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Summary Report of the 2020, 2021, and 2023 Airborne Methane Plume Mapping Studies



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Common Terminology

Plume or plume detection: A single snapshot measurement, that is, a single image of a continuous span of methane originating from one location.

Source: The localized area at the origin of the plume. Examples of sources include an oil well, a section of gas pipeline, or a section of landfill cover.

Operator: The company or individual who operates the source in question.

Incidence: A collection of plumes from a single source over a defined time period which are shared between CARB and operators.

Type A Incidence: An incidence where an operator was able to locate the cause of emissions, the source of emissions was not known previously to the operator, and the emissions could be mitigated.

Type B Incidence: An incidence where the operator identified the cause of emissions, and the operator stated the emissions were part of normal operation while meeting regulatory requirements, and the emissions may persist with some regularity (e.g., a normally-functioning pressure relief valve).

Type C Incidence: An incidence where the operator identified the cause of emissions and attributed them to maintenance, construction, or some other allowable short-duration event that is not expected to persist or recur with any regularity.

Incidence Not Found: An incidence where the operator was unable to confirm the existence of a methane enhancement near the source identified by CARB.

Executive Summary

California's climate goals include cutting emissions of methane – a potent greenhouse gas with a global warming potential 25 times larger than carbon dioxide over a 100-year period - 40% below 2013 levels by 2030. A novel class of airborne remote sensing instruments, referred to as methane "plume mappers", have shown great promise for surveying broad areas and identifying large, localized sources of methane emissions. This report details efforts undertaken by CARB and its partners to demonstrate that data collected by these airborne plume mapping sensors can be used to directly support methane mitigation.

As part of this project, CARB partnered with the University of Arizona in 2020 and Carbon Mapper in 2021 and 2023 to perform plume mapping flights over select regions of California. From these flights, a total of 502 methane plumes were detected resulting in 245 correspondences with 75 different operators from two primary sectors: landfills and oil & gas facilities. A small number of plumes were also detected from other sectors, including dairy farms, composting operations, anaerobic digesters, refineries, and cogeneration plants, however, these plumes are outside the scope of this report. CARB staff identified the owner of infrastructure at each methane plume's source and shared findings directly with landfill and oil & gas operators via 245 unique "incidence reports." Operators were asked to identify the exact source of the emissions via on-the-ground surveys (if necessary), repair the source of emissions (if possible), and report their findings to CARB. Operators responded to these incidence reports 94% of the time. Oil & gas sector operators generally took action within a day or two and responded to CARB within two weeks. Landfill operators generally took action within a week or two, but many landfill operators were slow to respond and did not share their findings until months later. Based on operator responses, 40% of incidences were classified as "Type A," meaning the operator was unaware of the emissions without CARB notification, for example a broken or malfunctioning component. 12% of the incidence reports were classified as "Type B" emissions, meaning the detected methane plume(s) arose from emissions that occurred from normal operation while meeting regulatory requirements. 27% of incidences were classified as "Type C," meaning the detected plume(s) were associated with emissions occurring during short-term maintenance or construction. The remainder of the incidence reports had sources that were not found by operators after conducting an on-the-ground inspection (15%) or did not respond (6%). In all cases of "Type A" emissions, the operator was able to stop or repair the associated component and mitigate the source of emissions. *Thus, in about 40% of identified cases, this technology directly supported the mitigation of methane emissions.*

This report provides greater detail about these airborne campaigns and documents how this technology can be used to directly support methane emissions mitigation. Data by itself does not mean that mitigation will occur; in addition to the observations described here, enforceable regulations or voluntary action by operators is needed to address identified methane leaks. Also, although this technology shows great promise, its application could be greatly expanded if similar instruments were housed onboard satellites, rather than airplanes, which would enable observation of methane plumes over a broader extent of California and with greater frequency. Beyond that, satellites would collect data globally, meaning that CARB's work to develop procedures for translating these data into methane emissions mitigation actions could serve as a template for action beyond California – thus reducing global emissions of this important greenhouse gas.

Introduction

Methane is an important greenhouse gas (GHG) that is responsible for more than 25% of current global warming. According to the Intergovernmental Panel on Climate Change, methane has a global warming potential 25 times greater than CO₂ over a 100-year timespan, and 84 times greater than CO₂ over a 20-year timespan.¹ Methane's relatively short lifetime in the atmosphere (about a decade) means that emission reductions will rapidly reduce methane concentrations in the atmosphere, quickly slowing the pace of temperature rise. Inger Andersen, Under-Secretary-General of the United Nations (UN) and Executive Director of the UN Environment Programme recently stated that "Fast and ambitious methane mitigation is one of the best strategies available today to deliver immediate and long-lasting multiple benefits for climate, agriculture, human and ecosystem health." Methane emissions continue to increase globally; however, it has been a focal point at recent international climate meetings, including UN Climate Change Conference (COP) 26, where the Global Methane Pledge was launched in 2021², and at COP 28, where California kicked off the Subnational Methane Action Coalition in 2023.³

In California, methane is estimated to account for about 10% of all GHG emissions after accounting for differences in global warming potentials, and the intra-annual trend analysis from the CARB GHG inventory indicates that statewide anthropogenic methane emissions have plateaued over the past decade.⁴ Enteric fermentation and manure management, which are associated with dairies and livestock, are estimated to be responsible for over half of the State's total methane emissions. Landfills are estimated to contribute nearly 22% of the State's total methane emissions, and oil & gas (including production and distribution) is believed to contribute about 15%. CARB's short-lived climate pollutant (SLCP) reduction strategy identifies the strategies by which the State will reduce total methane emissions 40% below 2013 levels by 2030, as codified in Senate Bill 1383.⁵

Methane emissions from oil & gas and landfills are regulated by California's *Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities* (also known as the *Oil and Gas Methane Regulation*)⁶ and *Methane Emissions from Municipal Solid Waste Landfills Regulation* (also known as the *Landfill Methane Regulation*)⁷, respectively. One of the key features of these regulations is a set of practices known as leak detection and repair (LDAR). With LDAR practices, operators are required to perform quarterly or annual surveys of their equipment to search for excess methane emissions - such as from broken valves in a gas pipeline or cracks in a landfill cover - and make repairs⁶⁻⁷. These inspections are performed manually by trained staff, who survey each piece of infrastructure with handheld methane monitoring instruments. In recent years, new technologies have emerged that may boost the effectiveness of California's existing methane regulations. One of the most promising technologies is a class of instruments referred to as remote sensing "plume mappers," which enable detection of large, localized methane emissions via suborbital platforms such as airplanes. These technologies use precise measurements of sunlight reflected from Earth's surface to acquire estimates of methane concentrations but are limited by the fact that they can only detect localized methane enhancements, making them unsuitable for monitoring diffuse or low-emission sources. Nevertheless, these technologies, when mounted on suborbital platforms, enable sampling of thousands of potential sources over large spatial extents, representing a novel approach that is complementary to conventional LDAR methods. Most recently, CARB has updated the Oil and Gas Methane Regulation to require inspection and repair of leaks detected by satellite-based technology.⁸

The California Methane Survey⁹ was the first large-scale demonstration of this technology for methane plume detection, using an instrument called a hyperspectral imager. The California Methane Survey took place in two phases between 2016 and 2018, where more than 10,000 square miles were covered by airborne sampling. This survey area included nearly 300,000 potential methane-emitting pieces of infrastructure. During this survey, 564 localized emission sources were detected across the agriculture, oil & gas, and landfill sectors within the State. It is challenging to extrapolate the measured emissions rates for these 564 sources to an annual basis; however, these localized emission sources could potentially be responsible for a significant fraction of the State's total methane emissions.

Importantly, it was discovered that the distribution of emissions across these sources was not uniform – a handful of very large sources made up a disproportionate amount of the total emissions observed (the combined emissions from the top 10% of sources were equal to approximately half of all observed emissions). Many of the emissions were also found to be highly intermittent, meaning they do not occur continuously, and repeated measurements are needed to find them.

In follow-up to the California Methane Survey, three airborne field campaigns have taken place over California in 2020, 2021, and 2023, with the goal of exploring how this type of data can be used by regulatory programs to support methane emission mitigation. Specifically, the purpose of the 2020 and 2021 set of flights was to determine if the identified localized methane sources were due to leaks that could be fixed, while the 2023 campaign built upon these results and served as a 'dry run' to prepare and test internal data systems for future satellite observations. The first airborne campaign was funded by CARB (Nov 9-23, 2020) and conducted by the University of Arizona (UA). The second was funded and conducted by the non-profit Carbon Mapper¹⁰ (Nov 5-13, 2021). The third flight campaign was funded by CARB for 13 flight days (June 12-26, 2023) and by Carbon Mapper for 2 extra flight days (June 27-28, 2023). This report provides a summary of the findings from these three campaigns and aims to quantify the mitigation potential of regular hyperspectral monitoring of methane-emitting infrastructure in California.

Methodology

The methane plume mapping sensor used in these flight campaigns measures outgoing (ground-reflected) solar radiation in the visible and shortwave infrared regions of the electromagnetic spectrum. The sensor can detect light between 380 and 2,510 nanometers (nm) with 5 nm spectral resolution. This instrument has a 34° field of view and operates on high performance aircraft, allowing for efficient mapping of large regions.¹¹ For these surveys, flights were typically conducted at an altitude of 10,000 feet (~3 kilometers (km)) above ground level. At this altitude, the sensor "sees" the ground below in a 1.8 km swath and produces images with a spatial resolution of 3 meters (m). This enables detection of individual sources with emission rates as low as 5-10 kilograms of methane per hour under typical meteorological conditions. Each research flight was typically 4-5 hours in duration including transit to the target areas from the aircraft base in Bakersfield, CA. Mapping was conducted between 10:00 and 15:00 local time, during peak solar illumination. In 2020, the aircraft flew 15 days between Nov 9 – Nov 23. In 2021, the aircraft flew 8 days between Nov 5 – Nov 13. In 2023, the aircraft flew 15 days between June 12 – June 28.

Generating Plume Images

The methane plume mapping sensor acquires “level 0” raw photon counts that are processed to create calibrated radiance measurements that are orthorectified (i.e., corrected to remove distortions from terrain and sensor tilt). From here, two types of data products can be generated. The first is a ‘Quick View’ product that can be generated very quickly and may contain large amounts of image noise, but it is sufficient to locate methane plumes. The second, a ‘Fully Developed’ product, provides higher quality plume images with emission rate estimates, but takes longer to generate. The Quick View product is used to support mitigation quickly, while the Fully Developed product is used to provide high-quality plume images that are suitable to be shared with the public and estimate emissions rates at the time of the flight.

Specifically, by focusing in on specific wavelengths of light that are absorbed by methane, signal processing algorithms (matched filter) separate the signal representing large methane enhancements from the background signal. The matched filter algorithms have previously been used to identify and quantify methane enhancements in multiple field campaigns using the same type of instrument on NASA’s AVIRIS-NG in California¹²⁻¹⁴ and the Four Corners region.¹⁵ The resulting images of localized methane enhancements, referred to as plumes, were produced by UA (2020) and Carbon Mapper (2021 and 2023) and shared with CARB generally one or two days after the flight. These ‘Quick View’ plumes can be used to very quickly identify where plumes are likely located. Subsequently, UA and Carbon Mapper staff performed additional analysis to improve the quality of the image and estimate the emission rate for each plume by merging calculations of integrated methane enhancement with wind field outputs from the National Weather Service’s High Resolution Rapid Refresh Model (HRRR), producing the Fully Developed product.

Airborne Campaign Planning

In preparation for the 2020 airborne campaign, CARB reached out to infrastructure owners from oil & gas companies and landfill operators to identify voluntary participants who would ‘enroll’ their infrastructure in the program and have them surveyed. The purpose of this set of flights was to determine the cause of detected methane plumes and mitigate them, if possible. CARB coordinated a communication pathway whereby CARB would provide plume detections promptly and industry participants agreed to validate the plume’s existence and perform repairs to mitigate the leak (if feasible).

For the 2021 and 2023 campaigns, industry groups from the oil & gas and landfill sectors were informed that the flights would be happening in November 2021 and June 2023, respectively, but were not informed about specific target areas or which pieces of infrastructure would be overflown. Without first ‘enrolling’ participants, CARB was better able to test internal infrastructure databases developed to identify owners of infrastructure and industry points of contact, and gauge industry’s willingness to voluntarily take action when provided with airborne results.

Figure 1 shows the flight area covered for the 2020, 2021, and 2023 airborne campaigns. CARB staff developed the proposed areas of observation by analyzing existing emissions inventories and infrastructure databases, and by reviewing findings from previous airborne surveys focused on

methane plume detection (i.e., California Methane Survey¹²). This analysis highlighted three main regions to focus on: large landfills clustered around the Bay Area, oil fields in Kern County, and large landfills clustered around the Los Angeles metro area. The 2021 and 2023 observed areas were also influenced by the locations of facility operators who had voluntarily expressed interest in participating in the 2020 campaign.

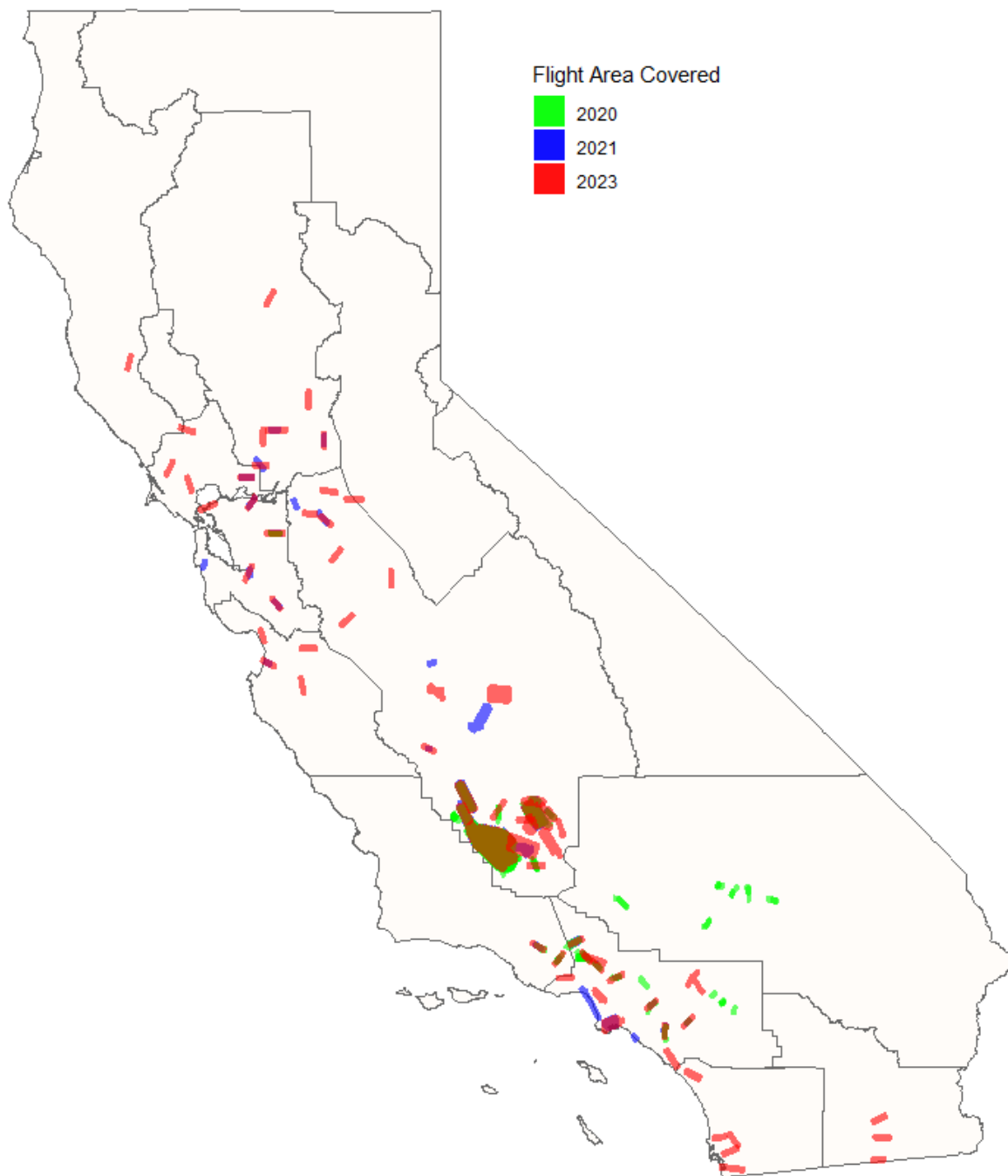


Figure 1. Air basin map of flight area covered from airborne campaigns in 2020, 2021, and 2023. Some areas were overflowed in multiple years and may appear as a mix of colors.

Terminology

The terminology used to describe the methodology and results from these campaigns is carefully chosen to avoid confusion and will be described here. “Plume” or “plume detection” refers to a single snapshot measurement, that is, a single point-in-time image of a connected region of methane concentrations that are elevated above the background concentration. Each plume detection belongs to a “source,” referring to the localized area at the origin of the plume. If multiple sources are in close proximity, their respective plumes may merge together into a single “plume complex.” If a source is sampled multiple times, it may have multiple associated plume detections. Therefore, “source” is more appropriate than “plume” when referring to situations in need of inspection or mitigation. Examples of sources include an oil well, a section of gas pipeline, or a section of landfill cover. “Operator” refers to the company or individual who operates the source in question. Operators may manage more than one source – for example, a company may operate numerous oil wells, or an operator of a single landfill (which may cover multiple square kilometers) may have multiple potential sources (emission points) on their landfill. “Incidence” refers to a collection of plumes from a single source over it’s lifecycle which are shared between CARB and operators. A diagram depicting this terminology is shown below in Figure 2. In the hypothetical example shown here, five plumes were detected, with plumes 1, 2, and 3 belonging to Source 1, and plumes 4 and 5 belonging to Source 2. Both Source 1 and Source 2 are owned by Operator X. In this example, CARB lumped plumes 1 and 2 together as “Incidence 1” because they belong to the same source and were detected during the same time period (the 2020 campaign). For Incidence 1, CARB communicated findings with Operator X. Plume 3, which was detected during the 2021 campaign, is packaged as Incidence 2 and represents a separate set of communications between CARB and Operator X.

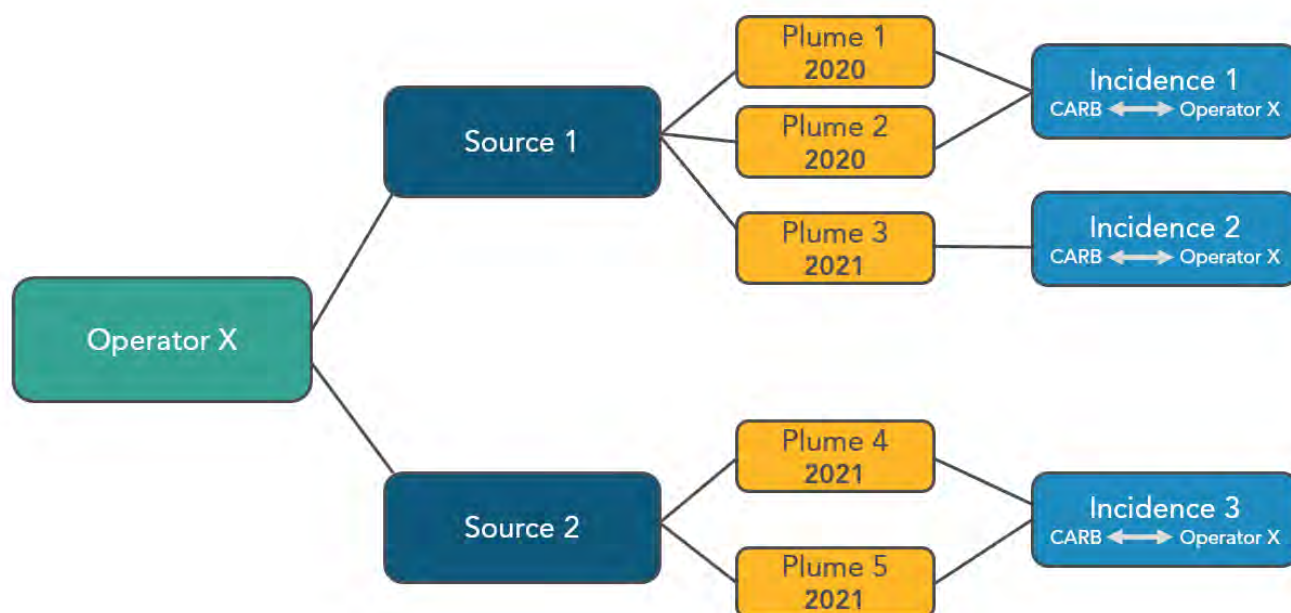


Figure 2. A hypothetical example depicting the hierarchical relationships between operator, sources, plumes, and incidences.

These communications between CARB and operators yielded results that will be expanded upon later in this report. Generally, CARB shared plume detections with operators and asked that they perform inspections on their equipment to find/validate the source of the methane emissions and fix it (if possible). Based on operators' responses, each incidence was classified in one of four ways. "Not found" refers to incidences where an operator performed an inspection but could not find or verify the source of the plume(s) shared with them. "Type A" refers to incidences where an operator was able to confirm the source of emissions, the source of emissions was not known previously to the operator, and the source of emissions could be mitigated. "Type B" refers to incidences where the operator attributed the emissions to normal operation while meeting regulatory requirements, and the emissions may persist with some regularity (e.g., a normal functioning pressure relief valve). Lastly, "Type C" refers to incidences where the operator attributed the emissions to maintenance, construction, or some other allowable short-duration event that is not expected to persist or recur with any regularity.

CARB's Data Processing: Using Plume Images to Support Methane Mitigation

The UA and Carbon Mapper generated and transferred Quick View plume images to CARB usually within 24-72 hours of each flight. Here, plumes underwent their first CARB quality control (QC) check, and plume images that were affected by signal processing anomalies (also referred to as "retrieval artifacts") were flagged as potential false positives. Suspected false positives were confirmed with UA and Carbon Mapper. Each plume was assigned to a source, which was assigned a unique Source ID. If a plume detection was determined to be from the same source as a prior detection, it was assigned the same Source ID. The next steps for determining ownership of the source differed between the 2020 and 2021/2023 flights. In 2020, CARB staff quickly determined the operator of each source since the flights and resulting plumes covered voluntary participants who had provided locations of their assets. In 2021 and 2023, CARB staff performed a nearest-neighbor spatial match to identify best candidates for operators based on infrastructure data from multiple sources, including the California Geologic Energy Management (CalGEM) WellFinder database, CARB's stationary source inventory (CEIDARS/IMPEI), and parcel data. Automated scripts were run on batches of plumes and typically took between 10 and 20 seconds per plume to produce a list of likely operator candidates. An analyst then looked at the list of candidates and manually identified the most likely operator and determined the emission sector. For sources where ownership was ambiguous (e.g., plumes that originated in an area with multiple owners/assets), the analyst identified likely owners by working with project stakeholders including other government agencies and industry trade groups.

This report only includes plume data collected from oil & gas facilities and landfills, which are regulated for methane emissions as discussed in the Introduction Section of this report. CARB staff created incidence reports for each source where ownership was determined. Occasionally, multiple plume images were needed to create an incidence report. These incidences generally were associated with plumes in complex environments with multiple owners (i.e., multiple plume images were needed to confidently assign a source to one owner) or when a plume image was weak, indistinct, or otherwise ambiguous. An overview diagram of CARB's data process for 2021 and 2023 is shown in Figure 3.

In 2020, 2021, and 2023, for incidences with high quality plume images, clear ownership, and attributed to the oil & gas and landfill sectors, CARB staff sent an email to the operator providing information on the project, images of the plume(s) overlaid on satellite maps of the infrastructure, and a request for the operator to perform an on-the-ground investigation. The typical time between CARB's initial receipt of a plume and an email being sent to an operator was 0-3 days. Adding in the time for UA and Carbon Mapper to produce and transfer the plume images to CARB, the average time between initial plume detection and email send was about 5 days. Notifications that took longer than average typically fell into one of two categories: 1) the first plume detection was ambiguous, requiring a second or third plume detection to confirm before notification, or 2) assistance was required to determine ownership of the equipment associated with the plume. A total of 25 plumes from 2021 and 2023 required additional assistance to identify an operator. CARB staff, along with external partners, were able to identify ownership of all but 11 plumes from 2021 and 2023 (belonging to seven different sources, overflowed on multiple days).

The emails sent to operators in 2021 and 2023 contained a standardized feedback form for the operator to fill out. A sample of the email is available in Figure A1 of the Appendix. In 2021, a general feedback form was sent to both oil & gas and landfill operators and a sample can be found in Figure A2. In 2023, a feedback form was created for each sector and asked for greater detailed information of the operator findings than the 2021 feedback form. A sample can be found in Figure A3 for the oil & gas sector and Figure A4 for the landfill sector. Operators returned emails to CARB to report their findings, including whether the plume source was repaired or not.

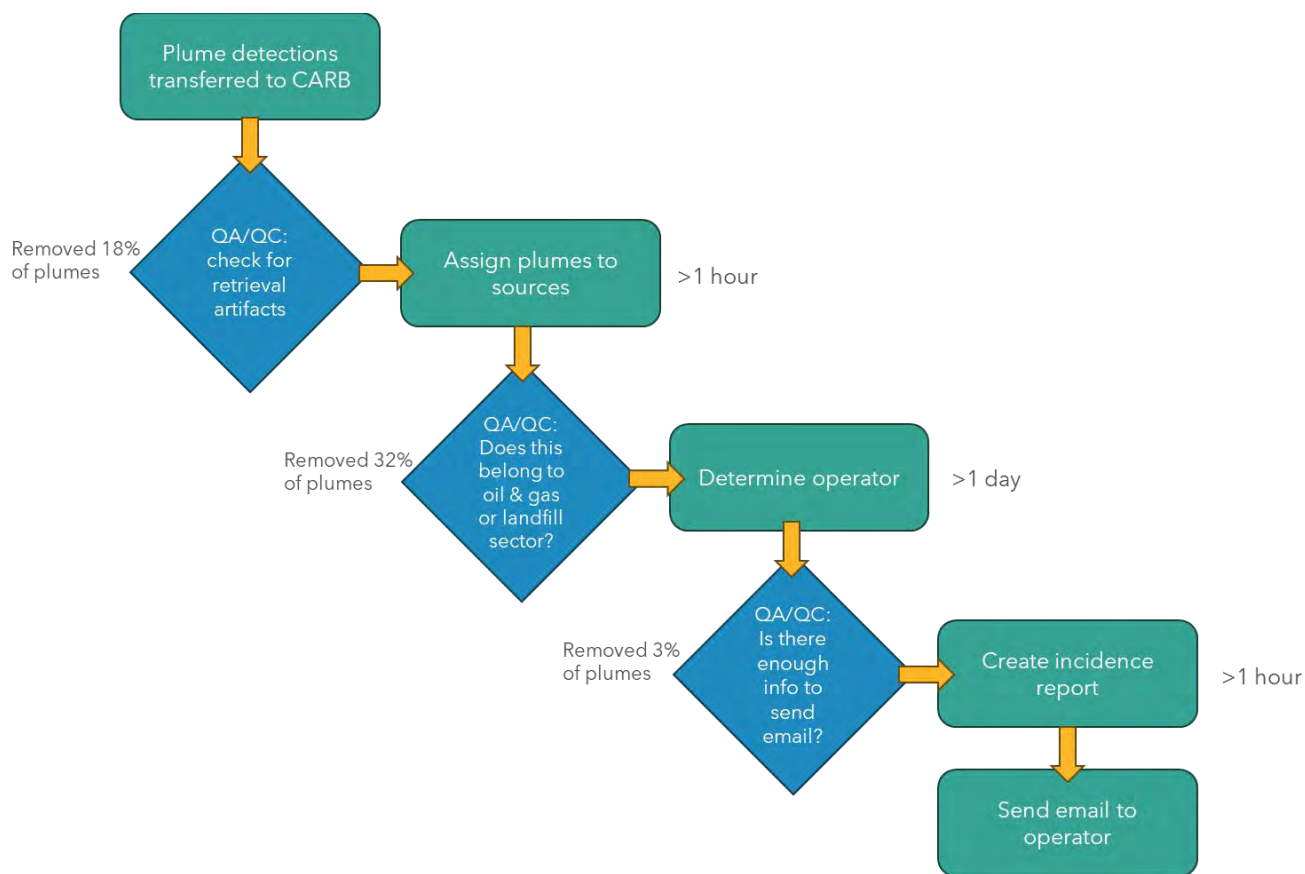


Figure 3. Visualization of CARB's data processing pipeline (from plume to email) used in 2021 and 2023.

Results

Summary Statistics from 2020, 2021, and 2023

Table 1 shows a breakdown of landfill and oil & gas plume detections, sources, operators, and incidences from the 2020, 2021, and 2023 airborne campaigns. The difference in total number of plume detections between 2020, 2021, and 2023 is likely due to several factors, including the number of flights (15 flight days in 2020 and 2023 versus 8 in 2021), voluntary participation in 2020 versus non-voluntary participation in 2021 and 2023 (see “Airborne Campaign Planning” section), different coverage areas, and different seasons surveyed (November in 2020 and 2021 versus June in 2023).

The first column of data refers to plumes that passed the initial QC process: these plumes were determined to be free from signal processing anomalies (retrieval artifacts). The second column indicates the number of unique sources where methane plumes were observed. The third column indicates the number of operators responsible for those unique sources. As described above, the 2020 campaign focused on operators who voluntarily participated. Incidental plume detections were occasionally made at assets belonging to non-participatory operators; however, CARB staff did not attempt to assign ownership to these sources, and they are not included here. Thus, the asterisk (*) serves to highlight that the slightly different procedures between 2020 and 2021/2023 are expected to yield different results. The final column in the table indicates the number of incidence reports sent by CARB to operators. Again, the asterisk (*) indicates that the 2020 numbers are the result of a slightly different procedure compared to 2021/2023.

Table 1. Plume, source, operator, and incidence statistics from the 2020, 2021, and 2023 airborne campaigns. All columns exclude plumes removed by initial QC (generally, fewer than 18% of plumes were removed by QC). In 2020, plumes were only shared with operators who volunteered to be part of the study, whereas in 2021 and 2023 plumes were shared with all identified operators.

Year	Sector	Number of Plumes that Passed QA/QC	Number of Sources	Number of Operators	Number of Incidences sent to Operators
2020	Oil & Gas	78	40	10*	32*
	Landfills	53	31	9*	30*
	<i>2020 Total</i>	<i>131</i>	<i>71</i>	<i>19*</i>	<i>62*</i>
2021	Oil & Gas	59	43	13	40
	Landfills	23	16	7	15
	<i>2021 Total</i>	<i>82</i>	<i>59</i>	<i>20</i>	<i>55</i>
2023	Oil & Gas	146	79	16	75
	Landfills	143	56	20	53
	<i>2023 Total</i>	<i>289</i>	<i>135</i>	<i>36</i>	<i>128</i>
Grand total		502	265[†]	75[†]	245[‡]

[†] Grand totals do not include duplicates; thus, these grand totals are not simply the sum of each annual total. For example, sources detected in both 2020 and 2021 would only count once towards the grand total.

* The asterisks for 2020 indicate that these numbers only include plumes found at participating operators’ facilities.

[‡]All 2021 and 2023 incidences and their outcomes are available in Table A1 and A2 in the Appendix.

Case Studies: Examples of Data in Action

Three incidences that demonstrate how these data were used to support methane mitigation from the 2021 and 2023 airborne campaigns are shown. Figure 4 shows an incidence from the oil & gas sector. In this case, the source was flown over on June 12 and 14, 2023, with both flights detecting methane plumes (the plume image from June 14 is shown). CARB staff identified the operator of this piece of equipment and sent an email notification on June 16. The operator performed an inspection with a handheld methane monitor on June 20 and determined that this was an emission of methane and that the emission source originated from a leak in a low-pressure field fuel gas line. The operator was able to repair and stop the leak on the same day (June 20). The site was flown over again on June 27 and no plume was detected. The estimated emission rate from this source was approximately 200 kg of methane per hour at the time of the flyovers (both were around noon local time). Based on the operator's response, the example shown in Figure 4 was categorized as a "Type A" incidence by CARB staff because the emissions were not previously known to the operator and were able to be mitigated.

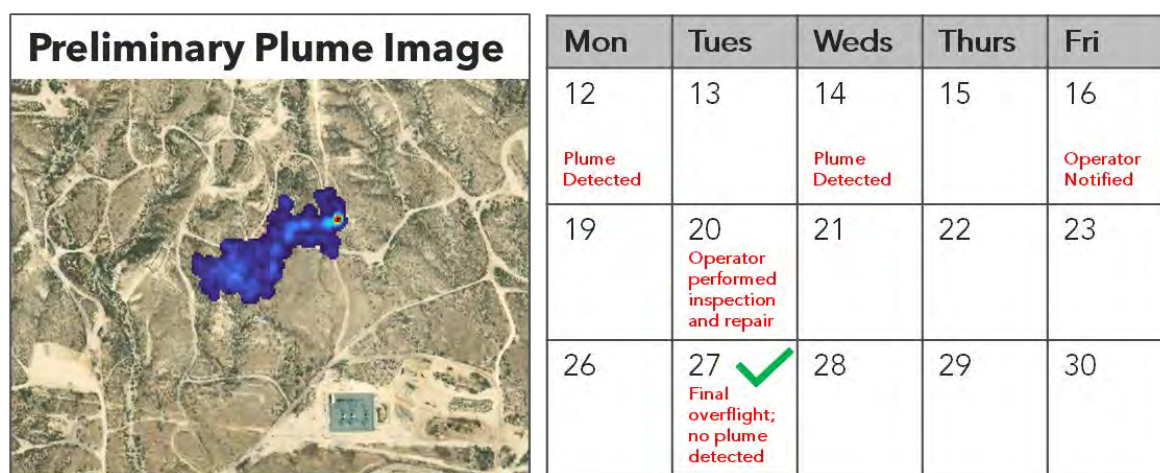


Figure 4. Methane plume data in action from June 2023. Left: A preliminary image of a methane plume detected during the second overflight on June 14. The preliminary plume image is overlaid on a satellite image of the area. The colors represent methane concentrations, with red representing the highest concentrations and purple the lowest. Right: A calendar of events associated with this incidence.

Figure 5 shows an incidence with potential plume detections on June 12, 2023. Staff identified and notified the operator of the potential methane plume detections on the morning of June 15. On June 19, the operator performed an inspection and determined that this was a methane emission, and that the emission source was an oil well that had been undergoing maintenance that involved venting of a tank that day. The site was overflown again the following day on June 20 and on June 28 with no plume detection. Based on the operator's response, the incidence shown in Figure 5 was categorized as a "Type C" incidence by CARB staff, since it was associated with a maintenance event and would likely have been resolved on the same timeline without intervention (detection and notification).

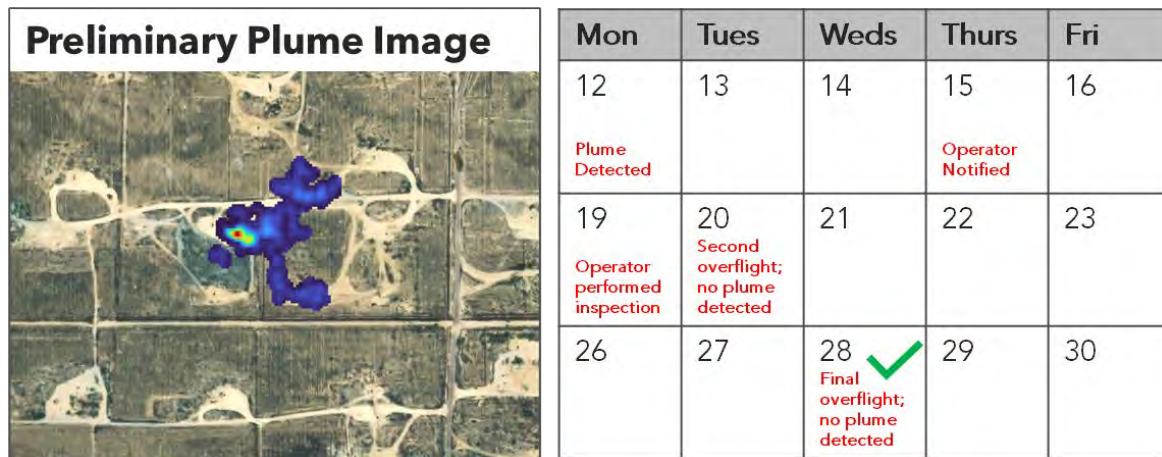


Figure 5. Methane plume data in action from June 2023. Left: A preliminary image of a methane plume detected during a June 12 overflight. The preliminary plume image is overlaid on a satellite image of the area. The colors represent methane concentrations, with red representing the highest concentrations and purple the lowest. Right: A calendar of events associated with this incidence.

Figure 6 shows an incidence with a potential methane plume detection from November 5, 2021; however, a subsequent fly over on November 8 did not detect a plume. On the morning of November 10, the operator was identified and notified of the first potential plume detection. Later that same day, the operator performed an inspection and determined that this was a methane emission, and that the emission source was a broken manway hatch on an oil storage tank. Based on the operator's response, the example shown in Figure 66 was categorized as a "Type A" emission by CARB staff. In this example, a piece of equipment was broken, but emissions occurred intermittently only if the pressure inside the tank reached a certain level. This incidence highlights an important consideration that must be recognized for future work: intermittent leaks such as this may be missed if observations are not collected at a sufficient frequency. In this example, if this site had only been overflown on November 8, this leak would not have been detected. This highlights the importance of repeated, frequent observations over target areas.

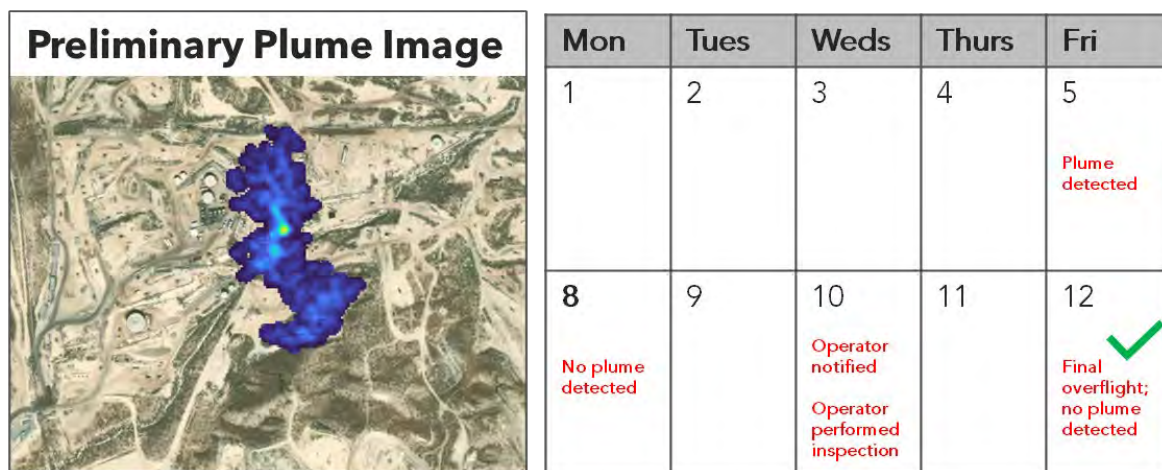


Figure 6. Methane plume data in action from November 2021. Left: A preliminary image of a methane plume detected during a November 5 overflight. The preliminary plume image is overlaid on a satellite image of the same area. The colors represent methane concentrations, with red representing the highest concentrations and purple the lowest. Right: A calendar of events associated with this incidence.

Operator Feedback Statistics

Operator Feedback: Response Times

Key action times from the 2021 and 2023 airborne campaign are shown in Table 2. This dataset is limited to 2021 and 2023 because insufficient data were recorded in 2020 to perform similar analysis. In 2020, records included plume detection dates and operator response dates, but did not include email notification dates, operator inspection dates, or emission mitigation dates.

The median total response time (i.e., from the date when the operator was first notified up to the date the operator submitted a final response to CARB) was 14 days. In general, operators in the oil & gas sector responded to incidents faster than operators in the landfill sector (median of 12 days versus 52 days). However, these medians do not convey the wide range of response times. 33 incidences (about one fifth of the total across all sectors) had total response times of one week or less. No oil & gas incidence had a total response time above 38 days, with two thirds of all oil & gas incidences having total response times of two weeks or less. The landfill sector, on the other hand, had typical response times that were much longer. Four landfill incidences (out of 68) had a total response time of less than one week, while eight sources had total response times in excess of 100 days (with three in excess of 200 days). It is unclear why such a discrepancy exists between the oil & gas and landfill sectors. In both sectors, the median time for operators to perform inspections was less than one week after being notified by CARB. Oil & gas operators voluntarily shared their findings with CARB in a shorter time than it took many landfill operators. A complete table of all incidences for 2021 and 2023, with key dates, is provided in Table A1 and A2 in the Appendix, respectively.

Table 2. Key elements of operator response times from the 2021 and 2023 airborne campaigns, in units of days. Note that "Type A" emissions accrued an additional step (mitigation), thus are highlighted in a separate bin. Note that "All Emission Types" includes "Type A" emissions, as well as "Type B", "Type C", and "not found" categories. The median number of days for each time period is given for each sector, with the minimum and maximum range given in parentheses.

Emission Type based on operator response	Time Period Description	Oil & gas Sector Response Times median days (minimum- maximum days)	Landfill Sector Response Times median days (minimum- maximum days)
All Emission Types	First plume detected by CM to CARB sends email notification to operator	4 (0 - 41)	4 (3 - 84)
	CARB sends email notification to Operator to operator performs inspection	1 (0 - 20)	4 (0 - 19)
	CARB sends email notification to Operator sends response to CARB	12 (0 - 38)	52 (4 - 227)
"Type A" Emissions Only	Operator performs inspection to Operator mitigates source of emissions	0 (0 - 25)	3 (0 - 37)
	First plume detection by CM to Operator mitigates sources of emissions	8 (1 - 36)	12 (1 - 43)
	Operator mitigates source of emissions to Operator sends response to CARB	7 (0 - 23)	21 (4 - 209)

†Excluded cases where operator performed routine inspection at the same time as flight.

‡Excluded cases that did not provide the date of initial inspection.

Operator Feedback: Incidence Outcomes

Table 3 contains results from operator feedback binned into the categories described in the Terminology section, and

Table 4 contains information about operator inspection rates. In total, 14 incidences (6% of total) were considered unresolved due to no response from the operator. 12 of the 14 unresolved incidences are from the landfill sector, and they involve seven different landfill operators. About 15% of all incidences were categorized as “not found” by operators, meaning the operator performed an on-the-ground inspection and could not locate a source of emissions in the proximity of the plume detection. These incidences where emissions were detected by remote sensing but were not found on-the-ground could arise from two possible scenarios: 1) Some sources emit intermittently (see example in Figure 6), and it is possible a source was emitting at the time of our flyover but was not emitting at the time of on-the-ground inspection, or 2) there was no emission source, and the plume image was a false positive that was not removed by our QC process.

About 12% of incidences were categorized as “Type B” emissions based on the operator’s response. Incidences in this category were mostly supported by on-the-ground inspections where the operator confirmed the source of emissions via ground inspection, and reported that it was allowable, such as a pressure relief valve on a gas storage tank.

Around one quarter of incidences were categorized as “Type C” emissions. Like “Type B” emissions, this category of emissions saw inspection rates below 100%. In many instances, the operator was able to cross reference the location and date/time of the plume image(s) with known construction or maintenance activity. Examples of incidences where the operator did not perform on-the-ground inspections but was able to determine that the source was a “Type C” emission include a landfill gas collection well temporarily taken offline for maintenance, and oil well workovers, which involve pulling/replacing hardware on an oil well.

The remaining 97 incidences – which account for 40% of the total – were categorized as “Type A” based on operators’ responses. Responses in this category were almost always supported by an on-the-ground inspection. *Importantly, every incidence of a “Type A” emission source was eventually able to be stopped or repaired by the operator.*

Qualitatively, these results indicate the following: when CARB and operators coordinated and voluntary action was initiated, more than three quarters of methane sources detected by remote sensing could be verified or attributed to a specific process or event. In both the oil & gas and landfill sectors, 40% of all incidences were categorized as “Type A” emissions and could be stopped or repaired in a timely manner. For “Type A” emission sources, the typical (median) time between when the source was first detected by airborne hyperspectral remote sensing and emission mitigation was 8 days for the oil & gas sector, and 12 days for the landfill sector.

Table 3. Incidence follow-up statistics based on operator response to emails.

				Incidence Emission Type (Based on Operator Response)			
Year	Sector	Number of Incidences sent to Operators	Did not respond	Emission Source Not found	Type "A"	Type "B"	Type "C"
2020	Oil & Gas	32	0	9	10	3	10
	Landfills	30	1	5	15	1	8
2021	Oil & Gas	40	1	5	19	5	10
	Landfills	15	2	2	7	0	4
2023	Oil & Gas	75	1	14	29	21	10
	Landfills	53	9	2	17	NA	25
Grand total		245	14 (6%)	37 (15%)	97 (40%)	30 (12%)	67 (27%)

Table 4. On-the-ground inspection rates for incidences, binned by operator response category. Entries with percentages below 100% had incidences where an operator did not perform an on-the-ground inspection but shared other information with CARB to confirm the emission source and incidence classification. An example would be a landfill operator who identifies that the plume origin was over the active face of the landfill at the time of flyover.

				Incidence Rate binned by Operator Response			
Year	Sector	Number of Incidences sent to Operators	Did not respond	Emission Source Not found	Type "A"	Type "B"	Type "C"
2020	Oil & Gas	32	NA	100%	100%	100%	70%
	Landfills	30	NA	100%	100%	100%	12%
2021	Oil & Gas	40	NA	100%	100%	80%	80%
	Landfills	15	NA	100%	100%	50%	33%
2023	Oil & Gas	75	NA	100%	100%	100%	100%
	Landfills	53	NA	100%	88%	NA	76%
Grand total		245	NA	100%	98%	97%	69%

Operator Feedback: Causes of Emissions

Oil & gas sector

In the feedback form sent to operators, CARB also requested information on the specific causes or component(s) believed to be the source of emissions. Modern oil & gas infrastructure and landfills in California feature heavily-engineered systems designed to collect and control the flow of gas (e.g., natural gas, landfill gas). A brief introduction to these systems is provided here, and additional details can be found in the Landfill Methane Regulation⁷ and Oil and Gas Methane Regulation.⁶

The oil & gas sector is far more complex than can be described here; thus, this overview will focus only on components relevant to this report. Oil & gas products, which may refer to field quality natural gas,

commercial quality natural gas, crude oil, and emulsions (gas/liquid mixes) are extracted by wells. These products are transported by pipelines (which may utilize compressor stations and gathering and boosting stations to facilitate movement) to various points, depending on the product and its intended use. Products are commonly transmitted to gas processing plants, which are used to separate natural gas from other components. Movement of product across these locations often requires pumps or compressors to establish pressure gradients. Products are often housed in tanks, which may include storage tanks and separation tanks. Some components in the oil & gas sector must vent (either continuously or intermittently) as part of normal operation. Additionally, components such as wells, tanks, and compressors may emit methane directly to the atmosphere when undergoing routine maintenance.

In 2023, the feedback form sent to operators was updated to collect information in greater detail and used a different incidence emissions categorization scheme. Due to these reasons, the results from 2023 are not directly comparable to responses collected in 2020 and 2021. Thus, results are discussed separately in the following paragraphs and a visual summary of operator responses for the oil & gas sector are shown in Figure 7 for 2020 - 2021 and Figure 8 for 2023. "Incidence Emission Type" in Figure 7 and Figure 8 uses the same high-level categories described in the previous section (i.e., Table 3).

[Operator responses from 2020 and 2021](#)

The second column in Figure 7, "incidence emission component," refers to the specific piece of equipment identified by the operator to be at the source of the emissions, such as wells, compressors, tanks, pipelines, and emission control devices. In the oil & gas sector for 2021, the eight incidences classified as "Type B" emissions were attributed to a variety of components. Identified causes of "Type B" emissions from the oil & gas sector include regular venting from tanks (3 incidences) and compressors (2 incidences). Additionally, three "Type B" incidences were attributed to emissions control devices (i.e., flares) that were tested and determined to have combustion efficiencies that meet regulatory requirements. The twenty incidences classified as "Type C" from the oil & gas sector were always associated with maintenance, most commonly on oil & gas wells (16 incidences), but occasionally on compressors (2 incidences) and tanks (2 incidences). The 29 oil & gas incidences classified as "Type A" arose from a variety of components. Tanks and pressure relief devices were the most common component for "Type A" emissions (11 incidences) and associated with broken pressure and vacuum relief valves, leaks in the tank cover or structure, and other damaged/broken equipment. Ten incidences were located at pipelines, all caused by leaks (i.e., pinholes, cracks, or other damage to the pipeline or connection valves/flanges). Three "Type A" incidences were located at compressors and associated components, and three at wells.

Categorization of 72 Oil & Gas Incidences from 2020 & 2021

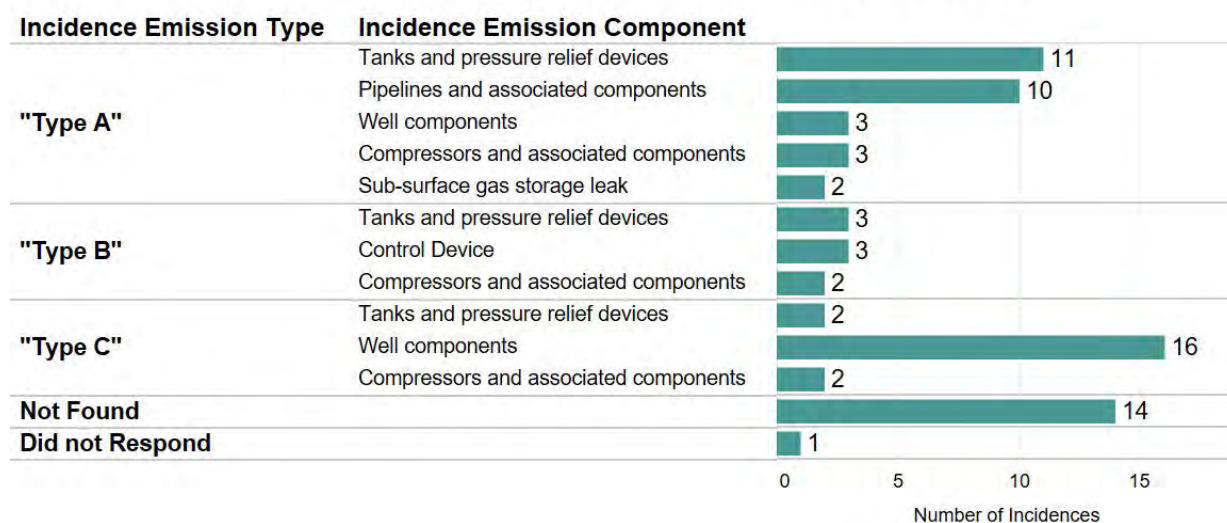


Figure 7. A graphic depicting the results of oil & gas operator feedback from the 2020 and 2021 airborne campaigns. Note that the Incidence classifications (Emission Type and Emission Component) were assigned by CARB staff based on operator responses.

Operator responses from 2023

As described above, the feedback form shared with operators in 2023 requested more detail than previous years. Thus, the 2023 operator feedback data are presented separately and in greater detail. In Figure 8a, "incidence emission location," refers to the facility or system type, such as oil or gas production facility, pipeline, and natural gas storage facility. In Figure 8b, "Incidence emission cause," describes the specific piece of equipment at the source of emissions, such as tanks, attached pipelines, flares, wellhead assembly, etc. In 2023, a total of 29 incidences were classified as "Type A" with the most common emission location at oil or gas production facilities (25 incidences) followed by pipelines (4 incidences). The most common causes for "Type A" incidences at oil & gas production facilities were attached pipelines, tanks, and wellhead assemblies. 21 incidences were classified as "Type B" emissions, and similar to "Type A", the most common location of emission was at oil & gas production facilities. Among the most frequent causes for "Type B" emissions were tanks, wellhead assemblies, and open well casing vents. In "Type C", there were only 10 incidences, and they were always associated with a maintenance event. Oil or gas production facilities were also the most common locations that emission sources were found for "Type C" and often at tanks and wellhead assemblies.

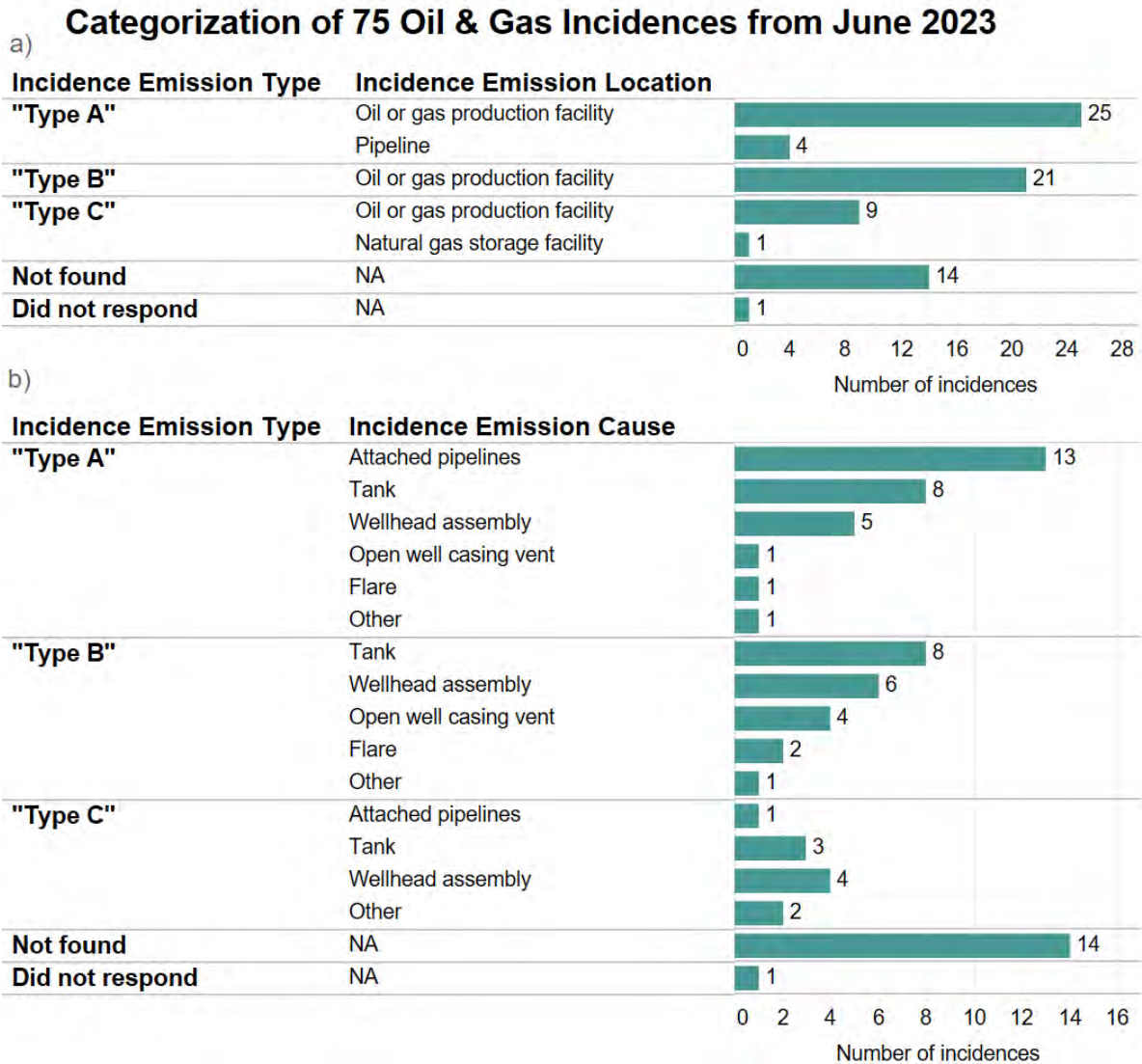


Figure 8. A graphic depicting the results of oil & gas operator feedback of a) Incidence Emission Locations and b) Incidence Emission Causes from the 2023 airborne campaigns. Note that the Incidence classifications (Emission Type, Emission Location, and Emission Cause) were assigned by CARB staff based on operator responses.

Landfill

Under California's Landfill Methane Regulation, certain municipal solid waste landfills are required to install and continuously operate gas collection and control systems and conduct monitoring, such as the LDAR requirements described in the introduction, to minimize methane emissions. In such systems, landfill gas (which is typically 30-50% methane) is recovered using a system of gas collection wells and connected piping in conjunction with mechanical blowers, fans, pumps, or compressors to create a pressure gradient and actively extract landfill gas. Portions of the gas collection system may be temporarily disconnected during construction periods, including performing maintenance on existing wells and installation of new wells. Landfill surfaces are covered to minimize emissions, odors, litter, and disease vectors. Additional details about operational, monitoring, and reporting requirements at California landfills can be found in the Landfill Methane Regulation⁷.

Operator responses from 2020 and 2021

A summary of landfill operator responses from 2020 and 2021 is shown in Figure 9. In the landfill sector, across all emission types, the greatest number of incidences originated from the landfill surface, and the leading causes were construction, collection well downtime, and cover cracks. The incidences with the highest emission rates were associated with construction and the practice of taking collection wells offline when depositing waste in an area on top of existing waste layers. One incidence was classified as "Type B," attributed to the carbon adsorption system used to treat volatile organic compounds at a landfill that is not subject to methane emissions control. Twelve incidences were classified as "Type C." Seven of these "Type C" incidences were located at the landfill surface; arising from construction at the gas collection system and downtime of a gas collection well such as during repair or maintenance. Four "Type C" incidences were located at the active or "working face", i.e., the area where waste is actively being deposited, and resulted from taking collection wells offline during waste placement. One "Type C" incidence was identified as a leak from a new well (i.e., a component rather than the landfill surface) that had been recently constructed and was not yet connected to the collection system. The locations of the 22 "Type A" incidences from landfills were split between the general landfill surface (11 incidences) and landfill gas collection and control system components (11 incidences). "Type A" emissions at the landfill surface were caused by cover cracks and insufficient vacuum. The most common causes of "Type A" emissions at landfill gas system components were damaged/broken equipment and surface penetrations.

Categorization of 45 Landfill Incidences from 2020 & 2021

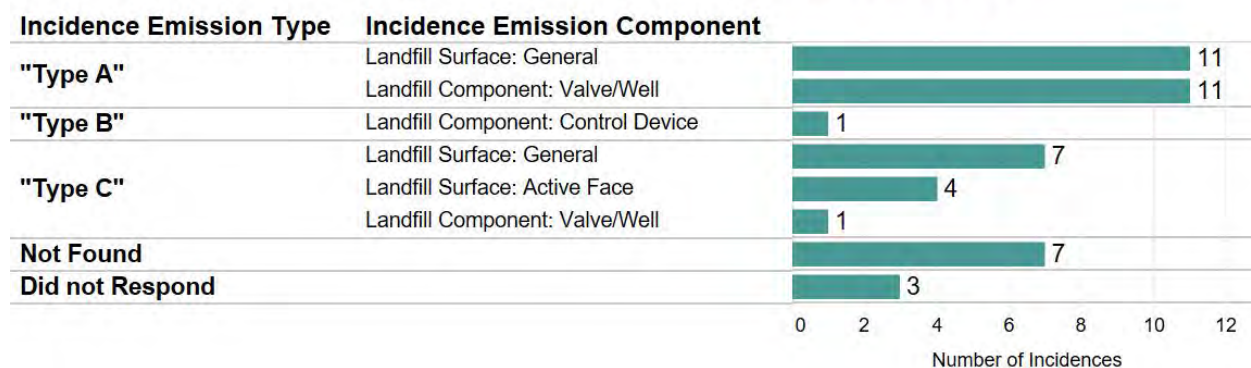


Figure 9. A graphic depicting the results of landfill operator feedback from the 2020 and 2021 airborne campaigns. Note that the Incidence classifications (Emission Type and Emission Components) were assigned by CARB staff based on operator responses.

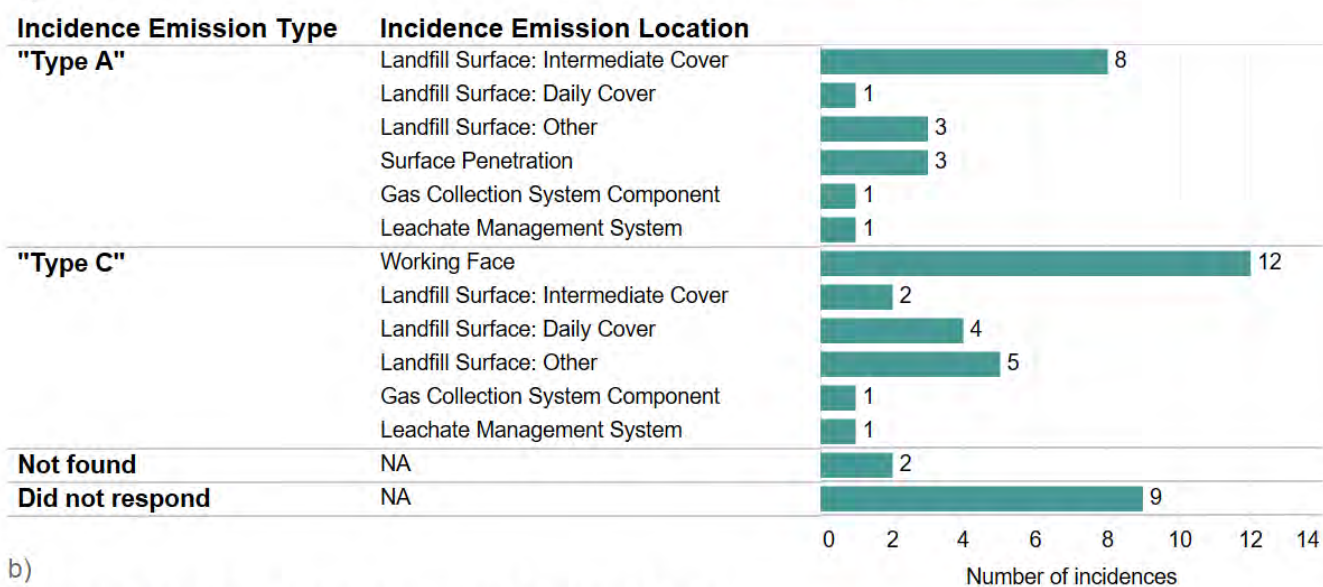
Operator responses from 2023

As described above, the feedback form shared with operators in 2023 requested more detail than previous years. Thus, the 2023 operator feedback data are presented separately and in greater detail. In 2023, there were a total of 17 incidences classified as "Type A" and 25 incidences classified as "Type C". Incidences at the landfill surfaces were the most common location for "Type A", occurring at either the intermediate cover (8 incidences), daily cover (1 incidence), or other (3 incidences). Leading causes at the landfill surfaces were cover cracks, construction, and damaged components. Another common cause for "Type A" incidences were issues at the wellbore seal at surface penetrations. Other "Type A" emissions were associated with the wellbore seal at a gas collection system component and exposed liner at a leachate management system. For "Type C" incidences,

construction related work tended to be the leading cause across all emission locations split between the working face (12 incidences) and landfill surfaces: daily cover, intermediate and other (11 incidences). The remaining two "Type C" incidences were associated with downtime at a gas collection system component due to new well installation and construction at a leachate management system.

Categorization of 53 Landfill Incidences from June 2023

a)



b)

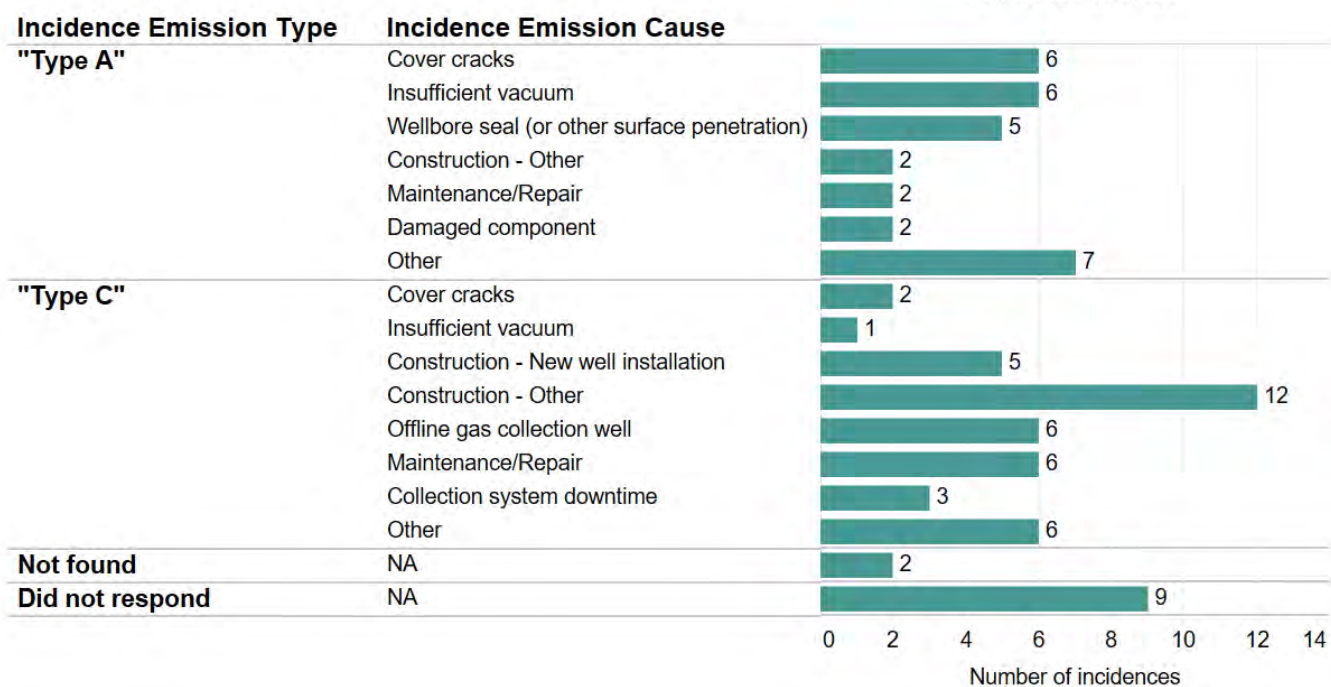


Figure 10. A graphic depicting the results of landfill operator feedback of a) Incidence Emission Locations and b) Incidence Emission Causes from the June 2023 airborne campaigns. Note that the Incidence classifications (Emission Type, Emission Location, and Emission Cause) were assigned by CARB staff based on operator responses. Multiple causes for an incidence as identified by the operator are displayed in figure.

Discussion: Future Considerations

The mitigation potential of this technology is clearly demonstrated in this report. About 40% of the incidences identified in this report were classified as “Type A,” meaning the operator was unaware of the emissions and the emission source was able to be mitigated, typically within 1-2 weeks of detection. The remaining incidences were classified as either “Type C” (27%), not found (15%), or “Type B” (12%) - some of which may have the potential to be addressed as described in the Policy Implications section.

Mitigation Potential with Satellites

While these flight campaigns provided valuable research opportunities and lessons for learning how to optimize future airborne campaigns, we must consider the short duration and limited spatial coverage of these campaigns. Flights in 2020 took place over two weeks (Nov 9-23), while flights in 2021 took place over ten days (Nov 5-13), and flights in 2023 took place over two weeks (June 12-28). The three airborne campaigns were spatially limited to the areas of interest shown in Figure 1. While these areas of interest are believed to be home to many of the densest concentrations of detectable plumes, we acknowledge that this observation deck is far from exhaustive. With the limited spatial and temporal coverage of these two airborne campaigns, we are far from realizing the full mitigation potential of this technology. Using airplanes alone, it would be cost-prohibitive and technologically infeasible to survey “everywhere all of the time” in California. Airplanes also use fossil fuels and emit other pollutants that are undesirable. To this end, new and upcoming satellite constellations developed by commercial satellite companies, which use similar sensors capable of detecting individual methane plumes, are an intriguing technological innovation that could push us closer towards the ideal of measuring “everywhere all of the time.” CARB is a founding member of the Carbon Mapper consortium¹⁰, a public-private partnership including government and non-government entities which will launch and operate satellites capable of detecting methane plumes. Carbon Mapper will launch two philanthropically-funded demonstration satellites in early 2024. The capabilities of the Carbon Mapper satellite-based sensors will be similar to those flown on the aircraft, although the spatial resolution will be coarser (30 m pixel resolution as opposed to 3 m), and the limit of detection will be higher (likely between 50-100 kilograms of methane per hour under typical atmospheric conditions). Nevertheless, the performance of these satellites will still be adequate to utilize the resultant data in a similar manner to the airborne data described in this report – to identify and support mitigation of large methane leaks. The two Carbon Mapper satellites are expected to provide somewhat regular sampling of select high-priority areas of interest in California. In addition, the State of California has allocated \$100 million to fund the purchase of additional plume-mapping satellite methane data, which will enable California to survey broad portions of the State with high frequency. This \$100 million will be awarded to a commercial satellite vendor selected through a competitive proposal solicitation process.

Policy Implications

These findings raise several policy questions that may be considered in the future: regulatory inclusion, coverage of inspection, and co-benefits.

CARB has methane regulations on both landfills and the oil & gas sector with a robust enforcement program. While remote sensing via aerial or satellite monitoring was not incorporated into CARB regulations at the time of the flight campaigns, the identified plumes can inform compliance inspections by CARB and local air district staff. Operators were generally responsive in a timely manner when notified of a plume by CARB. However, some of those responses were late, did not involve on-the-ground inspections, or were lacking in detail. Many of the operators were voluntary participants and all were operating in a highly regulated industry. There were also cases where the plume was the result of a source that is not regulated and does not require action. Additional regulatory language could address operator response rate, response speed, and response quality as well as consider if there are additional sources that need to be covered. Recent amendments to the Oil and Gas Methane Regulation will require operators to respond to methane plume detections from satellite-based remote monitoring⁸. Required operator actions include on-the-ground investigation or consultation of activity records, leak repair (if required), and reporting findings to CARB.

In 2021, CARB also asked oil & gas operators to indicate whether a subset of leaks would have been found by regular LDAR surveys. Operators provided information for only 19 incidences and indicated 4 would not have been found as those were exempt from LDAR. With this limited dataset, it is difficult to quantify or extrapolate. However, it is important to note it is likely that this technology would find not only those plumes outside existing regulations but may also find plumes covered by the regulation sooner if the measurements are done on a more regular basis than required by the regulation.

Finally, there are co-benefits of using this technology to initiate leak repairs. In addition to methane, which is non-toxic, oil & gas developments and landfills are known to emit malodorous and hazardous air pollutants (HAPs), which can cause discomfort, acute and chronic health problems¹⁶⁻¹⁸. Furthermore, exposure to these emissions is not equally shared by all people; indeed, disadvantaged communities often suffer from higher exposures to these co-emitted pollutants¹⁹. Therefore, using this technology to initiate rapid repair of high-emitting sources can have a co-benefit of reducing pollutant exposure for affected communities. The direct pathway to action offered by this technology has direct tie-ins to State programs such as the Community Air Protection Program initiated by Assembly Bill 617²⁰, which are aimed at producing much-needed mitigation in exposure for disproportionately affected communities.

Conclusion

Methane plume-mapping remote sensing has emerged as one of the most intriguing next-generation technologies that could be incorporated into regulatory toolkits for reducing greenhouse gas emissions. This report details the use of this technology in California to support mitigation of methane, a potent short-lived greenhouse gas. In 2020, 2021, and 2023, CARB worked with external partners to plan and conduct airborne flights over California with the goal of detecting plumes of concentrated methane emissions, then sharing these findings with facility operators to initiate repairs.

The value of this technology could be maximized by performing flights more often and by covering larger parts of the State. However, such spatial and temporal coverage would be infeasible from airborne studies alone. CARB, along with its partners, aims to foster the creation of a constellation of satellites equipped with similar sensor capabilities to those flown on the aircraft. Like the airborne

platforms, the satellites will be able to detect methane plumes that can be traced to a specific source and operator, thus enabling rapid mitigation where possible.

At full capacity, a satellite constellation could enable routine observation of relevant infrastructure as often as once a week across the whole State, and up to daily for high-priority events. The orbit of the satellites will not limit observations to California alone; indeed, satellite constellations will provide global coverage. Therefore, actions taken by CARB to integrate this technology into our regulatory toolkit could serve as a model to be replicated by other local, state, subnational, and national jurisdictions. A key element for driving global adoption of this technology will be transparency, access to the data, and public trust. CARB hosts the California Methane Source Finder (<https://msf.carb.arb.ca.gov/>), which displays plumes detected in California. As part of phase 1 of the Carbon Mapper partnership, CARB will play an important role in validating that the satellite data are of sufficient quality to be used for regulatory purposes. CARB is also working with other national and sub-national jurisdictions.

While this report demonstrates the potential utility of this technology for supporting actions to reduce GHG emissions, we must consider its role as part of a broader, integrated monitoring system. As described in the Methodology section, hyperspectral remote sensing of methane enables detection of highly-localized plumes of methane, which is useful for detecting large leaks emanating from a single, localized source. It is very likely that more than half of California's total methane emissions will *not* be detectable by satellites equipped with similar technology. These emissions include diffuse area-wide sources as well as small-but-abundant localized sources. An integrated monitoring system should have the ability to provide ambient measurements of methane and enable observation-based estimates of *total* emissions. To do this, an integrated monitoring system may include coarse ambient-observation satellites such as TROPOMI²¹, surface-based sensor networks, flux towers, and periodic field campaigns. These data enable scientists to perform analysis that may be useful for studying emissions at state, regional, and local scales and creating regulatory guidance based on these findings. However, it cannot be understated that such a system does not produce directly actionable data, but rather, enables *indirect* reductions in emissions where it may take years to collect sufficient data, perform robust scientific analysis, and update regulations. In contrast, methane plume-mapping remote sensing data can produce *directly actionable data* to reduce emissions at short timescales. In addition to the *direct* mitigation pathway, long-term studies of emissions from plume-mapping remote sensing can be used to produce *indirect* emissions reductions by providing source-level and component-level context that is missing from integrated monitoring systems. Thus, plume-mapping remote sensing can be a useful standalone tool for producing rapid, *direct* emissions reduction, but can also play an important role in an integrated monitoring system that produces *indirect* emissions reductions by informing rules and regulations. Additionally, plume-mapping remote sensing can be used to detect potentially hazardous events (such as gas blowouts and leaking oil wells within communities), leading to rapid mitigation. By harnessing this emerging technology, regulatory agencies such as CARB can support the direct mitigation of GHG emissions, develop an improved understanding of operational and environmental conditions that result in higher emissions, more efficiently enforce new and existing regulations, better-protect Californians from potentially hazardous events, and track success in reducing GHG emissions.

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