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AIR RESOURCES BOARD

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Summary Report of the 2020 and 2021 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 specific coordinates of 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

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 explore whether 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 to perform plume mapping flights over select regions of California. From these flights, 213 methane plumes were detected from the oil & gas sector and from landfills. CARB staff identified the owner of infrastructure at each methane plume's source and shared findings directly with operators via 117 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 97% of the time. Oil & gas operators generally took action within a day or two and responded to CARB within one week. 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 many months later. Based on operator responses, 44% of incidences were classified as "Type A," meaning the operator was unaware of the emissions, for example a broken or malfunctioning component. 8% of the incidence reports were classified as "Type B" emissions, meaning the detected methane plume(s) arose from emissions that occurred 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. 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 nearly half 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 percent of current global warming. According to the Intergovernmental Panel on Climate Change, methane has a global warming potential 25 times greater than CO_2 over a 100-year timespan, and 84 times greater than CO_2 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 and Executive Director of the UN Environment Programme recently said 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 COP26 where the Global Methane Pledge was launched in 2021[2].

In California, methane is estimated to account for about 10% of all GHG emissions after accounting for differences in global warming potentials, and statewide methane emissions are believed to have remained flat over the past decade. 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 percent 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[3].

Methane emissions from oil & gas and landfills are regulated by California's *Oil & Gas Regulation*[4] and Methane Emissions from Municipal Solid Waste Landfills Regulation (also known as the *Landfill Methane Regulation)*[5]. 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 repairs [4-5]. 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 emissions 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 *highly 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 complimentary to conventional LDAR methods.

The California Methane Survey[6] 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 highly-localized emission sources were detected across the agriculture, oil & gas, and landfill sectors. It is challenging to extrapolate the measured emissions rates for these 564 sources to an annual basis; however, these highly-localized emission sources could potentially account for a significant fraction of the State's total annual 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, two airborne field campaigns took place over California, with the goal of exploring how this type of data can be used by regulatory programs to support reductions in methane emissions. Specifically, the purpose of this set of flights was to determine if the identified highly-localized methane sources were due to leaks that could be fixed. The first follow-up airborne campaign was funded by CARB (Nov 9-23, 2020) and conducted by the University of Arizona (UA), and the second was funded and conducted by the non-profit Carbon Mapper[7] (Nov 5-13, 2021). This report provides a summary of the findings from these two 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 2020 and 2021 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[8]. For these surveys, flights were typically conducted at an altitude of 10,000 feet (~3 kilometers (km)). 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). For methane, 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 the hours of 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.

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 methane plumes can be generated. One, a 'Quick View' product can be generated very quickly and may contain large amounts of image noise, but is sufficient to locate methane plumes. The second, a 'Fully Developed' product, provides higher quality plume images with emissions estimates, but takes longer to generate. The Quick View product is used to support mitigation quickly, while the Fully Developed product is used to estimate emissions rates and provide a high-quality plume images that are suitable to be shared with the public.

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 California[9-11] and the Four Corners region[12]. The resulting images of localized methane enhancements, referred to as plumes, were produced by UA (2020) and Carbon Mapper (2021) and shared with CARB generally within one or two days of each flight. These 'Quick View' plumes can be used to very quickly identify where plumes are likely located. However, University of Arizona and Carbon Mapper staff subsequently 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).

Airborne Campaign Planning

In preparation for the 2020 airborne campaign, CARB reached out to infrastructure owners from the oil & gas and landfill sectors 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 campaign, industry groups from the oil & gas and landfill sectors were informed that the flights would be happening in November 2021, 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 target areas for the 2020 (left column, green regions) and 2021 (right column, pink regions) airborne campaigns. CARB staff developed the proposed target areas by analyzing existing emissions inventories and by reviewing findings from previous airborne surveys focused on methane plume detection (i.e., California Methane Survey[9]). This analysis highlighted three main regions to target: large landfills clustered around the Bay Area (top row in Figure 1), oil fields in Kern County (middle row in Figure 1), and large landfills clustered around the Los Angeles metro area (bottom row in Figure 1). The 2020 target deck was also influenced by the locations of facility operators who had voluntarily expressed interest in participating in the 2020 mitigation dry run.

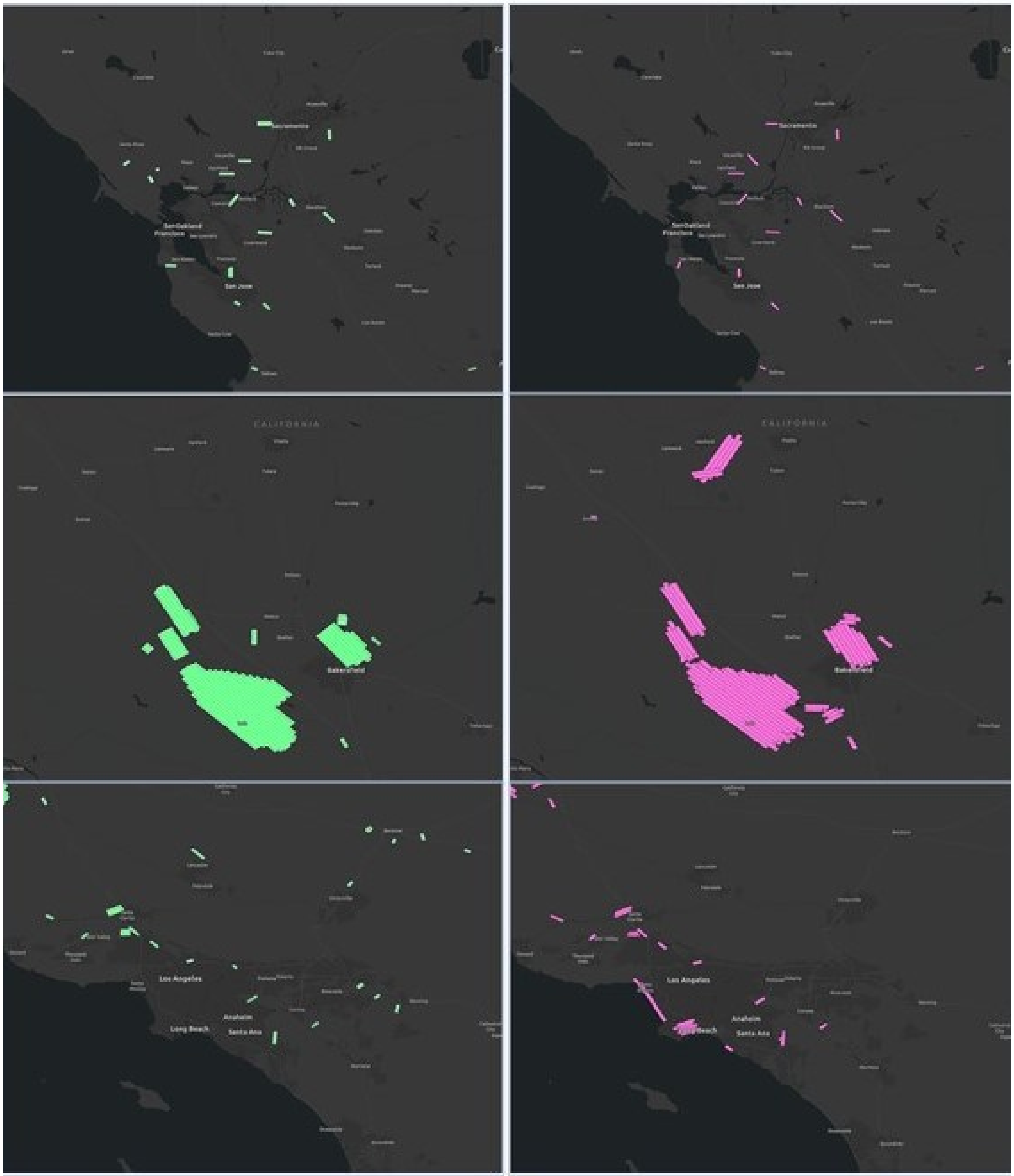


Figure 1. Maps of target areas from airborne campaigns in 2020 (left column; green) and 2021 (right column; pink). The top row shows landfills target areas in the SF Bay Area and surrounding areas, the middle row shows targets in the Southern San Joaquin Valley, and the bottom row shows target areas in Southern California.

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 image of a continuous span of methane from one point in time. Each plume detection belongs to exactly one "Source," referring to the specific coordinates of the origin of the plume. If a source is flown-over multiple times, a single source may have multiple associated plume detections in different locations. 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 dozens of 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 a defined time period 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.

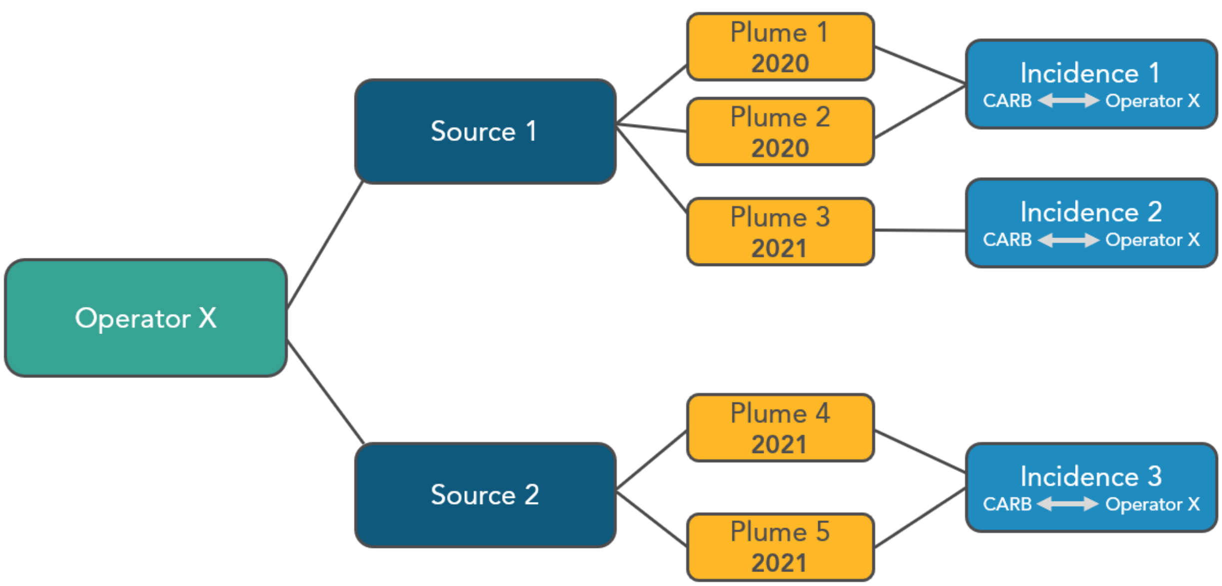


Figure 2. A hypothetical example depicting the hierarchical relationships between operator, sources, plumes, and incidences.

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 operator's 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 locate 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 identified the source 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). Lastly, "Type C" refers to incidences where the operator identified the source 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.

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

The University of Arizona and Carbon Mapper generated and transferred Quick View plume images to CARB usually within 24-72 hours of each flight. Each plume was assigned to a source, and plumes within 200 meters of each other were tentatively assumed to be from the same source. 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/Carbon Mapper. The next steps differed between the 2020 and 2021 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, CARB staff performed a nearest-neighbor spatial match to identify best candidates for operators based on infrastructure data from multiple sources, including CalGEM's 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 output for each source, performed manual QC to identify the most likely operator, and determined the emission sector (e.g., landfill, oil & gas). 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.

It should be noted that the methane regulations discussed in the Introduction Section of this report apply to landfills and oil & gas infrastructure, and there are currently no comparable regulations for methane emissions from dairies and feedlots. Therefore, plumes detected at dairies and feedlots were QC'd in the same manner as other plumes but were flagged and not shared with operators. For sources in the oil & gas and landfill sectors, CARB staff then 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 is shown in Figure 3.

In both 2020 and 2021, for incidences with high quality plume images, clear ownership, and attributed to the oil & gas or 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 average time between CARB's initial receipt of a plume and an email being sent to an operator was 1-3 days. Adding in the time for UA/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 or weak, 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. Ten plumes from 2021 required additional assistance to identify an operator. CARB staff, along with external partners, were able to identify ownership of all but two plumes from 2021 (both belonging to the same source, overflown on multiple days).

The emails sent to operators also contained a standardized feedback form for the operator to fill out. A sample of the email and standardized form are available in the Figures A1 and A2 in the Appendix. Operators returned emails to CARB to report their findings, including whether the plume source was repaired or not.

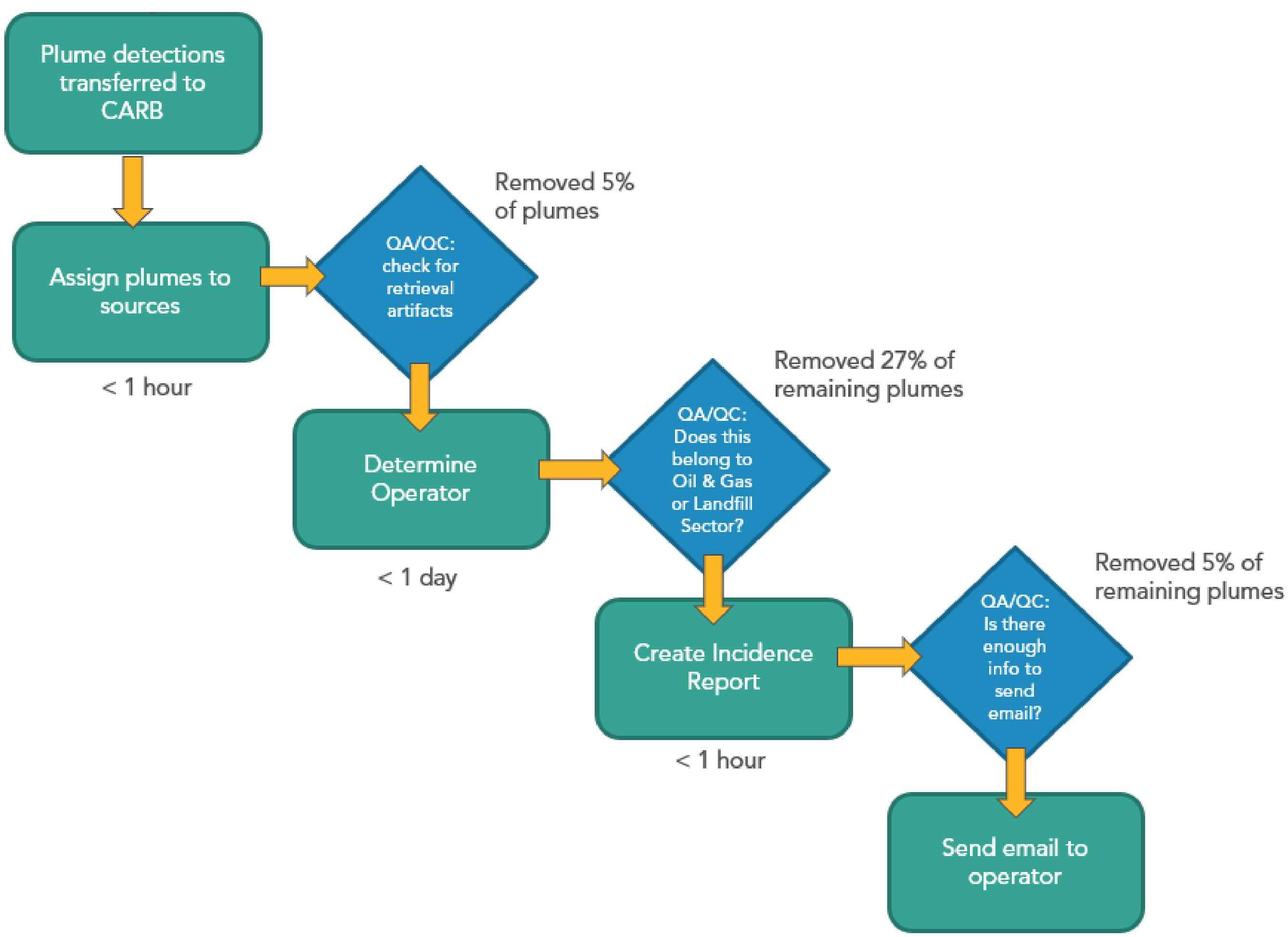


Figure 3. Visualization of CARB's data processing pipeline (from plume to email) used in 2021.

Results

Summary Statistics from 2020 and 2021

Table 1 shows a breakdown of plume detections, sources, operators, and incidences from the 2020 and 2021 airborne campaigns. As described above, plumes detected at dairies and feedlots were QC'd similarly to plumes from other sectors but were not shared with operators and thus are excluded from summary statistics henceforth. The difference in total number of plume detections between 2020 and 2021 is likely due to several factors, including the number of flights (15 flight days in 2020 versus 8 in 2021), voluntary participation in 2020 versus non-voluntary participation in 2021 (see "Airborne Campaign Planning" section), and different coverage areas. The first column 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 whose assets were sources of detected, QC'd plumes. 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 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.

Table 1. Plume, source, operator, and incidence statistics from the 2020 and 2021 airborne campaigns. All columns exclude plumes removed by initial QA/QC (generally, fewer than 5% of plumes were removed by QA/QC). In 2020, plumes were only shared with operators who volunteered to be part of the study, whereas in 2021 plumes were shared with all identified operators.

	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*
2020 Total	131	71	19*	62*
2021				
Oil & Gas	59	43	13	40
Landfills	23	16	7	15
2021 Total	82	59	20	55
Grand Total	213	115†	25†	117‡

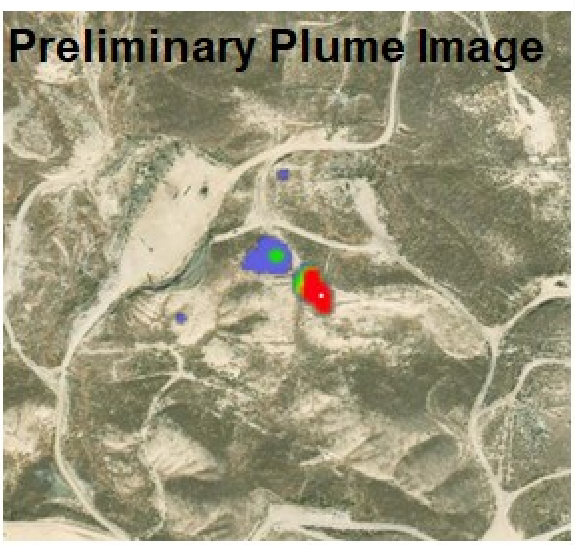
† Grand totals do not include duplicates; thus these grand totals are not simply the sum of each annual total. For example, sources detected in both 2020 and 2021 would only count once towards the grand total. The asterisks for 2020 indicate that these numbers only include plumes found at participating operators' facilities.*

‡All incidences and their outcomes are available in Table A1 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 airborne campaign are shown. Figure 4 shows an incidence from the oil & gas sector. In this case, the source was flown over on November 5, 2021 and November 8, 2021, with both flights detecting potential methane plumes (the plume image from November 5 is shown). CARB staff identified the operator of this piece of equipment and sent an email notification on November 8. The operator performed an inspection with a handheld methane monitor on November 9 and determined that this was an emission of methane and that the emission source originated from a crack in a 2-inch underground gas pipeline. The operator was able to isolate the line and stop the leak on the same day (November 9^{th}). The site was flown over again on November 12 and the plume was not detected. These plumes, while enough for voluntary follow-up, still need to undergo further quality checks and final plumes and quantification are not available until much later.

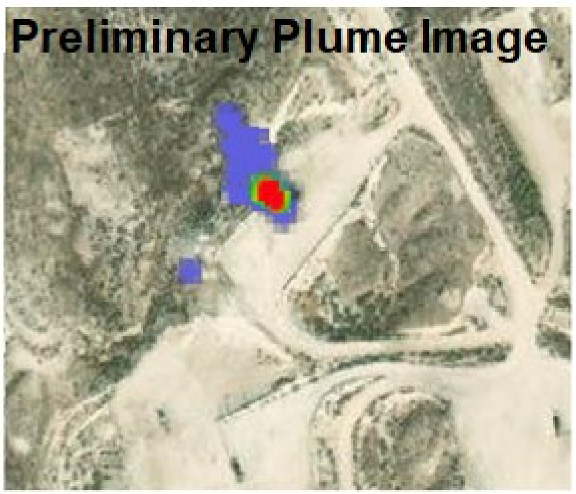
The estimated emission rate from this source was approximately 200 kg of methane per hour at the time of the flyovers (both were around noon local time). Based on the operator's response, the example shown in Figure 4 was categorized as a "Type A" incidence by CARB staff because the emissions were not previously known to the operator and were able to be mitigated.



Mon	Tues	Weds	Thurs	Fri
1	2	3	4	5 Plume Detected
8 Plume Detected Operator Notified	9 Operator inspected and repaired leak	10	11	12 ✓ Final overflight; no plume detected

Figure 4. Methane plume data in action from November 2021. Left: A preliminary image of a methane plume detected during a Nov 5 overflight. The preliminary plume image is overlayed 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 November 5, 2021 and November 8, 2021. Staff identified and notified the operator of the potential methane plume detections on the morning of Nov 10. Later that same day, 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 with a workover rig. The operator informed us that the maintenance was completed on November 9. The site was overflown again on November 12 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). These plumes, while enough for voluntary follow-up, still need to undergo further quality checks and final plumes and quantification are not available until much later.

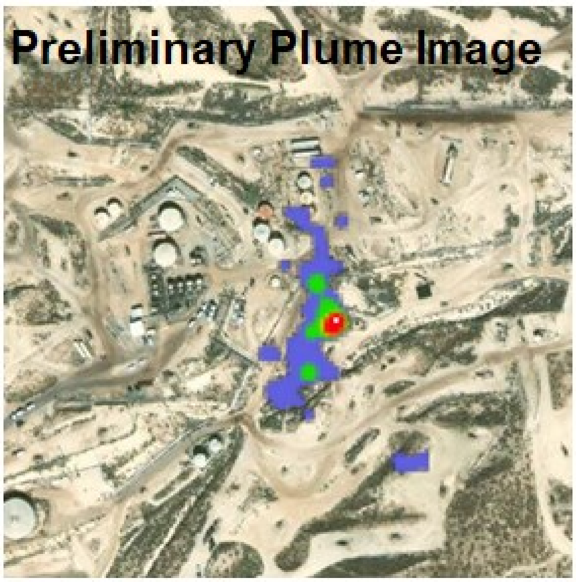


Mon	Tues	Weds	Thurs	Fri
1	2	3	4	5 Plume Detected
8 Plume Detected	9	10 Operator notified Operator performed inspection	11	12 ✓ Final overflight; no plume detected

Figure 5. Methane plume data in action from November 2021. Left: A preliminary image of a methane plume detected during a Nov 5 overflight. The preliminary plume image is overlayed 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 10th, 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 6 was categorized as a "Type A" emission by CARB staff. In this example, a piece of equipment was broken, but emissions occurred only intermittently 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 we had only overflown this site on Nov 8, this leak would not have been detected. This highlights the importance of repeated, frequent observations over target areas.

These plumes, while enough for voluntary follow-up, still need to undergo further quality checks and final plumes and quantification are not available until much later.



Mon	Tues	Weds	Thurs	Fri
1	2	3	4	5 Plume Detected
8 Plume Detected	9	10 Operator notified Operator performed inspection	11	12 ✓ Final overflight; no plume detected

Figure 6. Methane plume data in action from November 2021. Left: A preliminary image of a methane plume detected during a Nov 5 overflight. The preliminary plume image is overlayed 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 airborne campaign are shown in Table 2. This dataset is limited to 2021 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 13 days. In general, operators in the oil & gas sector responded to incidents faster than operators in the landfill sector (median of 8 days versus 105 days). However, these medians do not convey the wide range of response times. 18 incidences (about one quarter 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 35 days, with two thirds of all oil & gas incidences having total response times of two weeks or less. Landfills, on the other hand, had typical response times that were much longer. Only one landfill incidence (out of 15) had a total response time of less than one week, while eight landfill 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, operators performed inspections within one week of 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, with key dates, is provided in Table A1 in the Appendix.

Table 2. Key elements of operator response times from the 2021 airborne campaign, 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 Operator Response Times (median days (minimum – maximum days))	Landfill Operator Response Times (median days (minimum – maximum days))
All Emission Types (55 incidences)	First plume detection by UA/CM *to* CARB sends email notification to operator	**4** (2 - 6)	**5** (5 – 6)
	CARB sends email notification to operator *to* Operator performs inspection	**1** (0 – 20)	**6** (0 – 19)
	CARB sends email notification to operator *to* Operator sends response to CARB	**8** (0 – 35)	**105** (2 – 227)
"Type A" Emissions Only (26 incidences)	Operator performs inspection *to* Operator mitigates source of emissions	**0** (0 – 7)	**0** (0 – 7)
	First plume detection by UA/CM *to* Operator mitigates source of emissions	**6** (4 – 30)	**11** (7 – 24)
	Operator mitigates source of emissions *to* Operator sends response to CARB	**4** (0 – 14)	**99** (0 – 209)

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, four incidences (3% of total) were left unresolved due to no response from the operator. Three of the four unresolved incidences are from the landfill sector, and the three incidences all involve the same landfill operator. Nearly one fifth 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 hyperspectral 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 8% of incidences were categorized as "Type B" emissions based on the operator's response. Incidences in this category were not always supported by on-the-ground inspections. In some instances, the operator was able to look at the plume image and determine that the source of emissions was allowable while meeting regulatory requirements. An example of an incidence where the operator did not perform on-the-ground inspections but was able to determine that the source was a "Type B" emission is a flare in an oil & gas processing facility.

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 sections of a landfill gas collection system temporarily disengaged during maintenance, and oil well workovers, which involve pulling/replacing hardware on an oil well.

The remaining 51 incidences – which account for 44% of the total – were categorized as "Type A" based on operators' responses. Responses in this category were 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 hyperspectral remote sensing could be verified or attributed to a specific process or event. In both the oil & gas and landfill sectors, just under half 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 6 days for oil & gas, and 11 days for landfills.

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

			Incidence Emission Type Classification based on Operator Response				
		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
	Total	117	4 (3%)	21 (18%)	51 (44%)	9 (8%)	32 (27%)

Table 4. On-the-ground inspection rates for incidences, binned by operator response category.

			Inspection Rate binned by Operator Response				
		Number of Incidences sent to Operators	Did not Respond	Emission Source not Found	"Type A"	"Type B"	"Type C"
2020	Oil & Gas	32	N/A	100%	100%	100%	70%
	Landfills	30	N/A	100%	100%	100%	12%
2021	Oil & Gas	40	N/A	100%	100%	80%	80%
	Landfills	15	N/A	100%	100%	50%	33%
	Total	117	N/A	100%	100%	82%	55%

Operator Feedback: Causes of Emissions

Oil & Gas

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 Regulation[5] and Oil and Gas Regulation[4].

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 and 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.

A visual summary of operator responses from the oil & gas sector is shown in Figure 7. “Incidence Emission Type” uses the same high-level categories described in the previous section (i.e., Table 3). The second column in Figure 7, “incidence emission location,” refers to the specific location or piece of equipment at the source of the emissions, such as wells, compressors, tanks, pipelines, and emission control devices. The third column, “Incidence emission cause,” describes how the emissions arose from each location: “leak” refers to methane emissions originating from pinholes or cracks in a structure and includes connection valves/flanges, while “Damaged/Broken Equipment” indicates malfunctioning/non-functioning pieces of equipment, and “maintenance” implies the emissions were associated with routine maintenance activities. In the oil & gas sector, the eight incidences classified as “Type B” type emissions were attributed to a variety of locations and causes. The most common cause of “Type B” emissions from oil & gas was regular venting from tanks (3 incidences) and compressors (2 incidences). Three “Type B” type incidences were attributed to emissions control devices such (flares, 3 incidences) 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 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 locations and causes. Tanks and pressure relief devices were for most common location for “Type A” emissions (11 incidences) and had three separate causes of emissions: broken pressure and vacuum relief valves (7 incidences), leaks in the tank cover or structure (2 incidences), and other damaged/broken equipment (2 incidences). 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.

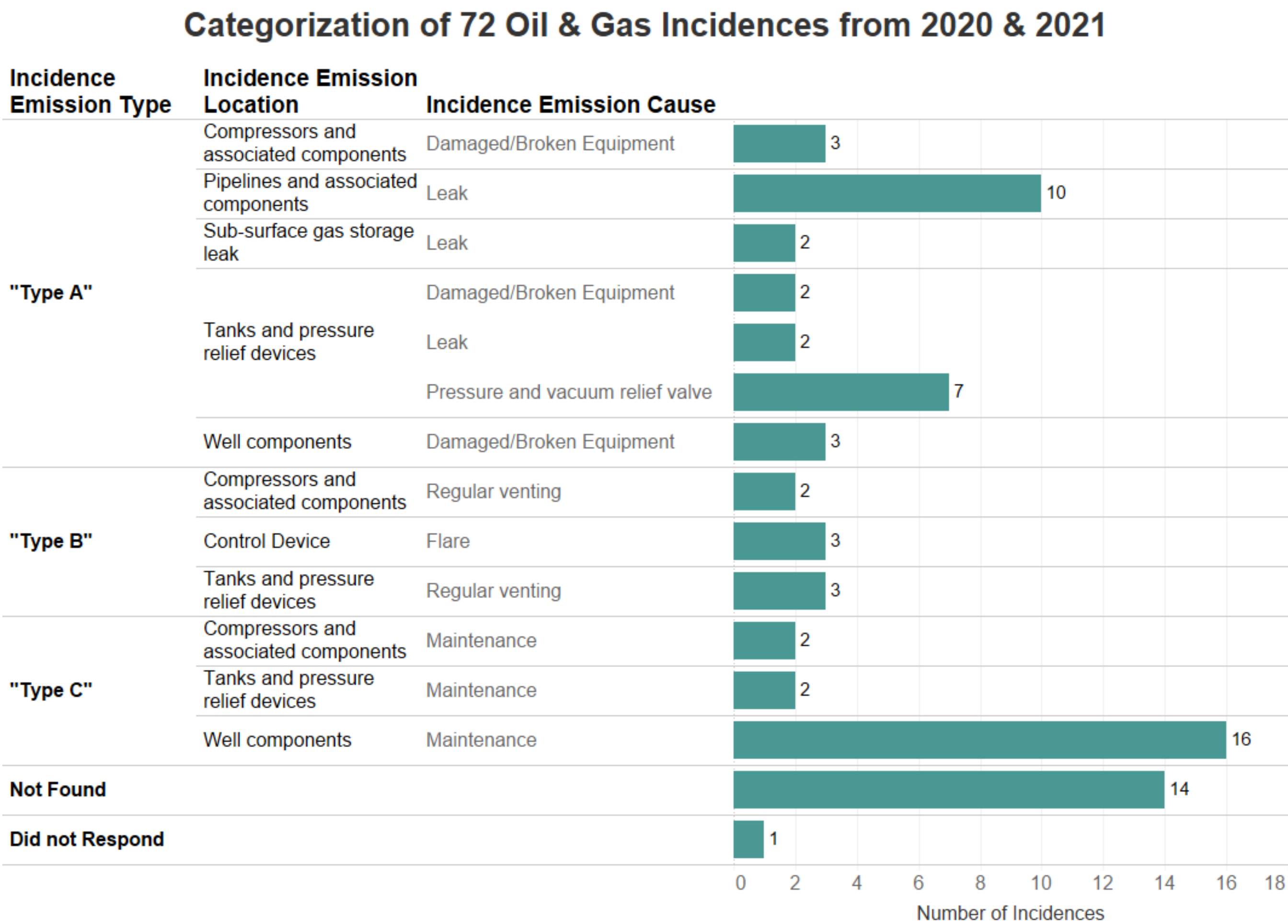


Figure 7. A graphic depicting the results of oil & gas operator feedback from the 2020 and 2021 airborne campaigns. Note that the Incidence classifications (Emission Type, Emission Location, and Emission Cause) were assigned by CARB staff based on operator responses.

Landfills

Under California's Landfill Methane Regulation, certain municipal solid waste landfills are required to install and optimally 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 Regulation[5].

A summary of landfill operator responses is shown in Figure 8. In the landfill sector, across all emission types, the greatest number of incidences originated from the landfill surface, and the leading causes were identified as 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 an uncontrolled 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 (5 incidences, generally construction on the gas collection system) and downtime of a gas collection well such as during repair or maintenance (2 incidences). 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 components (11 incidences). "Type A" emissions at the landfill surface were caused by cover cracks (9 incidences) and insufficient vacuum (2 incidences). The most common causes of "Type A" emissions at landfill components were damaged/broken equipment (5 incidences) and well or pipe perforations (3 incidences).

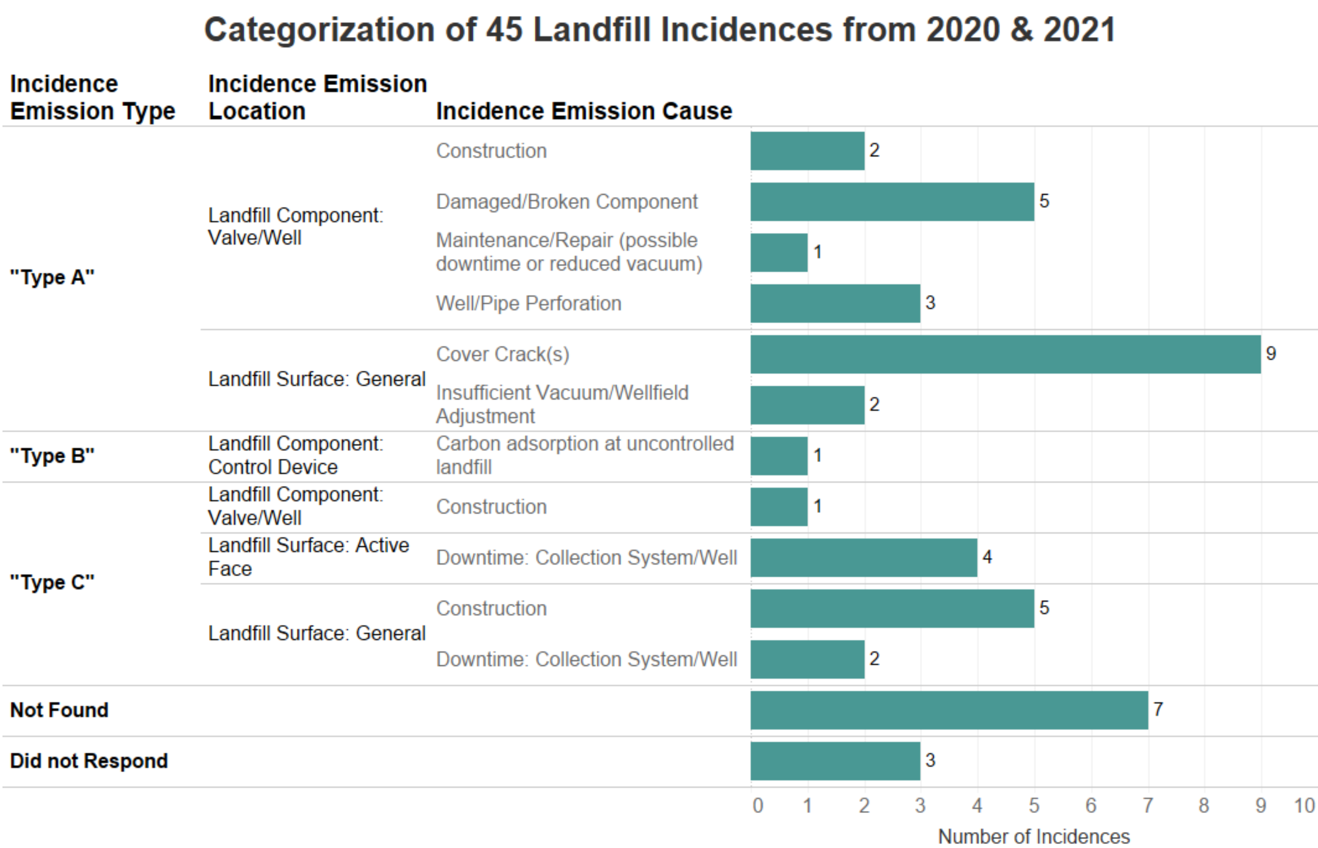


Figure 8. A graphic depicting the results of landfill operator feedback from the 2020 and 2021 airborne campaigns. Note that the Incidence classifications (Emission Type, Emission Location, and Emission Cause) were assigned by CARB staff based on operator responses.

Discussion: Future Considerations

The mitigation potential of this technology is clearly demonstrated in this report. 44% of the incidences identified in this report were classified as "Type A," meaning the operator was unaware of the emissions and the emission source able to be mitigated. The remaining incidences were classified as either "Type C" (27%), not found (18%), or "Type B" (8%) - 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). Both airborne campaigns were spatially limited to the target areas shown in Figure 1. While these target areas are believed to be home to many of the densest concentrations of detectable plumes, we acknowledge that this target 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 consortium [7], 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 near the end of 2023. 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 degraded (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 target areas in California. In addition to the Carbon Mapper satellites, 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: cost, coverage, and regulatory inclusion.

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 is not currently incorporated into CARB regulations for operator response; the identified plumes can inform compliance inspections by CARB or the local air district staff. Within this regulatory environment, 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 a 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.

As part of regulatory analysis, CARB considers costs to operators. In 2021, CARB asked a subset of operators from the oil & gas sector about the additional costs they incurred in dealing with these incidences. The operators' responses were in agreement that there were minimal costs. More data and feedback may be helpful to fully assess the costs associated in dealing with plume detection notifications in other sectors.

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 quarterly.

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 hazardous air pollutants (HAPs), which can cause acute and chronic health problems[13-15]. Furthermore, exposure to these emissions is not equally shared by all people; indeed, disadvantaged communities often suffer from higher exposures to these co-emitted pollutants[16]. 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 617[17], 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 find and support mitigation of methane, a potent short-lived greenhouse gas whose emissions are tightly controlled. In 2020 and 2021, 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.

While the airborne research showed that voluntary follow-up and mitigation could be achieved based off preliminary plume images, in a regulatory environment there are additional considerations. The plumes had not undergone the extensive quality control that is appropriate for regulations. Additional quality assurance checks must be made to ensure the image is accurate and most likely a methane emission source. Time is also necessary for appropriate regulatory follow-up including informing the proper agencies for regulatory implementation and enforcement, and any other actions that may need to be taken. Future plume detection and notification will likely be on a different time scale given these constraints.

At full capacity, a satellite constellation could enable observation of relevant infrastructure as often as once a week across the whole State. 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, 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 (www.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 TROPOMI[18], 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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