CALIFORNIA AIR RESOURCES BOARD

Summary Report of Airborne Methane Plume Imaging Studies: Dairy Farms and Digesters

Contents

Highlights

- Through airborne research studies conducted over the past decade, CARB has collected a unique dataset of remote sensing methane plume detections and operator survey responses from dairy and livestock operations across the State.

- Detectable methane plumes are relatively rare at dairy and livestock operations, including those with digesters: 80% of dairy overflights did not observe detectable emissions.

- Methane emissions from dairies and livestock are typically diffuse and hard to detect with plume imaging, whereas leaks from digester infrastructure are more concentrated and localized and therefore easier to detect.

- Digester emissions mostly stem from venting, maintenance, testing, and repairable leaks; when plumes are detected, coordination with operators enables quick repairs and reduced methane digester leak emissions.

- Plumes at dairies with digesters are not reliable indicators of total emissions or digester performance, as methane varies diurnally, seasonally, and annually; plume images and associated emission rates should not be considered reliable tools for estimating methane emissions from these facilities.

Executive Summary

Methane is a potent greenhouse gas and short-lived climate pollutant with a global warming potential 25 times larger than carbon dioxide over a 100-year period. California *Senate Bill (SB) 1383* (Lara, Chapter 395, Statutes of 2016) sets ambitious targets to reduce short-lived climate pollutants, including targets to reduce methane emissions 40% below 2013 levels by 2030 both statewide and within the dairy and livestock sector. The dairy and livestock sector is the largest source of methane in California, contributing more than half of statewide methane emissions. Dairy and livestock methane emissions come from two primary sources: manure management and enteric fermentation (a digestive process that occurs in ruminant animals such as cattle, sheep, and goats).

Among the emerging strategies to reduce methane emissions from the dairy and livestock sector, there are few that are commercially available, cost effective, and scientifically proven. Anaerobic digesters capture methane that would otherwise be emitted to the atmosphere from open anaerobic lagoons, the most common form of manure management in California. The increasing adoption of anaerobic digesters has significantly reduced methane emissions from manure management in California.

This report documents how a new class of remote sensing technology could be used to support additional mitigation of methane emissions by identifying unintended methane releases from digesters and working with operators to facilitate expedient repairs of leaks. Recent advancements in remote sensing have demonstrated the capability of imaging spectrometers (known as "plume imagers") to survey broad areas and identify methane emissions from large, localized sources including certain emissions from dairy and livestock operations. These technologies have relatively high spatial resolution and can detect methane emissions from discrete sources, supporting direct mitigation.

From 2016 to 2018, CARB partnered with the California Energy Commission and the National Aeronautics and Space Administration Jet Propulsion Laboratory (NASA-JPL) to conduct a statewide airborne methane survey, known as the California Methane Survey. In follow-up mitigation studies, CARB partnered with the University of Arizona in 2020 and Carbon Mapper in 2021 and 2023 to perform similar plume imaging flights over select regions of California. In these mitigation studies, operators were notified of the plume findings and were asked to investigate and report their findings on the emissions sources, causes, and whether the plume was able to be repaired. This report analyzes methane plumes found at dairies during these studies and presents two key takeaways: 1) methane emissions from dairies and other livestock operations are mostly diffuse and may not be detectable using plume imagers and 2) when plumes are detected at dairy and livestock operations with digesters, coordination with digester operators can help mitigate unintended methane digester releases.

Although methane plumes are occasionally observed at dairies with digesters, the presence of a plume should not be interpreted as evidence that digesters are ineffective. Multiple studies have shown that field measurements support the accuracy of the methane emission factors used by CARB to model methane emissions from the dairy and livestock sector. (Amini et al., 2022; Arndt et al., 2022). Observational evidence indicates that digesters reduce methane emissions from dairies by 75% (Rodriguez et al., 2025). While digesters successfully capture most manure-related methane emissions, digester infrastructure captures and pressurizes methane gas, meaning that any venting or leaks that do occur are more detectable by plume imagers compared to the more diffuse manure emissions from dairies without digesters. Furthermore, while plume imagers are useful for detecting methane plumes, single plume detections are not sufficient for estimating long-term methane emissions. Plume detections are only single snapshot-in-time measurements of emissions, while dairy methane emissions are known to vary diurnally, daily, and seasonally depending on environmental conditions and management factors.

Following the June 2023 flight campaign, CARB notified digester operators of digester related plumes detected at dairy and livestock operations and biomethane production facilities participating in the Low Carbon Fuel Standard (LCFS) program. As part of the notification process, CARB requested that the digester operators investigate to identify the source and potential cause of the emissions, and to make repairs where feasible. This resulted in 21 "incidence reports" sent to operators of 19 facilities, including at 17 dairy operations and 2 biomethane upgrading facilities. In one quarter (5) of the cases, the operator stated that the plume was a result of normal operations, such as intentional venting of excess gas, which is permitted by the local air district as an alternative to flaring. Three incidences were reportedly caused by a broken or missing component and were able to be repaired. Two incidences were associated with a short-term event such as maintenance or testing. Five incidences could not be identified by the operator upon conducting on-the-ground leak monitoring. For the remaining six incidences, the operator opted not to perform an inspection, but suggested that the location of the plumes did not appear to be associated with the digester or related infrastructure based on the plume images provided. The remaining two were from a gas cleanup operation.

This report indicates that methane plumes are occasionally detected at dairy and livestock operations, including those with digesters. At dairies with digesters, these plumes can be due to process emissions, unintentional leaks, or from activities that are not related to the digester and associated infrastructure. This highlights that while plume imaging has limitations in estimating overall dairy emissions, it has value in detecting leaks from discrete sources, which can support additional methane mitigation at digesters. The California Satellite Methane Project (CalSMP) provides regular observations of California dairy and livestock operations similar to those of the airborne campaigns. Combined with a rapid notification program, this information will both enhance CARB's understanding of emissions sources, and facilitate operator efforts to reduce methane emissions.

Introduction

It is critical to reduce emissions of short-lived greenhouse gases to reduce impacts from climate change (IPCC 2014; Saunois et al., 2016). Reducing methane, a potent, short-lived climate pollutant, is a priority in California's climate strategy. Methane is 11 percent of the greenhouse gases included in the AB 32 Greenhouse Gas Inventory (CARB GHG Emission Inventory Data). As depicted in Figure 1, the dairy and livestock sector is California's largest source of methane emissions, contributing just over half of statewide methane emissions (*Current California GHG Emission Inventory Data*; Marklein et al., 2021). Dairy and livestock methane emissions come from two primary sources: manure management and enteric fermentation (a digestive process that occurs in ruminant animals such as cattle, sheep, and goats). Methane emissions from enteric fermentation act as a diffuse source, and emissions from manure management may act as a diffuse or as a point source (Marklein et al., 2021).

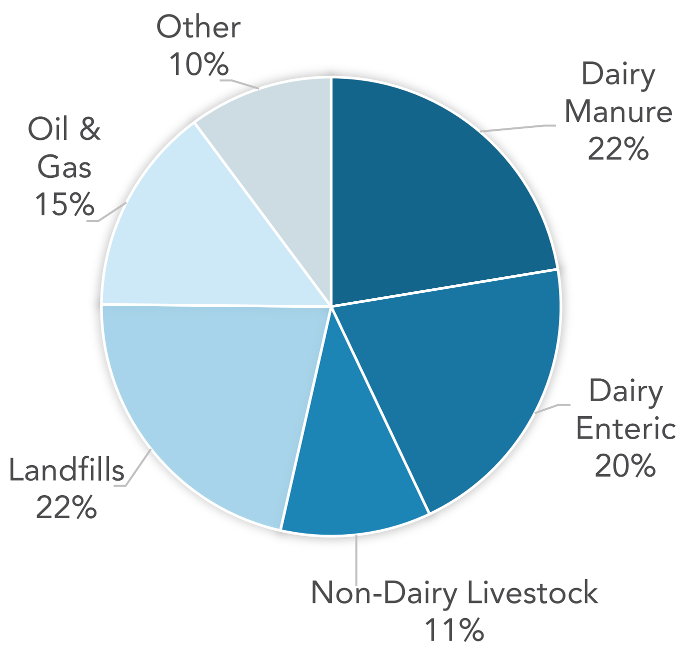

Figure 1. 2022 Methane Emissions in California by Source. Total 2022 methane emissions were 36.3 million metric tons carbon dioxide equivalent (MMTCO$_2$e). California AB 32 GHG Inventory 2000-2022 (2024 Edition)

Liquid manure management systems are the most common form of manure management in California. Liquid manure management involves flushing of dairy manure from animal housing to one or more anaerobic manure treatment and storage lagoons. Lagoon manure treatment and storage systems facilitate anaerobic (i.e., low-oxygen) conditions where bacteria break down manure and produce biogas. Biogas is primarily composed of methane, carbon dioxide, and nitrogen, with trace amounts of other compounds including ammonia and hydrogen sulfide. Biogas produced during this process is either emitted to the atmosphere from an open lagoon or captured using an anaerobic digester. While there are a variety of digester types, covered lagoon digesters are the predominant type used in California, especially in the San Joaquin Valley where most of the State's dairies are located.

To meet the 2030 target of reducing dairy and livestock sector methane emissions 40% below 2013 levels pursuant to SB 1383, the State has implemented strategies and actions from the *Short-Lived Climate Pollutant Emissions Reduction Strategy* for more than a decade. These strategies include providing incentives and technical assistance, and funding or conducting research and monitoring for methane emissions reduction projects at dairy and livestock operations. The State provides grants to implement alternative manure management practices that avoid methane generation by increasing dry manure management, and a variety of incentive-based programs to support the installation of anaerobic digesters. Anaerobic digesters are engineered systems designed to enclose dairy manure, which can help protect local air and water quality, and capture methane emissions from the decomposing manure (Jiang et al., 2024; Vergote et al., 2019; Miranda et al., 2015; Maranon et al., 2011). The captured methane can be put to a variety of beneficial uses including generation of electricity or hydrogen, or conversion to renewable natural gas, which can be used in sectors that are challenging to decarbonize. Currently, anaerobic digesters are the most effective technology for reducing methane emissions from individual dairies (Rodriguez et al., 2025).

A novel class of remote sensing methane plume imagers is a promising new technology for observing methane emissions rapidly across large regions (Thompson et al., 2015). This technology is best-suited for detecting methane "plumes", or areas of extremely high concentrations in the immediate vicinity of a point-like source. While this technology is not capable of detecting all methane emission sources and generally does not detect emissions from sources that are weak or diffuse, it has promise to support California's methane reduction targets by supporting the mitigation of larger point-source emissions.

Methane emissions from dairy and livestock operations include both point-source emissions that could be detected by plume imagers, and more diffuse sources that are less likely to be detected by plume imagers. Though the configuration of California dairy and livestock operations can vary significantly, Figure 2 provides an annotated illustration of a California dairy operation utilizing liquid manure management and an anaerobic digester. The figure identifies the potential methane emission sources and areas where methane emissions are more likely to behave as diffuse sources, and where emissions might behave more like a point source. Examples of diffuse emissions from dairies may include enteric fermentation emissions that appear from animal housing (e.g. free stall barns and open lot corrals) or areas with aerobic manure storage (e.g., drying or compost piles). However, certain meteorological and/or topographical conditions may promote "pooling" of methane from these sources into sufficiently high concentrations to be detectable. Anaerobic manure lagoons are typically diffuse sources, but can sometimes act as a point source if the top layer "crust" of the lagoon is disturbed (e.g., by weather effects or waste management processes such as effluent flowing into the lagoon, or agitation prior to land application), releasing large and detectable methane at a localized area. In addition to manure management, facilities with digesters employ various gas management components (e.g., pipes, gaskets, and compressors) that can be potential emissions sources. Biogas treatment may involve a variety of operations depending on the use of the biogas, such as conditioning, upgrading, and pipeline injection. Biogas conditioning means the removal of impurities such as water and hydrogen sulfide. Biogas upgrading involves the removal of carbon dioxide to produce nearly pure biomethane that can be injected into the fossil natural gas pipeline.

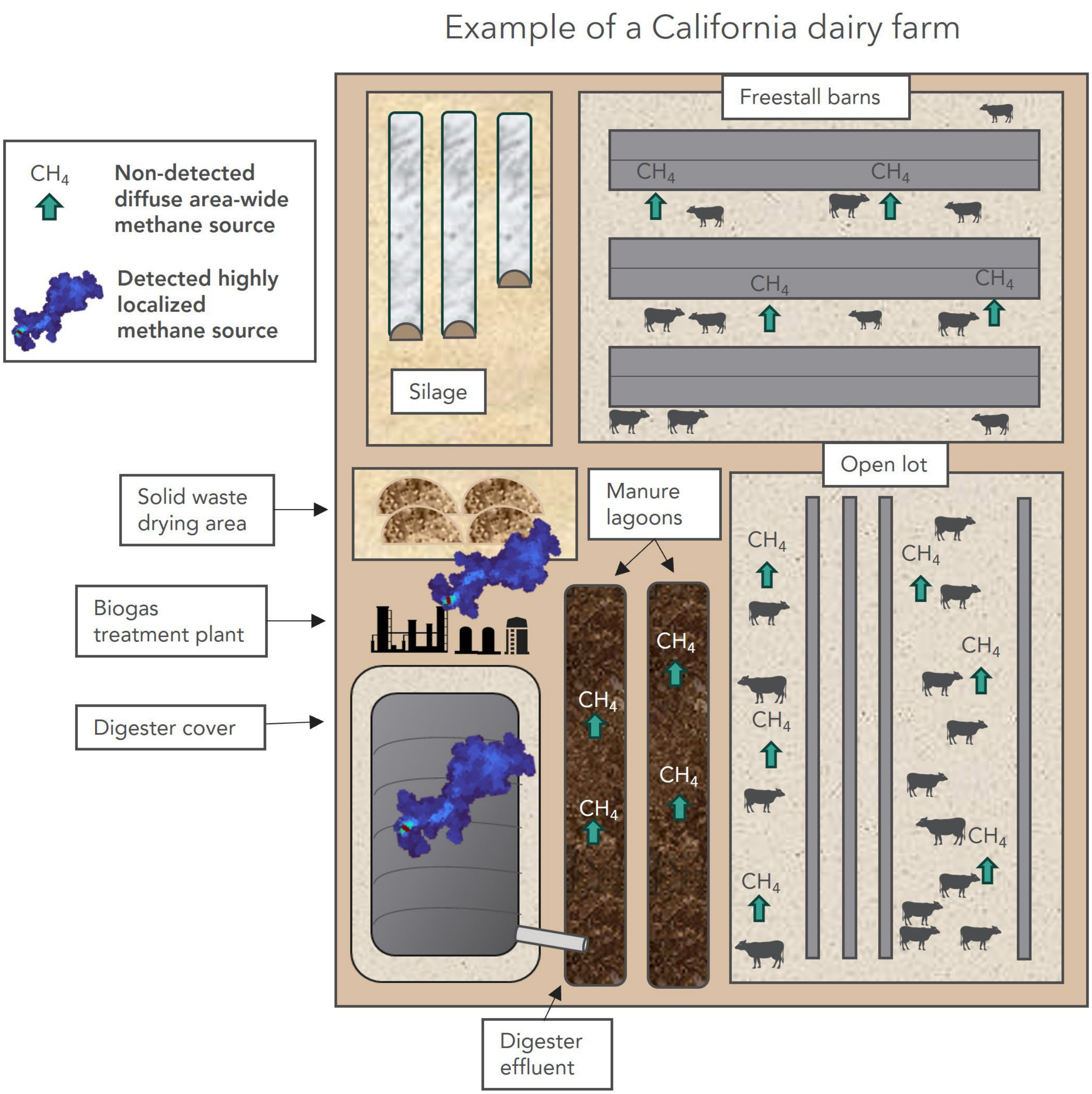

Figure 2. Annotated illustration of a dairy operation utilizing an anaerobic digester and open lagoon manure management. Diffuse area wide sources are shown with an arrow. Highly localized sources are indicated with a colorful plume image.

CARB has invested in plume imagers at multiple levels to evaluate their effectiveness and limitations, including the *California Methane Survey (2016-2018)*, and *follow up studies* with University of Arizona (2020) and Carbon Mapper in 2021 and 2023, each of which identified plumes at California dairy and livestock operations. Additionally, the State of California has allocated $100 million to purchase plume imaging satellite data through a competitive bid known as the Satellite Data Purchase Project, which has enabled routine satellite observations of potential methane sources throughout California, starting Summer 2025.

Observations from the 2016 – 2023 airborne campaigns have shown that methane plumes are sometimes found at California dairies. Findings from on-the-ground monitoring performed by digester operators during the 2023 flight campaign provides context on the sources of these emissions. This report summarizes findings from these efforts and discusses the implications for mitigating methane emissions in the dairy and livestock sector. Going forward, plume detections and associated findings from on-the-ground monitoring performed by digester operators will be critical in developing a better understanding of the types of emissions and potential mitigation strategies.

Methodology

This report summarizes data made available from the non-profit entity Carbon Mapper on *their data portal*. For this analysis, all published airborne plumes available as of July 2, 2024, on Carbon Mapper's data portal were downloaded, including data from flights not associated with the California Methane Survey and the 2020-2023 flights described in the introduction to this report. Figure 3 shows the location of plumes found at dairy and livestock operations in California between 2016 and 2024, color-coded by the year of observation.

Dairy and Digester Locations

To identify the operator of a facility where a plume was detected for notification purposes, spatial information was utilized from CARB's *California Dairy & Livestock Database* (CADD v1.0.0). CADD maintains a record of locations and facility-level cattle population and digester information for California dairy and livestock operations from 2012 to 2022. In CADD, the location of a dairy farm is reported as spatial coordinates that may fall anywhere on the dairy farm. The database was further expanded by using visible satellite imagery to map the outlines of digester covers and facility boundaries. The Low Carbon Fuel Standard (LCFS) *list of certified pathways* was used to identify the digester operator and determine whether a facility had a newly constructed digester that was not included in CADD.

For CARB-funded flights, Carbon Mapper generated and transferred plume images to CARB, usually within 24 to 72 hours after each flight. Plumes underwent their first quality control (QC) check, and plume images that were affected by signal processing anomalies (retrieval artifacts) were flagged as potential false positives. CARB's QC results were compared with Carbon Mapper's QC results, and some plume images were removed if they were determined to be likely false positives or were otherwise of low quality and unfit to be shared with operators.

Each plume image that met the QC requirements was assigned to a unique incidence number. If a plume detection was determined to be from the same point of origin as a prior detection, it was assigned to the same incidence ID. To identify the likely facility responsible for the plume, CARB's internal Plume Tracker database and graphical interface were developed. Plume metadata are automatically downloaded to the database from Carbon Mapper's portal, and the Plume Tracker interface allows analysts to add additional plume metadata by assigning source infrastructure information and event groupings. Plume Tracker was used to perform a supervised nearest-neighbor match based on known infrastructure data, such as Vista-CA and parcel information.

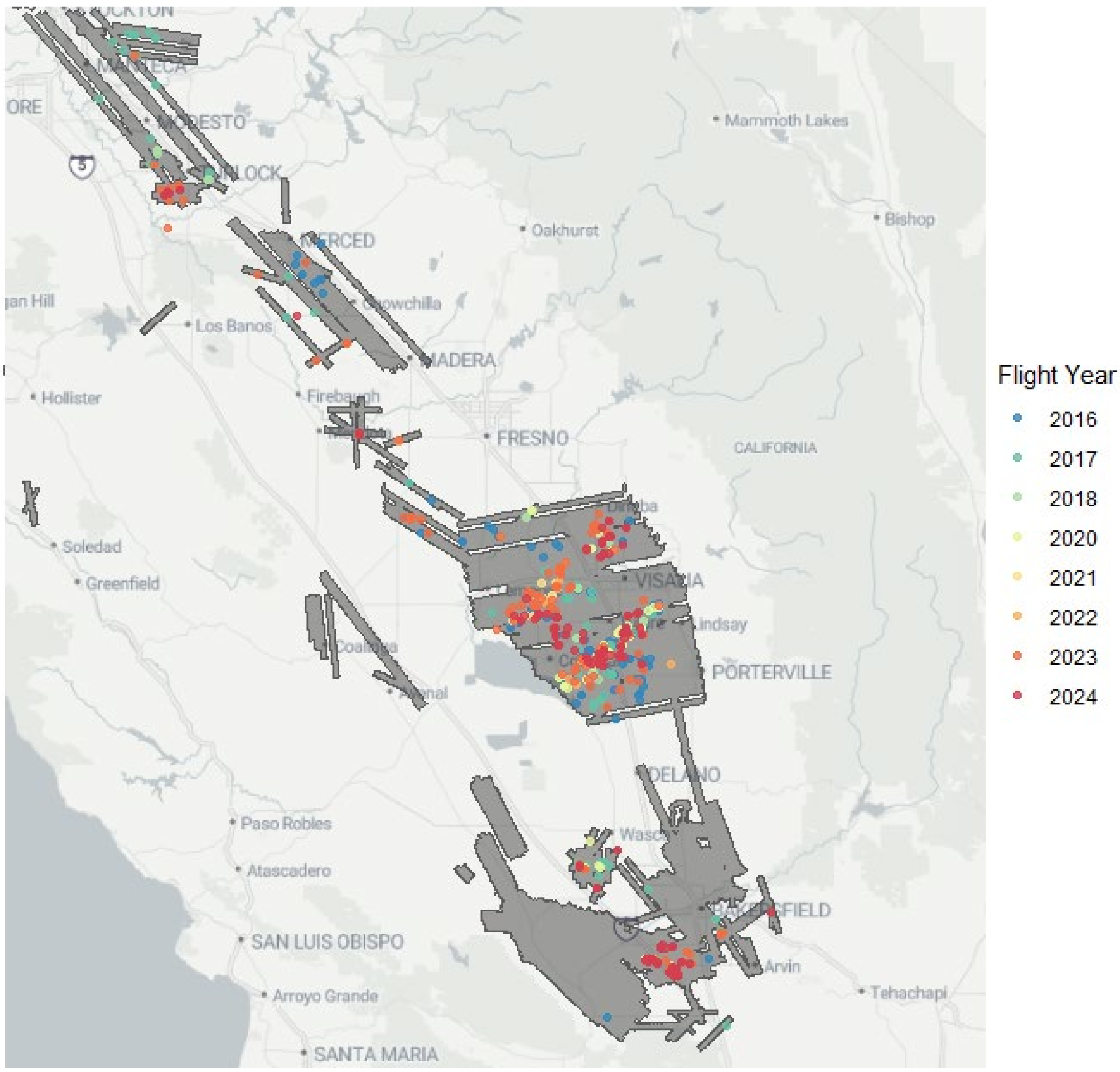

Figure 3. Map of areas overflown in California between 2016 and 2024 (shaded in grey) and the locations of methane plume detections at dairy and livestock operations, color-coded by the flight year.

Sharing Plume Images with Digester Operators

Plume information from the June 2023 flight campaign was shared with operators from the oil & gas sector, landfills, and dairies with digesters. CARB prioritized notifications to operations with digesters because these facilities are more likely to be able to repair leaks. In addition, the potential loss of economic value resulting from an unintentional loss of the biomethane may provide a monetary incentive for operators to expedite repairs. Unlike the oil & gas sector and landfills, which are subject to state regulations intended to minimize methane and other pollutant emissions, there are currently no requirements to control the diffuse methane sources common to dairy and livestock operations.

The plume images shared with operators were limited to plumes that appeared to originate from manure management practices, and excluded any that appeared to originate from enteric fermentation-related sources. A sample of the email sent to operators is available in Figure A1 of the Appendix. Operators were requested to conduct a voluntary site investigation to identify and repair any leaking equipment and provide information from their investigation back to CARB.

Results

Examples of Plume Observations

Methane plumes were observed over different parts of dairy and livestock operations. Figure 4 provides example images of plumes originating from various locations, including plumes that appear to originate from a digester biogas treatment plant, manure lagoons, and animal housing. The colors in each plume image indicate the methane concentration: red, orange, and yellow signify higher concentrations, while blue and purple denote the lowest concentrations detectable by the plume imager. Figure 4 (a) shows a highly localized source with the red color indicating the highest concentrations at the origin of the plume. Figure 4 (b), (d), and (f) show larger but more diffuse methane plumes. Figure 4 (b) also shows how a water body, in this case a manure lagoon, can interfere with plume detection, which may lead to an omission or segmentation of the plume image. Figure 4 (c) and (e) show examples of smaller, less diffuse plumes. Plume size and shape can vary depending on several factors including the type of source, emission rate, local meteorology, as well as any interference from the surface background.

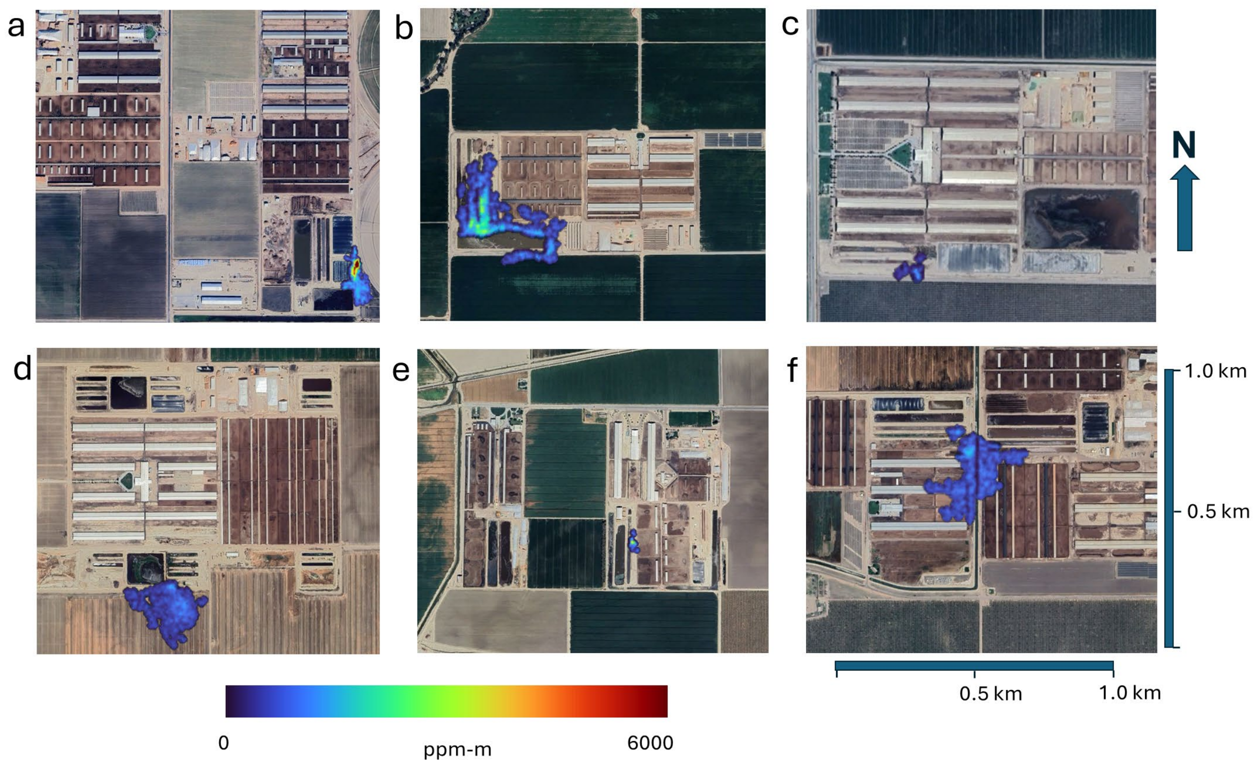

Figure 4. Example plume images found at California dairy and livestock operations. These plume images are overlaid onto a satellite image of the same area, which helps identify infrastructure that may exist near the plume origin. Images shown include plumes that appear to originate from dairy digesters (a, b), biogas treatment plant (c), manure lagoons (d, e), and animal housing (f). The colors in each plume represent relative methane concentrations, with red representing the highest concentrations and purple the lowest.

Flight Campaign Summary: 2016 - 2024

The data presented in this section is based on the evaluation of all airborne plume data available on the Carbon Mapper data portal, including flights not funded by or associated with CARB. A summary of plumes attributed to the dairy and livestock sector from this dataset is shown in Table 1. Dairies were overflown on 98 flight days during this period. In total, 4,240 relevant observations were collected (including multiple repeat flyovers of some facilities) and 879 plumes were found at dairy and livestock operations, meaning plumes were detected during about 20% of observations. Of these detections, 209 plumes were found at facilities that had a digester installed at the time of observation, 43 of which appeared to originate from a dairy digester. Notably, some of the digesters were likely under construction during this period and therefore may not be representative of emissions once digesters are fully functional. Improved evaluation of the occurrence of plumes at operational digesters will be possible once regular observations are made with satellites.

Table 1. Summary of published livestock sector plumes observed between 2016 and 2024.

Year	Total flight days	Number of livestock facility observations	Number of plumes detected[1]	Number of plumes found at facilities with digesters[2]	Number of plumes appearing to originate from digesters [3]
2016	14	1048	134	7	3
2017	24	736	186	19	8
2018	5	179	69	5	0
2020	27	778	188	28	4
2021	6	107	27	15	2
2022	4	82	17	10	1
2023	11	615	91	36	8
2024	7	695	167	86	17
Grand Total	**98**	**4,240**	**879**	**206**	**43**

[1] Refers to plumes found anywhere on any dairy and livestock operation in California.
[2] Refers to plumes found anywhere on the property of a dairy and livestock operation that had a digester at the time of overflight.
[3] Refers to plumes that appeared to originate from a digester.

Case Study: June 2023 Correspondence with Digester Operators

The previous section summarized aggregate statistics of all available Carbon Mapper data from 2016 to the most recent flights in 2024. This section describes results from the June 2023 flyover campaign. This was the first time that digester operators were notified of plumes detected over properties they service. CARB sent notifications to the digester operator a few months after the plumes were detected.

On October 27, 2023, CARB staff notified two digester operators of all plumes identified at their dairy digester sites during the June 2023 aerial surveys. Both companies specialize in the development and operation of dairy manure anaerobic digesters and operate multiple dairy digesters across California. The first digester operator replied on December 4, 2023, with a summary of their findings from on-the-ground leak monitoring, suspected causes, and corrective actions taken. These results are discussed in this report, and a summary table is provided in the Appendix. The second digester operator replied via email on November 14, 2023, providing suspected causes based on a review of the plume images provided by CARB, but opted not to conduct on-site leak monitoring. As such, information from their correspondence is not included in this report.

Table 2 provides a summary of dairy and livestock sector plume detections from the June 2023 campaign. The first column refers to plumes that met the initial CARB QC requirements: these plumes were determined to have minimal signal processing anomalies. The second column indicates the number of unique sources and the third column indicates the number of facilities responsible for those unique incidences. It should be noted that multiple distinct sources may be detected on the same property, as evidenced by the difference between the second and third columns.

Table 2. Dairy and livestock sector plumes, incidences, and facility statistics from June 2023 airborne campaign.

Number of plumes	Number of sources	Number of facilities
91	56	49

[1] *Includes all plumes found at any dairy and livestock facilities and biomethane upgrading facilities.*

Table 3 provides a summary of the subset of plumes that were identified as likely originating from a digester or associated infrastructure. These 37 plumes were communicated to the digester operators via 21 unique incidence reports. According to operator responses, the facilities where plumes were detected included two biogas upgrading facilities that convert biogas to biomethane.

Table 3. Plume notifications sent to digester operators in June 2023.

Number of plumes sent to digester operators	Number of incidences sent to digester operators	Number of facilities
37	21	13

Examples of Operator Correspondence from June 2023

Figure 5 provides an example of a methane plume detection and the timeline for operator notification and response. The digester operator reported that the plume was the result of either manure diverted from the digester to the adjacent lagoon, or intentional venting of biogas, because gas production exceeded the capacity of fuel cells to utilize the biogas.

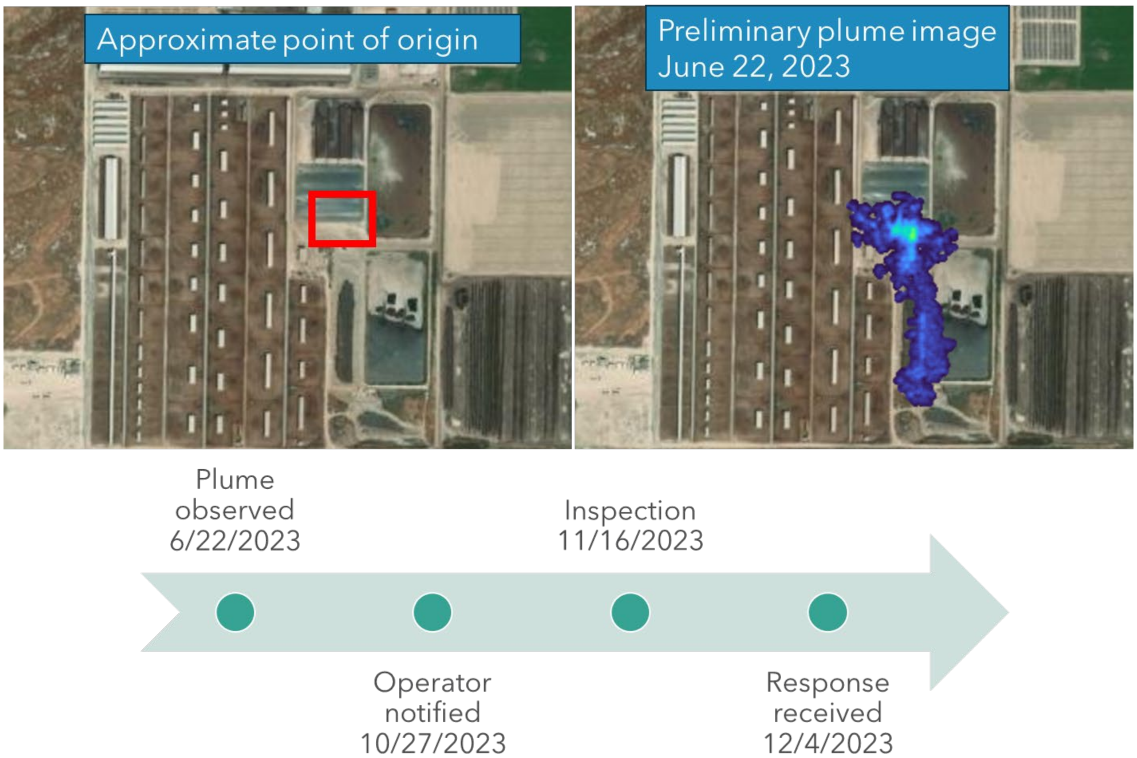

Figure 5. Plume image of methane detected during a June 22, 2023, overflight. A red polygon (left image) shows the approximate point of origin on visible satellite imagery without the plume image. The plume image is overlaid on a satellite image of the same area (right image). The colors represent methane concentrations, with red representing the highest concentrations and purple the lowest. The timeline highlights key dates.

Figure 6 provides an example of an incidence with plume detections on June 14, 16, and 26, 2023. The digester operator reported that they had inspected the facility using an infrared camera prior to receiving CARB's notification, and found missing bolts and bad gaskets on several digester mixer covers. The digester operator and had repaired the damaged components prior to the notification.

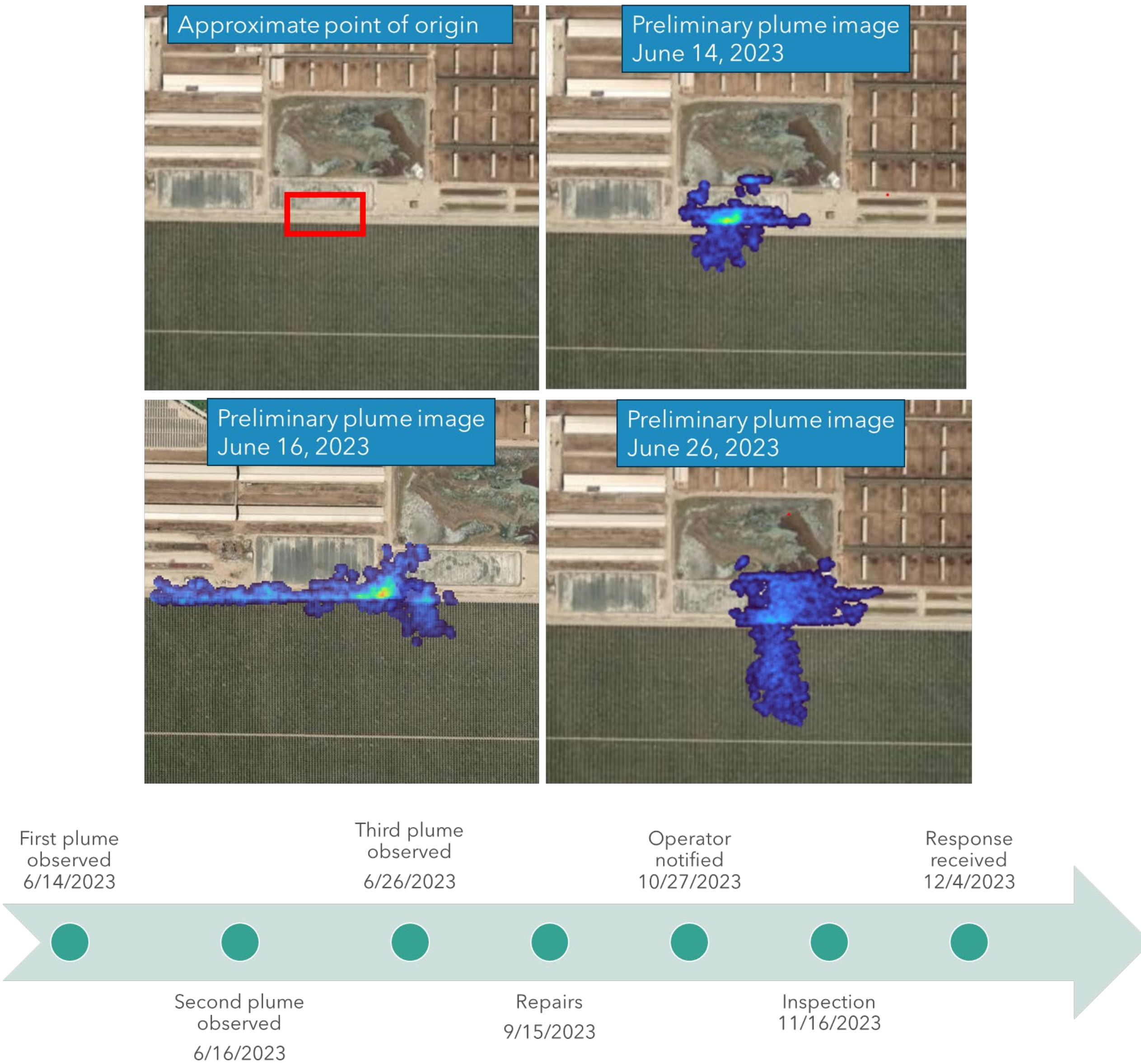

Figure 6. Image of three methane plumes detected during June 16 and 26, 2023 overflights. The plume images are overlaid on a satellite image of the same area. The timeline highlights key dates.

Figure 7 provides examples of repeated observations of multiple plumes that represent two separate incidences. The digester operator performed on-the-ground leak monitoring at both facilities and determined that for the incidence shown in part (a) the methane emissions originated from effluent that exited the digester and flowed into the adjacent storage lagoons. For the incidence shown in part (b), the operator reported that non-recoverable methane is vented as part of the biogas upgrading process. According to the operator, the membranes are expected to recover 96% of methane, however, approximately 10% of the methane content in biogas was vented during the hour that this flyover occurred, while the recovery rate for the month of June was 95%.

Figure 7. Methane plumes observed at multiple locations on adjacent facilities. At location a) two set of plumes were detected during June 16 and 26, 2023 overflights. At location b) three sets of plumes were detected during June 14, 16, and 26, 2023 overflights. The timeline highlights key dates.

June 2023 Operator Findings Statistics

Response Times

Upon notification of plume detections, the digester operator provided a single comprehensive response covering all incidences within 38 days of notification. The median time for the digester operator to perform on-the-ground monitoring was 20 days after being notified by CARB. Four incidences were resolved prior to notification.

Causes of Emissions

Figure 8 shows results from the operator response by emission type. According to the digester operator's response, all incidences were supported by on-the-ground monitoring.

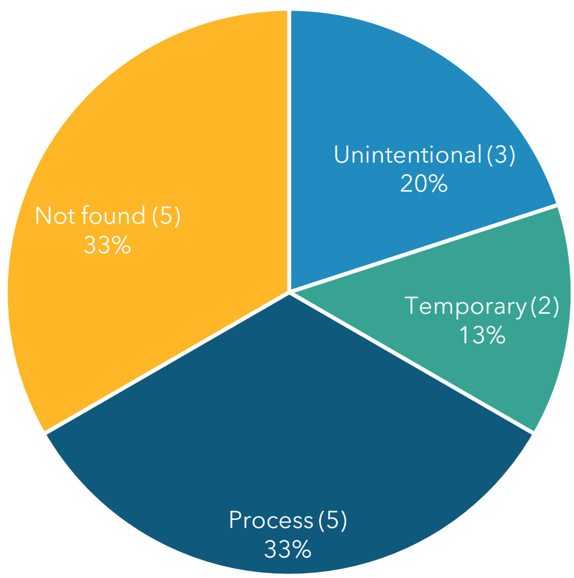

Figure 8. Incidence emission type categorization based on operator response.

A total of 15 incidences were sent to the digester operator. Five of these incidences were categorized as "not found" by the operators, meaning the operator performed on-the-ground leak monitoring and could not locate the source of the plume detection. This may be a result of the extended duration between the plume detection and operator notification (132 days, the time it took to establish the notification process this first time we sent out notifications. Future notifications sent out as part of the CalSMP program are expected be much shorter). In absence of a confirmed source, the operator speculated that two incidences may have originated from solid-liquid manure separation systems, one incidence appeared to originate from the digester effluent weir box or uncovered lagoons, one incidence potentially resulted from short-term routine venting from the conditioning plant, and one incidence appeared to originate from the facility's animal housing.

Three incidences were categorized as "unintentional" and were repaired by the digester operator. Of these, two were resolved prior to notification, and one was discovered upon monitoring and repaired shortly after. All three unintentional incidences were related to having damaged or missing components on the digester cover. One incidence had a tear in the digester cover, and the other two had a loose flange, missing bolts, or bad gaskets.

Five incidences were categorized as "process" emission types based on the digester operator's response. Three of these incidences were caused by planned and measured venting of biogas; at two facilities, non-recoverable methane is vented as part of the biogas upgrading process. The operator reported that the losses due to venting represented 3% and 5%, respectively, of the total methane captured in the month of June. One facility vents excess gas from the digester because the biogas production exceeds the capacity of its engine. This facility reported future plans to utilize the excess biogas. Another facility reported that biogas volume exceeds the engineering capacity of its fuel cells, which often necessitates venting from the conditioning plant, or diverting manure from the digester to the adjacent lagoon. Based on the location of the plume (pictured in Figure 5(a)), it appears most likely that the plume detection resulted from manure diversion on the day of the flight. Under the LCFS, emissions due to venting are required to be metered and accounted for in carbon intensity calculations. The remaining incidence was attributed to effluent exiting the digester into the digestate storage lagoon.

The remaining two incidences were categorized as "temporary." In both cases, the digester operator was able to cross reference the date and time of the plume image with known project development and/or pilot program testing at the biogas conditioning plant being performed during the flyovers. Upon completion of these projects, the operator reported that no methane venting was observed at either site.

The categorization, source, and cause of the 15 incidences described above is shown in Table 4. The "emission component" refers to the specific piece of equipment identified by the operator as the likely source of emissions, such as the digester cover, vent stack, or storage lagoon. The "emission cause" refers to the operator's description of why the emission occurred.

Emission Type	Location/Component	Cause	Number of Incidences
Unintentional	Digester cover	Damaged/broken/loose component	3
Process	Upgrading/CO2 Removal	Venting low-methane tail gas	2
	Digester vent	Gas volume exceeds engine capacity	1
	Manure Lagoon	Gas volume exceeds fuel cell capacity	1
	Effluent storage lagoon	Manure effluent exiting digester	1
Temporary	Biogas conditioning plant	Project development/Pilot testing	2

Table 4. Plume incidence classifications assigned by CARB staff based on digester operator findings from on-the-ground monitoring from 2023 airborne campaign.

Discussion

Plume Detection, Mitigation, and Operator Findings

Plume imaging technology has been used to survey methane emissions from California dairies and livestock operations since 2016. Plume detections at dairies are relatively infrequent, with over 80% of overflights observing no plumes. The low frequency of plume detection at dairies likely reflects the diffuse nature of methane emissions across dairy facilities as well as methane reductions from state-led methane mitigation measures, including increased use of alternative manure management practices.

Currently, anaerobic digesters are the most effective technology for reducing methane emissions from manure (El Mashad et al., 2023; Miranda et la., 2015; Maranon et al., 2011). Field measurements in California indicate that anaerobic digesters substantially reduce methane emissions from dairy manure management - Rodriguez et al. (2025) reported that digesters lower emissions from individual dairies by about 75% compared to anaerobic lagoons, consistent with reductions expected in inventory emission factors (from ~8.3 to ~2.1 $MTCO_{2e}$ per cow annually)[1]. Similar reductions have been reported from digesters in non-California settings (e.g. Vergote et al., 2019). The baseline lagoon emission factors against which these reductions are measured are supported by extensive California field studies (Amini et al., 2022; Schulze et al., 2023; Arndt et al., 2018), which show CARB inventory values align well with observed emissions. As shown in figure 9, the *CARB Greenhouse Gas Inventory* data shows a declining trend in methane emissions from dairy and livestock manure management over the past decade. From 2013 to 2022, emissions from dairy manure management were reduced by 2.1 MMTCO2e. Approximately 1.6 MMTCO2e, or 75%, of these reductions are due to the addition of nearly 100 anaerobic digesters, with the remainder due to a slight decrease in the statewide cow population.

Although plume detections at dairies are relatively rare, correspondence with dairy and digester operators indicates that they represent a mix of process-related emissions and leaks, with a variety of infrastructure types and repair mechanisms. For example, sharing a subset of detections from the June 2023 flight campaign led to on-site leak monitoring, corrective actions, and new insights into emission sources and causes. Regularly providing detection results to operators can help build a more representative picture of methane emissions at dairies and digesters and support ongoing mitigation. Increasing the frequency of observations combined with low-latency notifications and rapid operator engagement would enable more timely identification and repair of unintentional emissions.

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[1] *California GHG Inventory (2024 edition)*

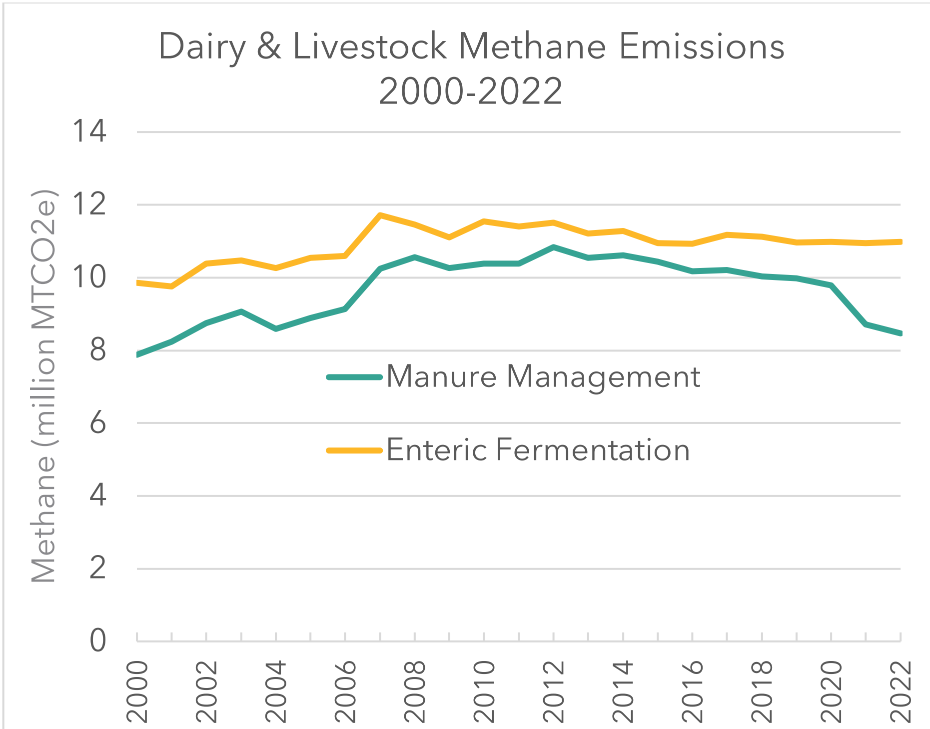

Figure 9. Manure management and enteric fermentation methane emissions from the dairy and livestock sector from 2000-2022 based on data from California GHG Inventory (2024 edition).

Limitations of Plume Imaging Technology

Flight campaigns have provided a valuable research opportunity for understanding the potential and limitations of plume imaging technology in methane mitigation. Methane emissions from dairy and livestock operations tend to act as diffuse area-wide sources which are often undetectable by plume imaging technology. While digesters are effective in reducing methane emissions, leaks from biogas-associated infrastructure are more likely to be detectable by plume imagers than the more diffuse manure emissions from dairies without digesters or from enteric emissions over animal housing.

Plume imaging remote sensing technology is useful for detecting methane leaks over extensive regions, including areas that are difficult to access on the ground, and accessing plume images often within hours of observation, supporting expedient mitigation actions where feasible. However, there are limitations to using this data to characterize facility-level emissions. Although it is possible to estimate emissions rates from single plume images, the presence of retrieval artifacts and decisions about plume segmentation result in uncertain quantification of the source, especially at complex facilities with varied terrain and infrastructure.

Given the uncertainty in estimating emission rates, CARB does not provide emission rate data to operators and advises against relying on plume observations as accurate measures of facility-level emissions. Plume images are single snapshot-in-time measurements. Dairy and livestock emissions, however, have diurnal, seasonal, and annual variability due to a variety of environmental and management factors. This makes it challenging to use plume images to estimate annual emissions. In summary, neither the presence of plumes nor their estimated emission rates are sufficient tools to estimate methane emissions from dairies, nor should they be used to imply the effectiveness of anaerobic digesters.

Future Efforts

For over a decade, the State has pursued a range of strategies to drive progress toward the 2030 goal of reducing methane emissions both statewide and within the dairy and livestock sector by 40% below 2013 levels. These efforts have included offering incentives, providing technical assistance, and investing in research and monitoring to advance methane reduction projects at dairy and livestock operations. Incentives have included participation in CARB's market-based climate programs, the LCFS and Cap-and-Trade Offset Protocol for Livestock Projects; grants administered by the California Department of Food and Agriculture, including the Dairy Digester Research and Development Program (DDRDP), Alternative Manure Management Program (AMMP), and Dairy Plus Program. These efforts, together with private investments, have rapidly expanded the adoption of anaerobic digestion and alternative manure management practices in California, resulting in more than 300 dairy and livestock operations implementing some form of methane reduction strategy. As of June 2025, there were approximately 127 active dairy manure digestion projects participating in the LCFS. Plume imaging technology can help maximize methane emissions reductions achieved by public and private investments into improved manure management practices.

Satellite-based plume imaging has the potential to expand the effectiveness of the technology while providing more frequent information to support the evaluation of dairy and livestock emissions sources. The California Satellite Methane Project will provide a larger sample size of incidence notifications and operator responses. This information will improve our understanding of the different conditions for fugitive and process-based emissions at dairies and provide insights into how they can be limited by operators.

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Appendix

Example:

From: CARB LCFS Pathway Processing
Sent: Friday, October 27, 2023 12:02 PM
To: [redacted]

Subject: Notification of methane plume(s) from livestock facilities participating in LCFS
Importance: High

Hello [redacted],

This email is to notify you that the California Air Resources Board has identified methane plumes originating from the facilities listed below. Images of the plumes are attached. As background on this effort, between June 12-28, 2023, CARB and its research partners conducted an airborne research survey aimed at detecting individual methane plumes from dairy and livestock, oil and gas, and landfill operations in California. The flights included surveys in Southern, Central, and Northern California.

Based on the review of the attached images, CARB staff suspect the plumes originate from the digester or upgrading facilities. As a participant in the Low Carbon Fuel Standard Program at CARB, we recommend that you or your designee conduct a site visit to identify and repair any leaking equipment.

We appreciate your participation and support in reducing methane emissions. As a next step, we would also appreciate any additional information you can provide in response to this notification (specifically including whether you are able to detect and repair the leaks we observed). Please let us know if you have any questions or would like to discuss more. Thank you again.

Sincerely,

LCFS staff

Figure A1. Example of the email sent to the digester operator where plumes were detected.

Summary of Incidence Notification and Responses

Table A1. Summary of digester operator findings from leak monitoring in response to notifications from June 2023 plume detections.

Incidence ID	Earliest Plume Measurement	Number of Plumes in Incidence	Incidence Emission Type	Incidence Notification Date	Incidence Inspection Date	Incidence Mitigation Date	Incidence Reply Date
192	6/14/2023	4	Temporary	10/27/2023	7/17/2023	7/17/2023	12/4/2023
193	6/14/2023	5	Unintentional	10/27/2023	9/15/2023	9/15/2023	12/4/2023
196	6/14/2023	2	Unintentional	10/27/2023	7/1/2023	7/1/2023	12/4/2023
189	6/14/2023	1	Unintentional	10/27/2023	11/16/2023	11/16/2023	12/4/2023
198	6/14/2023	4	Process	10/27/2023	11/16/2023		12/4/2023
187	6/15/2023	3	Process	10/27/2023	11/16/2023		12/4/2023
188	6/16/2023	2	Process	10/27/2023	11/16/2023		12/4/2023
190	6/16/2023	2	Not Found	10/27/2023	11/16/2023		12/4/2023
199	6/20/2023	2	Not Found	10/27/2023	11/30/2023		12/4/2023
194	6/22/2023	1	Process	10/27/2023	11/16/2023		12/4/2023
197	6/22/2023	1	Temporary	10/27/2023	9/23/2023	9/23/2023	12/4/2023
195	6/22/2023	1	Process	10/27/2023	11/16/2023		12/4/2023
191	6/26/2023	1	Not Found	10/27/2023	11/16/2023		12/4/2023
200	6/26/2023	1	Not Found	10/27/2023	11/16/2023		12/4/2023
201	6/26/2023	1	Not Found	10/27/2023	11/16/2023		12/4/2023