the inlets of settling basins and lagoons were in the ranges of 6.93-7.97, and 6.80-7.75, respectively. The pH of the surface of the lagoons were in the range of 6.92-7.45. The TS content (% wet basis) of the settling basin and lagoons inlets were in the ranges of 0.45%-1.65%, and 0.47%-1.75%, respectively. As can be seen in Table 13, comparing all the dairies, Alpha had the highest TS contents in the settling basin inlet while the Charlie dairy had the highest TS contents in the inlet of the lagoon. The latter may be due to the absence of a settling basin. The Bravo dairy had the lowest TS contents in inlet of the setting basin. The Bravo and Foxtrot dairies had the lowest TS content in the inlets of lagoon. The relatively higher TS contents in the inlets of the settling basins and the lagoons during the sampling event conducted in late winter/early spring than that conducted in late summer/early fall might be attributed to the increased amount of manure flush water in the summer compared with winter. The lowest TS contents in the lagoon surface were determined in the Alpha and Bravo dairies and the highest TS contents were measured in the Echo and Charlie dairy. The high TS in the lagoon surface in the Charlie and Echo dairies might be attributed to the presence of floating solids present during sampling. Moreover, it was observed that the Echo dairy was using a mixer to agitate the lagoon during the sampling day. The VS/TS contents of the settling basins and lagoons inlets were in the ranges of 50.99%-65.49%, and 48.98%-49.59%, respectively. The VS/TS in the lagoon surface was in the range of 30.93% -66.95%. Among all the studied dairies, the lagoon inlet in the Charlie dairy had the highest VS/TS contents. This probably because Charlie dairy does not recirculate lagoon water for manure flushing. For the Echo and Foxtrot dairies, the VS/TS content in the lagoon surface were similar to that of the lagoon inlets.

Table 14 shows the concentration of dissolved organic carbon (DOC), nitrogen and VFAs in manure samples collected in the late winter/early Spring. The highest DOC content (0.12 g/gTS) in the settling basin inlet was determined on Alpha dairy while the lowest (0.03 g/gTS) was determined on Delta dairy. Most of the studied dairies had DOC in the lagoon inlets in the range of 0.05-0.07 g/g TS. The lagoon on Alpha dairy had the highest value of 0.11 g/gTS. For the settling basin inlets, the highest organic nitrogen content (0.031 g/g TS) was determined on Delta dairy and the lowest (0.023 g/ gTS) was determined in Alpha dairy. The lagoon surface in Charlie dairy had the highest organic nitrogen contents. For most of the studied dairies, lagoon surface had the highest ammonium concentrations than the settling basin and lagoon inlets. For most of the studied dairies the highest total nitrogen contents was determined in lagoon surfaces. For Charlie, Delta, Echo, and Foxtrot dairies, the highest VFAs contents were determined in the fresh manure (the inlets of the settling basins and the lagoon on Charlie dairy)). Relatively higher VFAs contents was determined in the lagoon inlet on Alpha dairy.

**Table 11. pH, TS and VS of manure samples collected in late Summer/early Fall***

| 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 | 7.14 ± 0.03 | 6.88 ±0.07 | 7.22 ±0.04 | 0.32±0.15 | 0.37 ±0.06 | 0.22 ±0.04 | 55.32 ±5.26 | 56.75 ±0.81 | 47.78 ±2.53 |
| Bravo | 6.97 ±0.11 | 7.34 ±0.04 | 7.34 ±0.13 | 0.39 ±0.22 | 0.35 ±0.00 | 0.26 ±0.05 | 69.91 ±1.27 | 46.17 ±0.06 | 37.30 ±0.84 |
| Charlie | ** | 6.61 ±0.20 | 7.16 ±0.15 | ** | 1.24 ±0.19 | 0.39 ±0.02 | ** | 76.87 ±7.02 | 65.25 ±10.93 |
| Delta | 7.16 ±0.23 | 7.29 ±0.06 | 7.31 ±0.00 | 1.03 ±0.24 | 0.51 ±0.03 | 0.57 ±0.01 | 49.32 ±20.65 | 42.57 ±1.15 | 39.68 ±0.59 |
| Echo | 7.46 ±0.01 | 7.20 ±0.13 | 7.53 ±0.13 | 0.51 ±0.00 | 0.45 ±0.01 | 0.23 ±0.01 | 53.13 ±1.30 | 48.95 ±2.15 | 38.60 ±0.61 |
| Foxtrot | 7.36 ±0.04 | 7.25 ±0.01 | 7.32 ±0.02 | 0.35 ±0.29 | 0.35 ±0.03 | 0.35 ±0.04 | 54.08 ±5.67 | 47.60 ±2.38 | 44.172.33 |

*At least duplicate samples were analyzed for the composite samples; ** The dairy does not have a settling basin

**Table 12. Dissolved Organic Carbon (DOC), Nitrogen, and VFAs contents in manure samples in late Summer/early Fall (g/g TS)***

| Dairy | DOC | | | Organic N | | | Ammonium N | | | Total N | | | VFA | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 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 | 0.09 | 0.11 | 0.11 | 0.037 | 0.011 | 0.007 | 0.042 | 0.066 | 0.074 | 0.079 | 0.077 | 0.105 | 0.074±0.003 | 0.180±0.029 | 0.071±0.013 |
| Bravo | 0.07 | 0.09 | 0.08 | 0.030 | 0.027 | 0.015 | 0.008 | 0.039 | 0.050 | 0.039 | 0.066 | 0.065 | 0.061±0.039 | 0.022±0.001 | 0.014±0.005 |
| Charlie | ** | 0.04 | 0.07 | ** | 0.022 | 0.041 | ** | 0.004 | 0.042 | ** | 0.027 | 0.083 | ** | 0.049±0.007 | 0.004±0.002 |
| Delta | 0.08 | 0.09 | 0.09 | 0.030 | 0.035 | 0.034 | 0.030 | 0.052 | 0.054 | 0.060 | 0.087 | 0.088 | 0.089±0.013 | 0.013±0.007 | 0.108±0.022 |
| Echo | 0.09 | 0.11 | 0.10 | 0.033 | 0.031 | 0.041 | 0.024 | 0.026 | 0.027 | 0.057 | 0.057 | 0.068 | 0.129±0.077 | 0.066±0.010 | 0.016±0.001 |
| Foxtrot | 0.04 | 0.10 | 0.09 | 0.023 | 0.041 | 0.040 | 0.011 | 0.060 | 0.061 | 0.034 | 0.100 | 0.101 | 0.073±0.004 | 0.062±0.014 | 0.026±0.003 |

**duplicate samples were analyzed for VFAs for the composite samples; S.B. Inlet: settling basin inlet/flushing water outlet
Lg Inlet: lagoon Inlet/ settling basin outlet
Lg surface: lagoon surface water

**Table 13. pH, TS and VS of manure samples collected in late Winter/early Spring*.**

| 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 | 6.93± 0.09 | 6.92±0.02 | 7.19±0.06 | 1.65±0.77 | 1.61 ±0.30 | 0.48 ±0.00 | 65.49 ±1.84 | 66.97 ±3.81 | 49.71 ±0.93 |
| Bravo | 7.97 ±0.08 | 6.80 ±0.04 | 7.26±0.05 | 0.45±0.40 | 0.50 ±0.10 | 0.48 ±0.03 | 61.31 ±4.30 | 57.35±5.11 | 30.93 ±1.18 |
| Charlie | ** | 7.75 ±0.09 | 6.92 ±0.05 | ** | 1.75 ±1.76 | 1.03 ±0.55 | ** | 77.85 ±1.81 | 66.95 ±7.71 |
| Delta | 7.42 ±0.22 | 6.88 ±0.01 | 7.02 ±0.01 | 1.45 ±0.34 | 1.20 ±0.22 | 0.71 ±0.02 | 62.15 ±3.94 | 61.31±3.07 | 49.32 ±0.16 |
| Echo | 7.69 ±0.05 | 7.10 ±0.02 | 7.45±0.11 | 1.08 ±0.46 | 0.73 ±0.01 | 1.50 ±1.33 | 53.14 ±6.17 | 48.98 ±0.25 | 49.40 ±6.74 |
| Foxtrot | 7.38 ±0.10 | 7.11 ±0.04 | 7.22 ±0.02 | 0.63 ±0.28 | 0.47 ±0.02 | 0.61 ±0.31 | 50.99 ±2.03 | 49.59 ±0.59 | 50.79 ±6.97 |

*At least duplicate samples were analyzed for the composite samples ; ** The farm does not have a settling basis

**Table 14. Dissolved Organic Carbon (DOC), Nitrogen, and VFAs contents in manure samples in late Winter/early Spring (g/g TS)*.**

| Dairy | DOC | | | Organic N | | | Ammonium N | | | Total N | | | VFA | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 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 | 0.12 | 0.11 | 0.09 | 0.023 | 0.006 | 0.090 | 0.032 | 0.021 | 0.098 | 0.055 | 0.027 | 0.188 | 0.143±0.011 | 0.165±0.001 | 0.014±0.002 |
| Bravo | 0.05 | 0.05 | 0.06 | 0.028 | 0.037 | 0.013 | 0.017 | 0.022 | 0.048 | 0.045 | 0.06 | 0.061 | 0.027±0.030 | 0.285±0.340 | 0.234±0.286 |
| Charlie | ** | 0.05 | 0.03 | ** | 0.032 | 0.045 | ** | 0.015 | 0.019 | ** | 0.047 | 0.064 | ** | 0.083±0.001 | 0.007±0.001 |
| Delta | 0.03 | 0.05 | 0.12 | 0.031 | 0.031 | 0.034 | 0.033 | 0.033 | 0.054 | 0.065 | 0.064 | 0.088 | 0.058±0.003 | 0.010±0.005 | 0.004±0.001 |
| Echo | 0.04 | 0.07 | 0.03 | 0.028 | 0.034 | 0.031 | 0.029 | 0.041 | 0.021 | 0.057 | 0.076 | 0.056 | 0.020±0.005 | 0.017±0.013 | 0.001±0.000 |
| Foxtrot | 0.08 | 0.07 | 0.06 | 0.030 | 0.035 | 0.024 | 0.060 | 0.054 | 0.042 | 0.090 | 0.089 | 0.069 | 0.112±0.055 | 0.029±0.002 | 0.003±0.001 |

*duplicate samples were analyzed for VFAs for the composite samples; S.B. Inlet: settling basin inlet/flushing water outlet; Lg Inlet: lagoon Inlet/ settling basin outlet; Lg surface: lagoon surface water

**Results of the studied models**

The CARB/IPCC model was used to estimate the emissions of $CH_4$ from all the studied settling basins and lagoons. For the last studied dairy (Charlie dairy) that does not have settling basin, the CARB/IPCC, DairyGEM, and DNDC-manure models were used to predict the emissions of methane from the lagoons. No attempt was made to use DairyGEM, and DNDC-manure to model the emissions from the settling basins and lagoons from the dairies that had both emitting sources because the settling basin may change the characteristics of manure and hence the emissions of different gases.

**Measured and modeled emissions from the lagoon and settling basin on Alpha dairy**

Measured and modeled emission rates of $CH_4$ from the lagoon and settling basin on Alpha dairy are shown in Figures 75 and 76, respectively. The modeled values for the lagoons on September 11 and 12, 2018 represent 180%, and 112% of the measured values, respectively. The average modeled value (355 $g/m^2/day$) represents 144% of the average measured value (246 $g/m^2/day$). The modeled value for the settling basin on September 13, 2018 represents 147% of the measured value.

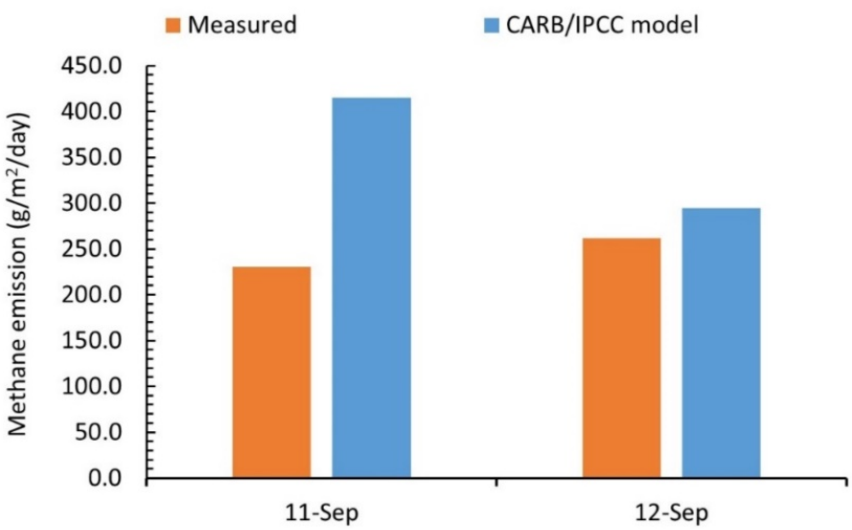


**Figure 75. Measured and modeled methane emissions from the lagoon on the Alpha dairy.**

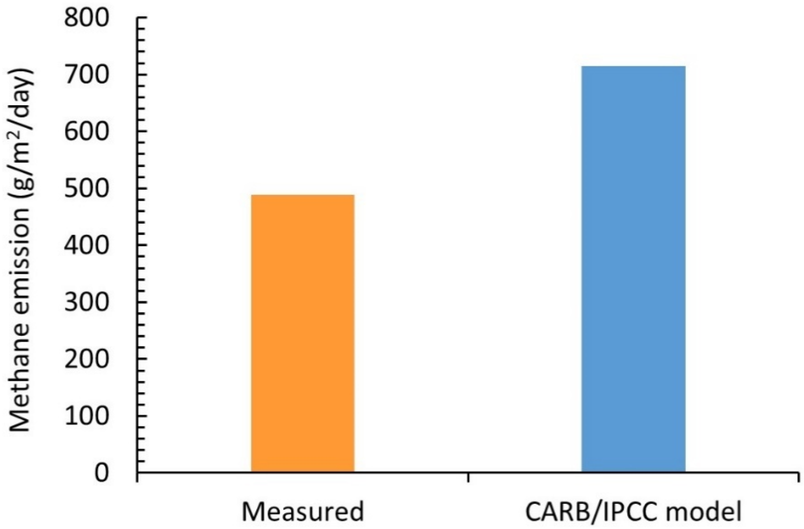


**Figure 76. Measured and modeled methane emissions from the settling basin on the Alpha dairy on September 13, 2018.**

## Measured and modeled emissions from the lagoon and settling basin on Bravo dairy

Measured and modeled emission rates of methane from the lagoon and settling basin on Bravo dairy are shown in Figures 77 and 78, respectively. The modeled values for the lagoon on September 16 and 17, 2018 represent 175% and 149% of the measured values, respectively. The average modeled value (98 $g/m^2$/day) represents 160% of the average measured value (61 $g/m^2$/day). The modeled values for the settling basin on September 18 and 19, 2018 represent 402%, and 406% of the measured values, respectively. The average modeled value (1090 $g/m^2$/day) represents 404% of the average measured value (270 $g/m^2$/day).

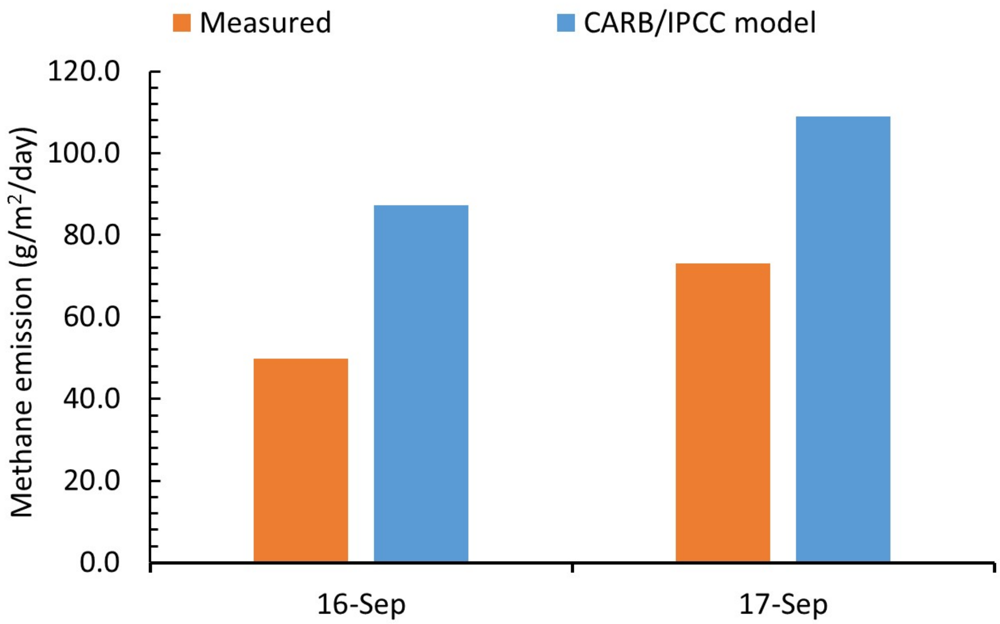


**Figure 77. Measured and modeled methane emissions from the lagoon on the Bravo dairy.**

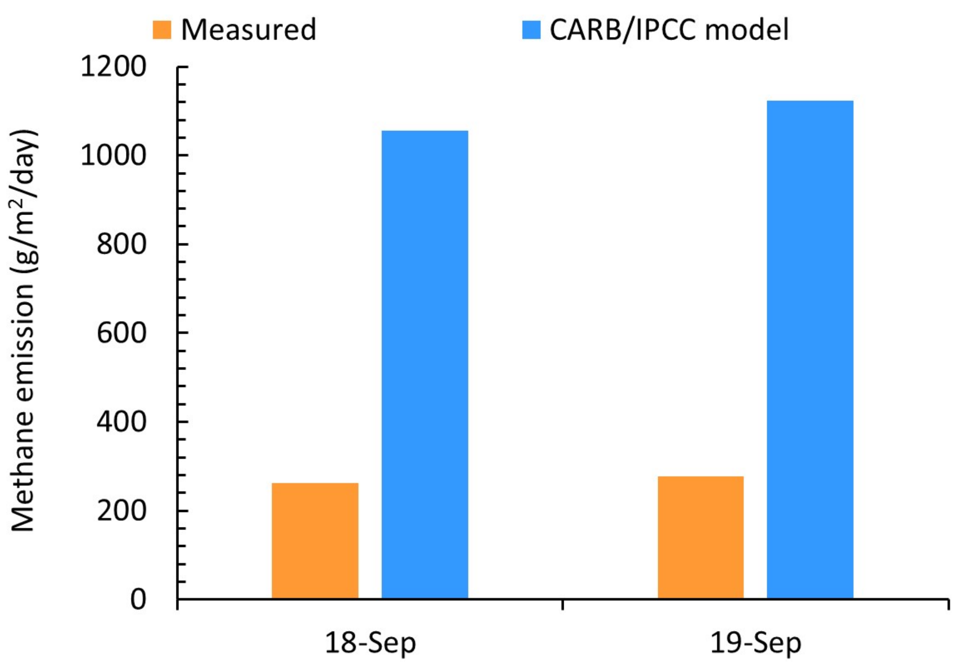


**Figure 78. Measured and modeled methane emissions from the settling basin on Bravo dairy.**

**Measured and modeled emissions from the lagoon on Charlie dairy**

Measured and modeled emission rates of methane from the lagoon on Charlie dairy using CARB/IPCC, DairyGEM, and DNDC-Manure models are shown in Figure 79. The measured values were greater than all the modeled values except the modeled value using the CARB/IPCC model on the third day. The modeled values using DairyGEM were greater than the values modeled using DNDC-Manure. The modeled values using CARB/IPCC represent 48%, 58%, and 168% of the measured values on September 23, 24, and 25, 2018, respectively. The average modeled value (207 $g/m^2/day$) represents 70% of the average measured value (296 $g/m^2/day$). The modeled values using DNDC-Manure represent 13%, 17%, and 40% of the measured values, respectively. The average modeled value (55 $g/m^2/day$) represents 19% of the average measured value (296 $g/m^2/day$). The modeled values using DairyGEM represent 20%, 28%, and 62% of the measured values, respectively. The average modeled value (87 $g/m^2/day$) represents 29% of the average measured value (296 $g/m^2/day$).

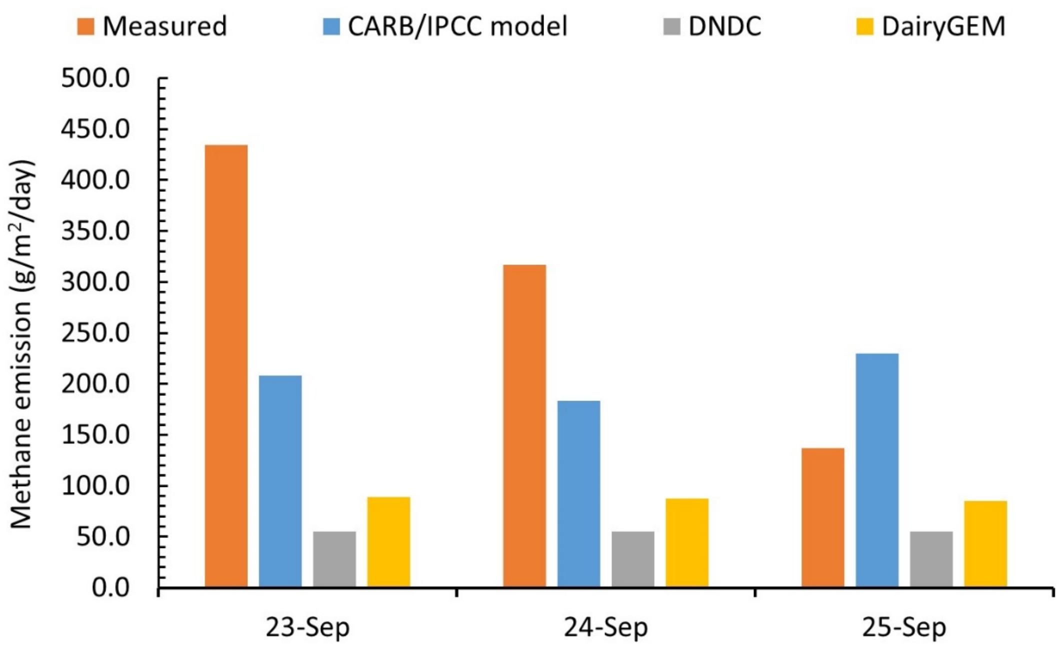


**Figure 79. Measured and modeled methane emissions from the lagoon on the Charlie dairy.**

**Measured and modeled emissions from the lagoon and settling basin on Delta dairy**

Measured and modeled emission rates of methane from the lagoon and settling basin on Delta dairy are shown in Figures 80 and 81, respectively. The modeled values for the lagoon on September 29 and 30, 2018 represent 200%, and 205% of the measured values respectively. The average modeled value (232 $g/m^2/day$) represents 203% of the average measured value (114 $g/m^2/day$). The modeled value for the settling basin on October 1, 2018 represents 118% of the measured value.

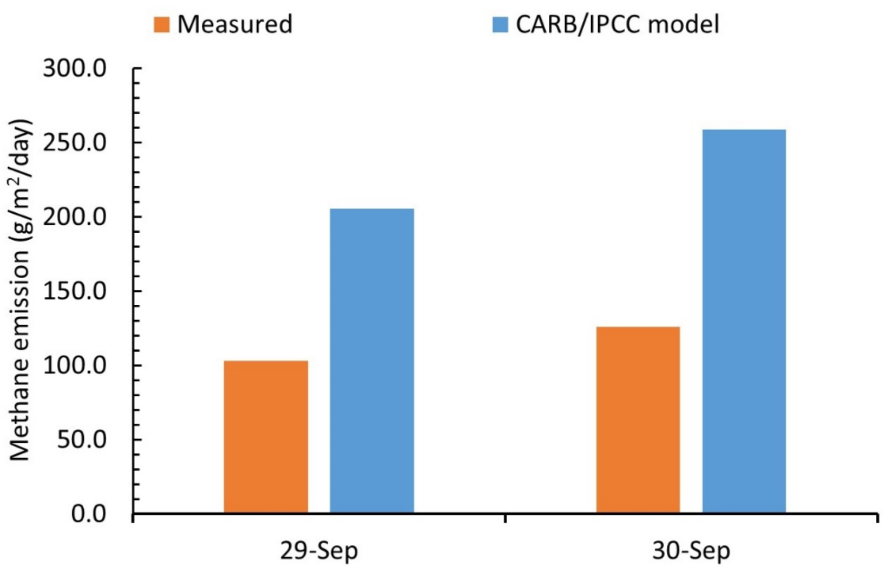


**Figure 80. Measured and modeled methane emissions from the lagoon on the Delta dairy.**

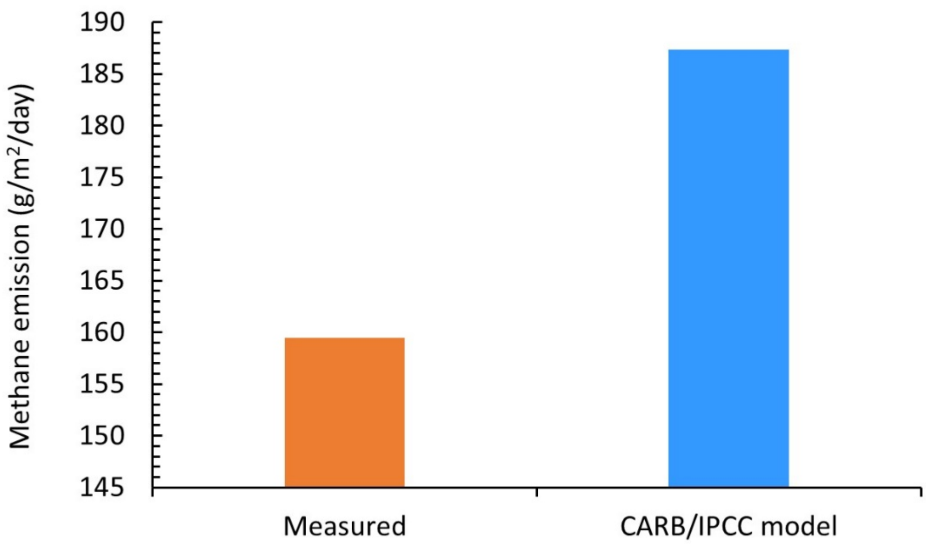


**Figure 81. Measured and modeled methane emissions from the settling basin on the Delta dairy on October 1, 2018.**

## Measured and modeled emissions from the lagoon and settling basin on Echo dairy

Measured and modeled emission rates of $CH_4$ from the lagoon and settling basin on Echo dairy are shown in Figures 82 and 83, respectively. The modeled values for the lagoon on October 6 and 7, 2018 represent 274% and 407% of the measured values, respectively. The average modeled value (65g/m$^2$/day) represents 341% of the average measured value (19 g/m$^2$/day). The modeled value for the settling basin on October 8, 2018 represents 1517% of the measured value.

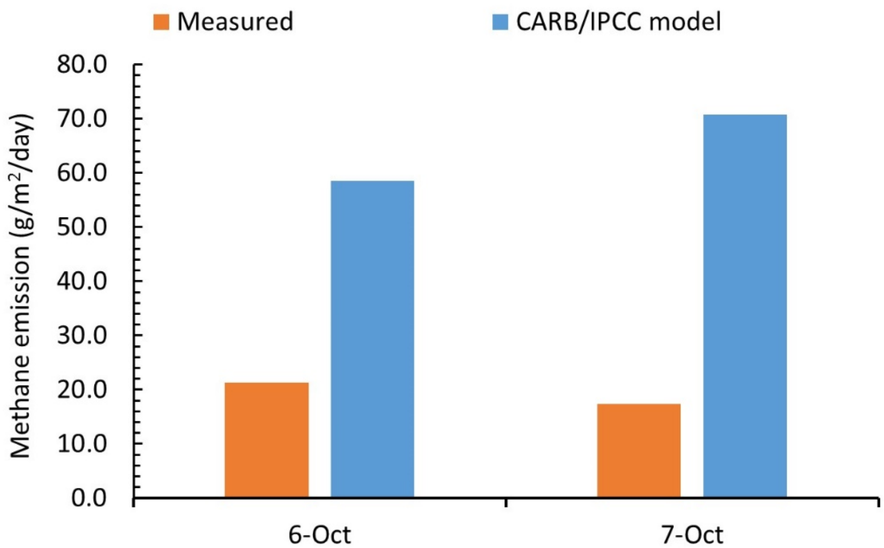


**Figure 82. Measured and modeled methane emissions from the lagoon on Echo dairy.**

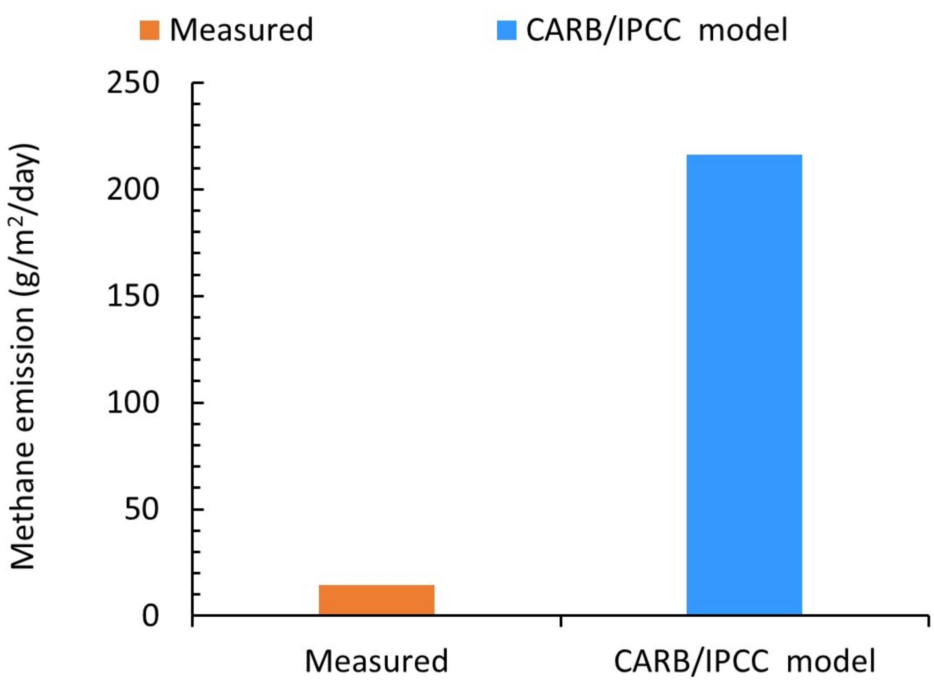


**Figure 83. Measured and modeled methane emissions from the settling basin on Echo dairy on October 8, 2018.**

### Measured and modeled emissions from the lagoon and settling basin on Foxtrot dairy

Measured and modeled emission rates of $CH_4$ from the lagoon and settling basin on Foxtrot dairy are shown in Figures 84 and 85, respectively. The modeled values for the lagoon on October 13 and 14, 2018 represent 181% and 348% of the measured values, respectively. The average modeled value (231 g/m$^2$/day) represents 246% of the average measured value (94 g/m$^2$/day). The modeled value for the settling basin on October 15, 2018 represents 69% of the measured value.

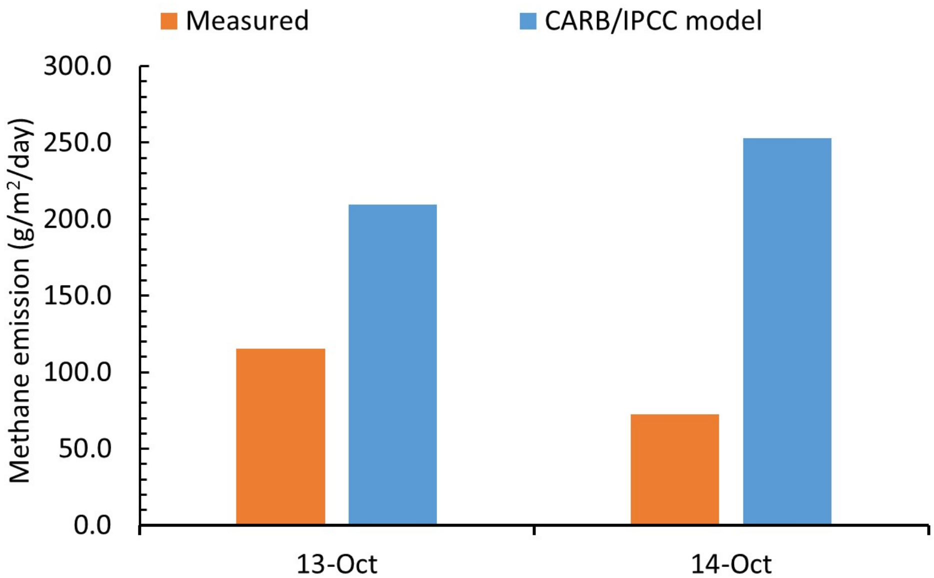


**Figure 84. Measured and modeled methane emissions from the lagoon on the Foxtrot dairy.**

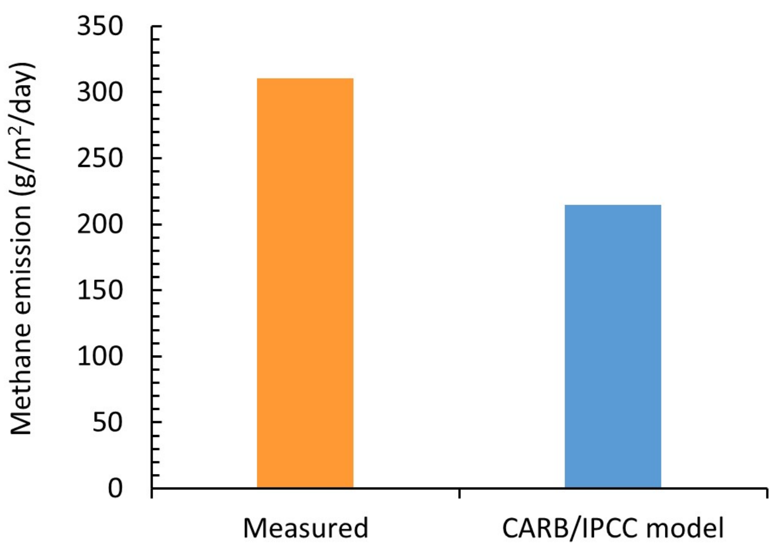


**Figure 85. Measured and modeled methane emissions from the settling basin on the Foxtrot dairy on October 15.**

**Discussion and conclusions**

The emissions of different gases pronouncedly varied among the sources in the studied dairies. The lagoon in the Charlie dairy had the highest daily emissions of $CH_4$ per milking cow equivalent. This may be because the dairy did not have a settling basin and all the produced volatile solids undergone anerobic conditions in the lagoon. The lagoons in the Echo and Foxtrot dairies had the lowest daily emission of $CH_4$ per cow than other dairies. The lowest emissions of $CH_4$ from the settling basins were determined on Bravo and Echo dairies. The low emissions from the settling basins and lagoons on Echo dairy might be because the dairy used a methanogenesis inhibitor to suppress the emission. The composition of the inhibitor was a proprietary of the selling company. Although the low emission of $CH_4$ from the lagoon in Foxtrot dairy, its emission from the settling basin was relatively higher than that from Bravo and Echo dairies. However, it was lower than that from the settling basin in Alpha and Delta dairies. The settling basin on Bravo dairy had relatively low emissions rates of $CH_4$. This may be attributed to the relatively small size of the settling basin that might led to shorter residence times of flushed manure in the settling basin.

It should be mentioned that all the dairies reported that they do not recall when they last removed settled solids from the farm's lagoons. They all reported that they only use the top layer of the lagoon for irrigation. However, during one the visits to the Echo dairy, after conducting the emission measurements, it was noticed that the dairymen was using a mixer to mix the accumulated sludge during pumping lagoon water for irrigation. This probably was another reason for the low emissions of $CH_4$ on that dairy. Among all the studied dairies, the settling basin in Alpha dairy had the highest daily emission per cow. The calculated daily emissions of $CH_4$ per cow from the lagoons of all the studied dairies, except Charlie dairy, lie in the range reviewed by Leytem et al. (2017) as shown in Table 15. Though the differences among different studies in locations of the dairies, the methods used the current study (wind tunnel), the configuration of manure storages, size of farms and manure storages, and weather conditions (Table 15).

**Table 15. On- farm $CH_4$ emissions from manure storages (Leytem et al., 2017).**

| Source | Season | Measurement method | Emissions (g/head/ day) | Reference |
|---|---|---|---|---|
| Lagoon | Annual | Inverse dispersion | 325 | Bjorneberg et al., 2009 |
| Settling basin | Summer | Flux chamber | 14.2 | Borhan et al., 2011a |
| Primary lagoon | Summer | Flux chamber | 666 | |
| Secondary lagoon | Summer | Flux chamber | 141 | |
| Lagoon | Annual | Inverse dispersion | 1028 | Leytem et al., 2011 |
| Lagoon | Summer | Inverse dispersion | 211 | Todd et al., 2011 |
| Lagoon | Annual | Inverse dispersion | 361 | Leytem et al., 2013 |

The highest and lowest daily emissions of $NH_3$ from the lagoons were determined in the Echo and Alpha dairies, respectively. While, for the settling basins, they were determined from Delta and Bravo dairies, respectively. The highest and lowest daily emissions of $N_2O$ from the lagoons were determined in the Foxtrot and Alpha dairies, respectively. While for the settling basins they were determined from Delta and Bravo, respectively. For $H_2S$, the highest and lowest daily emissions from the lagoons were determined in Bravo and Charlie dairies, respectively. While the highest daily emissions from the settling basins were determined in the Alpha dairy, and the lowest were determined in the Echo and Foxtrot dairies.

There are several factors affecting the emissions measured from the settling basins and lagoons. They include: cow diet; the type and amount of water used for barn flushing; amount, type and characteristics of bedding materials; sizing; loading rate; frequency of solid removal from the settling basin and lagoons; dimensions of the settling basins and lagoons; residence time of influent in the settling basins and lagoons; amount of feed spells that are usually flushed with manure; and animal feed type and amount. Although we tried to collect data from the studied dairies using a survey to specify possible reason (s) for the differences in emissions, the survey answers of most questions were not conclusive. For example, for Foxtrot it was not possible to determine how clean was the settling basins after excavation and how much solids were accumulated in the spot of measurements (under the wind tunnel during the measurements). Therefore, there might be unaccountable VS remaining in the settling basins that provide inoculum form the fresh manure and they might undergo breakdown. Therefore, there may be high levels of $CH_4$ generation even after the settling basins were excavated (Leytem et al., 2017). Moreover, the flow rate of manure and the solid removal from the lagoons were not measured in the current study. Therefore, it was not possible to determine the residence time in the settling basins. The amount and characteristics of bedding materials and feed spells flow to manure storage were not also determined.

The modeled values using the CARB/IPCC model are in the same order of magnitude for most of the modeled dairies. However, the modeled values were greater than the measured values. Lory et la. (2010) calculated greater emission of $CH_4$ using the IPCC methane emission factors than measured values. In their calculation, they also used different values for methane yield and VS destruction than the default values used in the IPCC model. For Charlie dairy, the DNDC-Manure gave smaller values than the CARB/IPCC and DairyGEM. It was not possible to model the settling basins using the DairyGEM and Manure-DNDC model because manure flow into and through the lagoons is different from that of the settling basins in several aspects:

- The lagoons are considered as fed batch systems with removal of top layers (mainly very diluted wastewater) for irrigation and barns flushing, while the settling basins are plug flow systems.
- The lagoons, preceded by settling basins, may have lower TS contents than the settling basins.
- The scum layers may be thinner in the lagoons than the settling basins that usually remove the fibrous materials from the flushed manure.
- The solids accumulated in the settling basins may be regularly cleaned (e.g., every six months), while the solid accumulated in the lagoon may be stored for longer periods. This might affect the biochemical processes in the lagoons and the settling basins.

More research is needed in the following areas:

- Long-term measurements of emissions from settling basins and lagoons are needed to determine seasonal variation on the emission rates of different gases.
- Measurements of emissions from different spots on the settling basins and lagoons are also needed to determine the spatial variations on emissions. Emissions at spots close to the inlets of the settling basins and lagoons may be different from other locations.
- Determine the residence times of manure solids in the settling basins and lagoons and their effect on the emissions of different gases.
- Determine the effect of the quantity and quality of manure flushing water on the emissions of different gases.
- Determine the seasonal variations of manure characteristics and specify the factors affect the variability in manure characteristics.
- Modify the DairyGEM and Manure-DNDC model to estimate the emissions of different gases from settling basins and lagoons when they are arranged in series
- Calibrate and validate the emissions models using long-term measurements of emissions.

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## Appendix

## Dairy Farm Survey

1. What is breed type?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .. . . . . . . . . .. . .. . . . . . . . . . . . . ... . . ..

2. What is the dairy herd size? Number of lactating, and dry cows; heifers and calves.

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3. What is the average milk yield, protein and fat content?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .. . . . . . . . . .. . .. . . . . . . . . . . . . ... . . ..

4. Do you house heifers on your farm?

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5. Do you house your calves on your farm?

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6. Describe barns and corrals? What are dimensions of each (barn and corrals)?

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7. What do you feed your various animal types? Can you provide your rations?

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8. Do you use crude protein and energy supplements? At what rate?

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9. Do you use sulfur feeding adjustment? If so, at what rate?

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10. What is the approximate amount of manure entering the lagoon versus staying in corrals?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

11. How often do you flush your freestalls?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

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?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

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17. What is the field application method of manure (if applicable)?

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18. What acreage of your land receives manure? What is the approximate depth of manure on field after application?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

19. What type of crops do you fertilize with lagoon water? What is your soil type? What is the cultivated area for each crop?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .. . . . . . . . . .. . .. . . . . . . . . . . . . ... . . ..

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20. How are manure solids handled and processed?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .. . . . . . . . . .. . .. . . . . . . . . . . . . ... . . ..

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

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