Airborne remote-sensing surveys of CH4 emissions in California: Fall 2020 campaign

Final Report

February 11, 2022

Principal Investigator: Riley Duren[1,2,3]
Contributions from: Andrew Thorpe[3], Daniel Cusworth[1,2,3], John Chapman[3], Joseph Heckler[4], Gregory Asner[4]

[1]University of Arizona
[2]Carbon Mapper
[3]Jet Propulsion Laboratory
[4]Arizona State University

1. Executive Summary

The University of Arizona, with the support of our partners at Arizona State University (ASU) and NASA's Jet Propulsion Laboratory (JPL), deployed the Global Airborne Observatory (GAO) to determine the locations and emission rates of methane (CH_4) point sources[1] in California. In addition to providing additional characterization of localized elevated CH_4 emissions[2] for the California Air Resources Board (CARB) and facility operators this study served as a "dry run" for the Carbon Mapper satellite constellation that is currently being developed with the first two launches planned for 2023. CARB is a key program partner and expressed interest in laying the groundwork for operational deployment of this technology towards quantifying and enabling the rapid mitigation of localized elevated CH_4 emissions in California.

Following the same methods described in Duren *et al.,* (2019) we used airborne infrared imaging spectroscopy to survey priority areas and facilities in northern, central, and southern California. Priorities were established by CARB based on high emission sources observed during the previous California CH_4 Survey in 2016-2017 and were also influenced by selected facility operators who indicated an interest in actively participating in this project. We leveraged data analysis support from NASA's JPL as part of our ongoing NASA funded Carbon Monitoring System project that includes multi-scale CH_4 analysis for California and other US states.

The campaign was conducted November 9 - 23, 2020. It included at least 3 complete surveys of all priority areas and 7 surveys of oil and gas operations in the southern San Joaquin Valley. In total, 56 facilities were surveyed including 32 landfills and composting facilities, 6 power/cogeneration plants, 16 oil and gas facilities (production fields and gas compressor stations), and 2 wastewater treatment facilities.

We identified 150 CH4 plumes[3] attributed to 82 unique sources at 35 facilities with a total persistence-adjusted emission rate of 18,812 $\pm$ 7,985 kilograms CH4 per hour ($kgCH_4/hr$). No CH4 point source emissions above our detection limit of 5-10 $kgCH_4/hr$ were observed at 21 facilities. For the 43 facilities that were previously observed during the 2016-2017 California CH4 Survey we estimate total, persistence-adjusted emissions of 17,507 $\pm$ 7,489 $kgCH_4/hr$ in Fall 2020 or approximately 0.11 TgCH4/yr. This is 42% lower than CH4 emissions from the same facilities in 2016-2017, driven equally by similar reductions in the landfill and oil and gas sectors. Embedded in that net reduction were significant increases in localized high methane

---

[1] As described in Duren et al 2019, we define "point source" to be a condensed surface feature or infrastructure component < 10 meters across that emits plumes of highly concentrated CH4.

[2] Super-emitters have been defined in the literature as a small fraction of facilities that contribute disproportionately to emissions from a given region or sector. E.g., Duren et al 2019 reported that < 0.2% of infrastructure in California contributes an equivalent to > 30% of California's total emissions.

[3] CH4 plumes generally refer to individual emissions that can then be spatially and temporally averaged into a source for a given location. Landfills are a special case and our convention here aggregates any CH4 detected at a landfill into a composite "plume". The number here reflects that convention. Our plume image products delivered to CARB provide insight into cases where multiple plumes were detected.

emissions activity at several facilities and a 20% overall growth in CH4 emissions from power plants surveyed in this study. The reasons for the observed net decrease are still being investigated but there are initial indications that at least half of the decrease may be associated with mitigation efforts informed by data our team shared with operators following the original California CH4 Survey.

Quick-look plume geolocation products were delivered to CARB staff within several days of each flight who in turn notified participating facility operators to support rapid follow-up and verification by ground teams. A summary of the feedback from industry provided to CARB, including whether or not an identified plume could be mitigated, and the reason for the emissions, is being prepared separately by CARB staff. Emission estimates with uncertainties were delivered to CARB to support assessments of point source emission distributions and to enable leak detection and repair efforts. CARB reported that several operators indicated cases where the data was used to support leak repairs. That list of repaired leaks is maintained by CARB and not included in this report. Subsequently, we delivered refined image products and plume lists to CARB following manual quality control review. Additionally, on November 1, 2021 we posted those data sets to the Carbon Mapper open data portal at https://carbonmapper.org/data/.

2. Introduction

Airborne imaging spectrometers like the next generation Airborne Visible Infrared Imaging Spectrometer (AVIRIS-NG) and the Global Airborne Observatory (GAO) have previously been used to identify CH4 point source emissions, estimate emission rates, attribute emissions to specific emission sectors, and inform emissions mitigation. A study in the Four Corners region characterized over 250 individual CH_4 plumes associated with coal bed CH_4 extraction, with the top 10% of emitters responsible for half of the total observed point source contribution (*Frankenberg et al.*, 2015). Our recent flight campaign in the Permian Basin identified 1,100 CH_4 point sources in the oil and gas sector responsible for over half of the regional total emissions, with 50% of detected sources attributed to oil and gas production sites, 38% to gas gathering and boosting, and 12% to gas processing (*Cusworth et al.*, 2021). Other studies have explored the underground gas storage (*Thorpe et al.*, 2020) and waste management sectors (*Krautwurst et al.*, 2017; *Cusworth et al.*, 2020) in California, and landfills and refineries in the San Francisco Bay area (*Guha et al.*, 2020).

The most systematic study of CH4 point sources in California was California Air Resources Board (CARB), the California Energy Commission, and NASA, the 2016-2017 California CH4 Survey identified and quantified point source emissions from multiple emission sectors and found 0.2% of California's infrastructure to be emitting the equivalent[4] of 34-46% of California total CH_4 inventory (*Duren et al.*, 2019). The results described in this report expand upon the California CH4 Survey by revisiting a subset of regions in California that were previously

[4] It is not yet known to what extent these localized elevated emissions are captured in California's existing CH_4 inventory.

surveyed, providing new measurements in other regions not covered in past flight campaigns, and facilitating more extensive follow up with boots on the ground to investigate the sources identified with the plane.

3. Methods

GAO measures ground-reflected solar radiation from the visible to shortwave infrared spectral regions (380 to 2,510 nanometers [nm]) with 5 nm sampling. This push broom instrument has a 34° field of view and operates on high performance aircraft, allowing for efficient mapping of large regions (Hamlin *et al.,* 2011). For this survey GAO flights were typically conducted at 10,000 feet (~3 kilometers (km)) above mean sea level. At this altitude the instrument has ~3 meter (m) pixels, ~1.8 km swath, and 5-10 kilograms (kg) of CH4 (CH_4)/hour (hr) detection limit for wind speeds up to 5 m/s. Each science flight day was typically 4-5 hours in duration including cruise flight to the mapping area from the aircraft base in Bakersfield. Mapping was conducted between the hours of 1000 and 1500 local time for peak solar illumination.

Our standard data pipeline acquires "level 0" raw image data cubes from the instrument and delivers calibrated and orthorectified radiance. Retrieval of CH_4 and carbon dioxide enhancement from radiance data is based on matched filter techniques that quantify the increased absorption of each gas in the shortwave infrared. Matched filter algorithms have previously been used to retrieve enhancements from radiance data in multiple field campaigns using the same type of instrument on NASA's AVIRIS-NG in California (Thompson *et al.,* 2015; Thompson *et al.,* 2016; Duren *et al.,* 2019) and the Four Corners region (Frankenberg *et al.,* 2016).

Briefly the data analysis workflow is as follows, as outlined fully in Duren *et al.,* 2019: a) standard processing including calibration and orthorectification of the AVIRIS-NG image cube data, b) retrieval of CH4 column mixing ratio-lengths and generation of CH4 plume maps, c) automated plume extraction and quality control, d) geolocation of CH4 plumes with latitude/longitude coordinates, e) calculation of integrated CH4 enhancement (IME) and length for each plume, f) acquisition and processing of High Resolution Rapid Refresh (HRRR) reanalysis wind fields, g) emission estimation and uncertainty quantification for individual CH4 plumes including adjustments for source persistence, h) attribution to nearest infrastructure or facility and IPCC emission sector based on the VISTA-CA infrastructure database (described in Duren *et al.,* 2019), and i) generation of source list (Excel file) and plume image products.

For most sectors, the extent of the observed CH4 plume was small compared to the full spatial extent of the associated facility and generally appeared in a repeatable fashion from the source to which it was attributed. Hence for most sectors we report emissions for individual sources, with larger facilities sometimes including multiple sources. For landfills where plumes were detected we often observed large plumes that spanned the spatial extent of the facility. Additionally, in most cases the location of each landfill plume evolved significantly over time in response to daily changes in waste deposition and surface cover. Landfills were not 100%

persistent, so the following approach was taken to estimate emissions (after Duren *et al.,* 2019):

1) For a given day overlapping plumes were removed
2) Source persistence was calculated for each landfill source (this could include multiple plumes for a landfill)
3) Frequency adjusted average emissions per source were calculated
4) Facility scale emissions for each landfill were generated by summing frequency adjusted average emissions for all sources in the landfill

4. Survey Design and Execution

The survey design used input from CARB staff to identify high priority landfills, oil and gas production fields, gas compressor stations, and power plants across the state based on results from previous airborne CH4 surveys and interactions with participating industry partners who were willing to have their own ground crews inspect each identified plume, mitigate emissions when possible, and provide feedback from those visits to CARB (Figure 1). A separate summary of feedback from operators is being prepared by CARB Staff. A minimum of 3 surveys per facility was planned for landfills which tend to have more persistent emissions. A goal of at least 6 surveys per facility was planned for oil and gas facilities given the tendency for more intermittent emissions. Surveys were conducted November 9 - 23, 2020 and included 2 crew rest and weather days. The campaign achieved 3 complete surveys of all priority areas and 7 surveys of oil and gas operations in the southern San Joaquin Valley and the Hinkley gas compressor station.

In total, GAO sampled 2,687 km^2 of unique land surface, 14,280 km^2 total when accounting for repeat overflights. A total of 56 facilities were surveyed including 32 landfills and composting facilities, 6 power/cogeneration plants, 16 oil and gas facilities (production fields and gas compressor stations), and 2 wastewater treatment facilities – see Table A.1 for complete list.

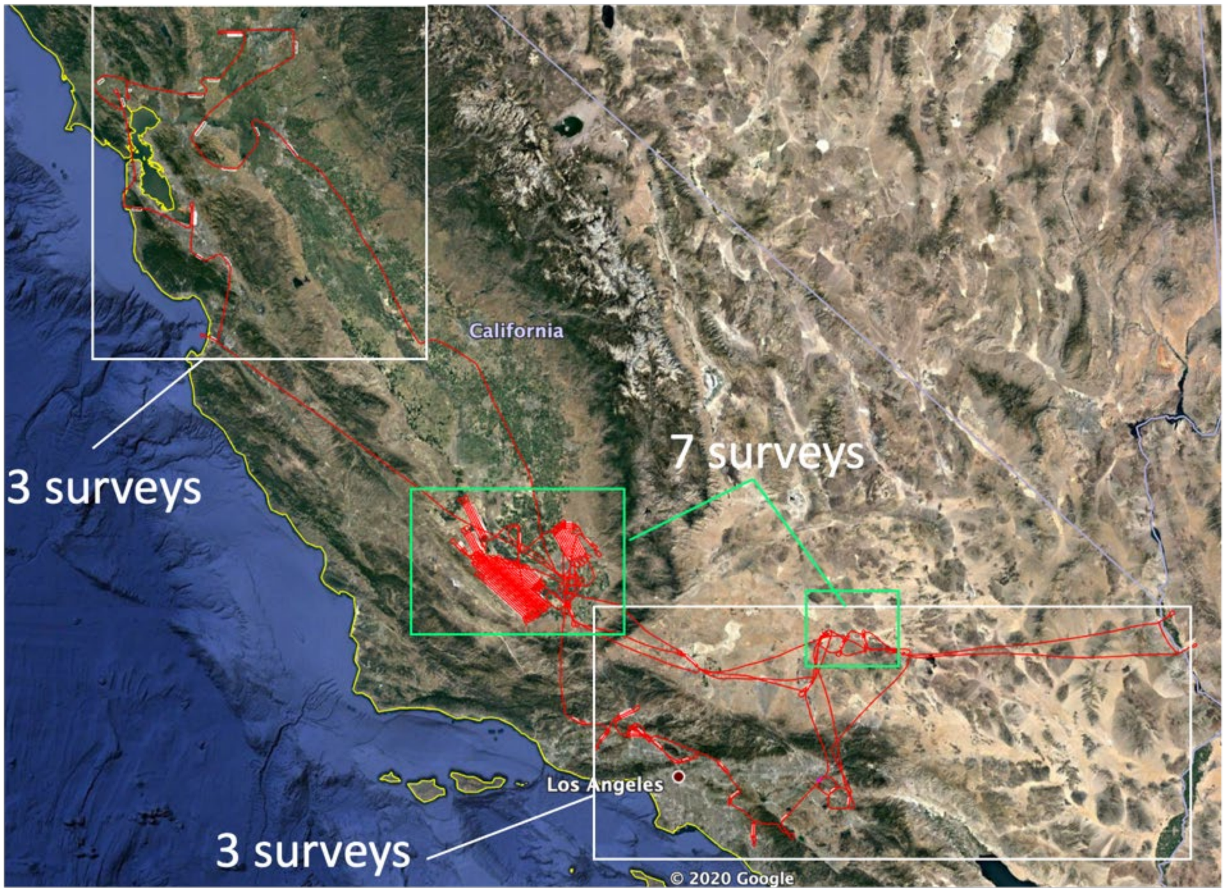

Figure 1 As flown survey areas. Red lines indicate aircraft ground tracks including transit flights between target areas. A set of as-flown flight lines has been provided to CARB.

5. Findings

We identified 150 CH4 plumes[5] attributed to 82 unique sources at 35 facilities with a total average, persistence-adjusted emission rate of 18,812 ± 7,985 kgCH_4/hr (equivalent to 4.1 MMTCO2e/yr based on a GWP for CH4 of 25). Over 100 of those plumes were located in oil and gas fields in Kern County (Figure 2). The spatial distribution is similar to that observed in previous campaigns however with some key differences. In this study we found that plume emission rates are skewed significantly higher than the earlier California CH4 Survey (Figure 3). This is likely due to the fact that the Fall 2020 survey was limited primarily to landfills, gas compressor stations, and oil and gas production fields which tend to have higher unit emissions

[5] CH4 plumes generally refer to individual emissions that can then be spatially and temporally averaged into a source for a given location. Landfills are a special case and our convention here aggregates any CH4 detected at a landfill into a composite "plume". The number here reflects that convention. Our plume image products delivered to CARB provide insight into cases where multiple plumes were detected.

than other sectors such as dairies and refineries that were included in the California CH4 Survey.

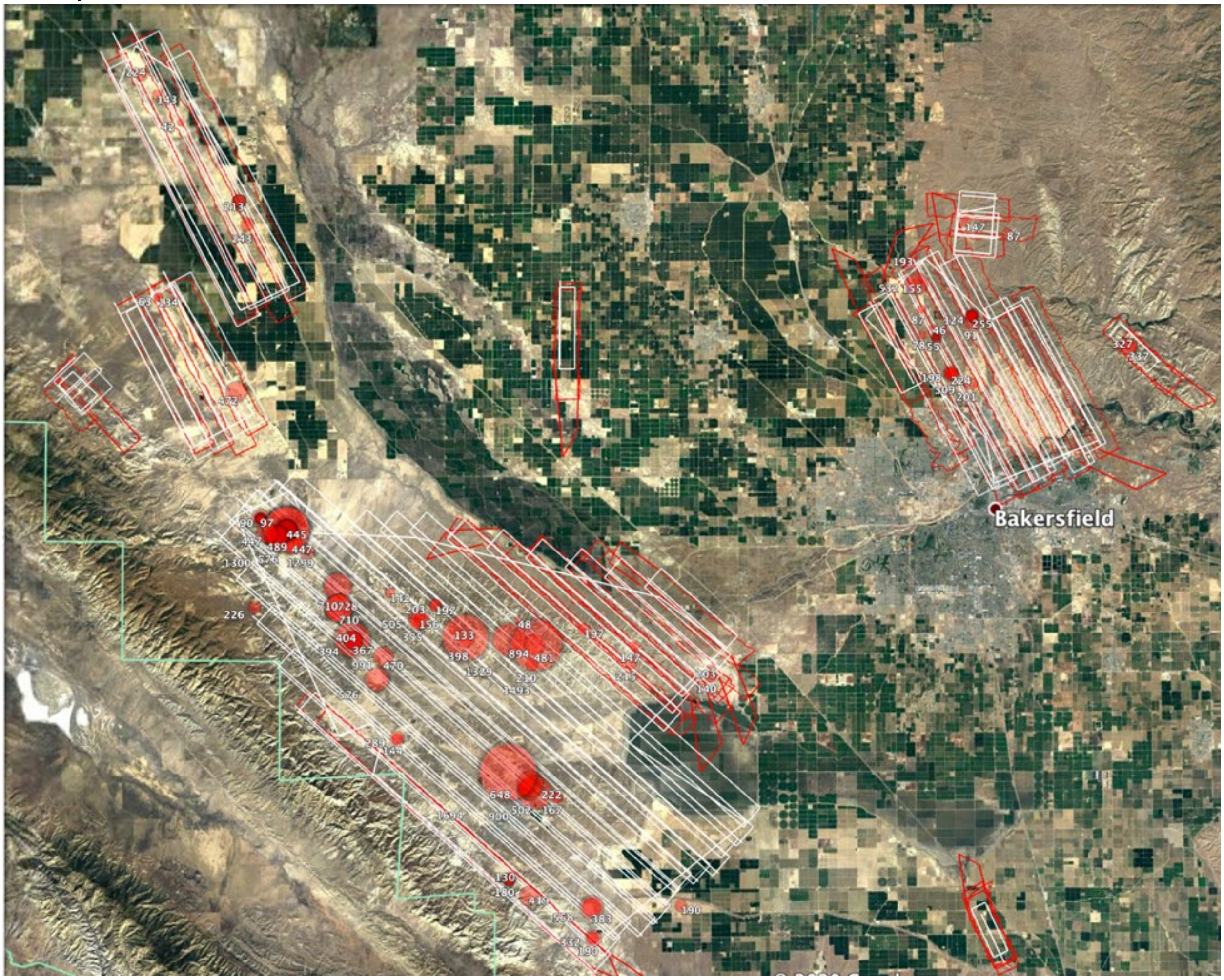

Figure 2 Closeup of Kern County indicating spatial distribution and relative magnitude of CH4 point sources (red circles) overlaid on planned flight lines (white polygons). The width of each polygon indicates the instrument swath width at the 10,000 ft survey altitude.

We observed a mean persistence of non-landfill sources in this study of 0.29 which is very similar to the California CH4 Survey. As in that previous study, for landfills where we detect strong CH4 emissions, they tend to be persistent even if variable in emission rate over the course of this study.

At 21 facilities, no CH4 point source emissions above our detection limit of 5-10 $kgCH_4/hr$ were observed. For 43 facilities in this study that were previously observed during the 2016-2017 California CH4 Survey we estimate total emissions of 17,507 $\pm$ 7,489 $kgCH_4/hr$ in Fall 2020 or approximately 0.11 $TgCH_4/yr$. This is 42% lower than CH4 emissions from the same facilities in 2016-2017, driven equally by overall reductions in the landfill and oil and gas sectors (Figure 4). Embedded in that net reduction are significantly higher emissions at several facilities and a 20% overall growth in CH4 emissions from power plants (Figure 4).

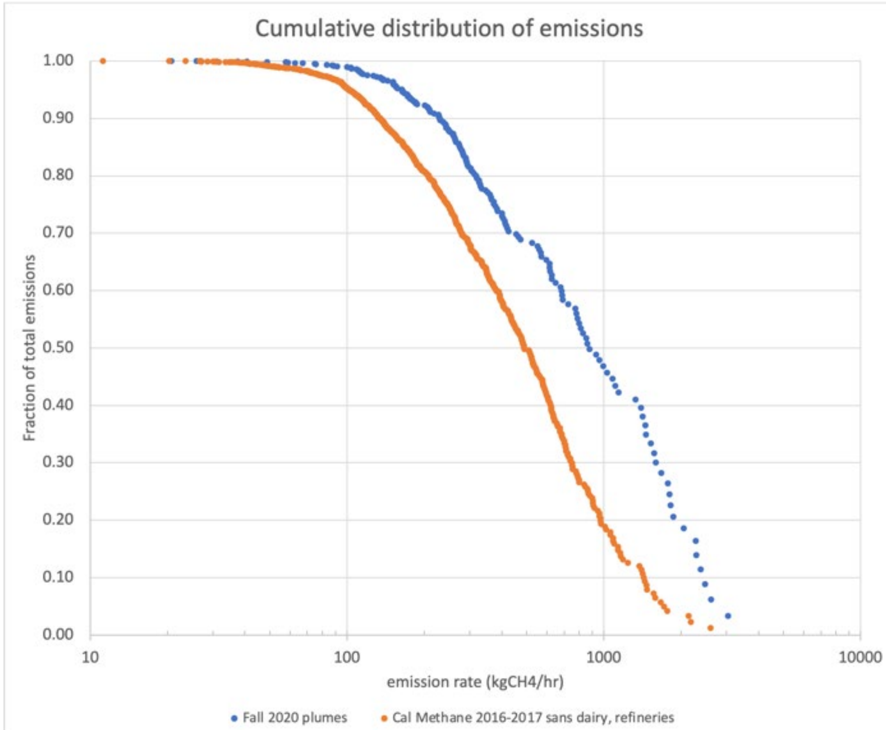

Figure 3 Cumulative distribution of CH4 plume emissions from this study are significantly skewed from the earlier California CH4 Survey (adjusted for sectors surveyed in this study), potentially because the previous 2016-2017 study covered a much larger area with more facilities, many of which exhibited less pronounced localized elevated emissions activity than those prioritized for follow up in this study.

The reasons for the observed net decrease are still being investigated but there are initial indications that at least half of the decrease may be associated with mitigation efforts informed by data shared with operators following the original California CH4 Survey and potentially new state oil and gas regulations. This is consistent with our experience with operators responding to CH4 plume images we shared from the earlier study as well as examples during the Fall 2020 campaign itself (see Figures 5 and 6). In this study our industry partners reported being able to mitigate 72% (landfills), 41% (oil and gas), and 49% (utilities) of the identified emissions from the plumes sent to them by CARB, totaling 10,800 kgCH4/hr. These reported reductions have not yet been independently validated.

Table 1 Summary of the number of emission plumes detected, emission rates, and uncertainties, organized by point source emission sector for facilities covered in both this study (Fall 2020 survey; blue columns) and the previous California CH4 Survey (2016-2017; brown columns).

	Fall 2020 survey					Cal Methane Survey (2016-2017)				
Emission Sector	**Num plumes**	Num facilities w/sources	Emissions (kg/hr)	Uncertainty (kg/hr)	% total emissions	Num plumes	Num facilities w/sources	Emissions (kg/hr)	Uncertainty (kg/hr)	% total emissions
1A1 Energy Industries	14	5	640	223	3%	11	4	526	150	2%
1B2 Oil & Natural Gas	115	14	5719	2073	30%	174	14	8970	2596	30%
4A1 Managed Waste Disposal Sites	17	17	12183	5583	65%	17	16	20353	8152	68%
4D1 Domestic Wastewater Treatment & Discharge	0	0	0	0	0%	1	1	193	98	1%
4D2 Industrial Wastewater Treatment & Discharge	4	1	270	106	1%	0	0	0	0	0%
totals	*150*	*37*	*18812*	*7985*		*203*	*35*	*30042*	*10996*	
N facilities surveyed		*56*					*56*			
facilities w/ no sources detected		*19*					*21*			
totals for facilities sampled both 2020 & 2016-2017	*140*	*56*	*17507*	*7489*		*203*	*56*	*30042*	*10996*	

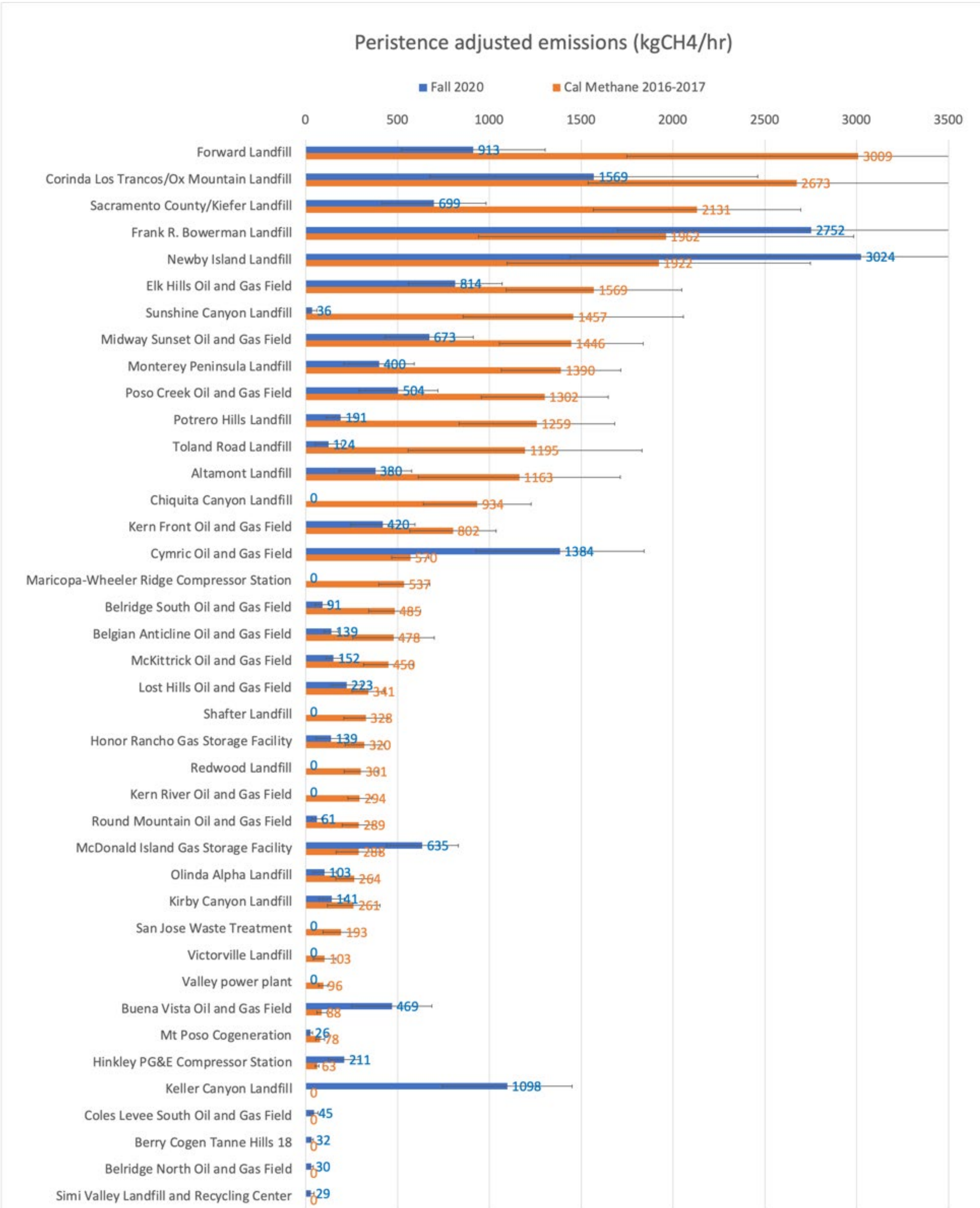

Figure 4 Comparing CH4 point source emissions from the 43 facilities in this Fall 2020 survey that were previously sampled by the California CH4 Survey in 2016-2017.

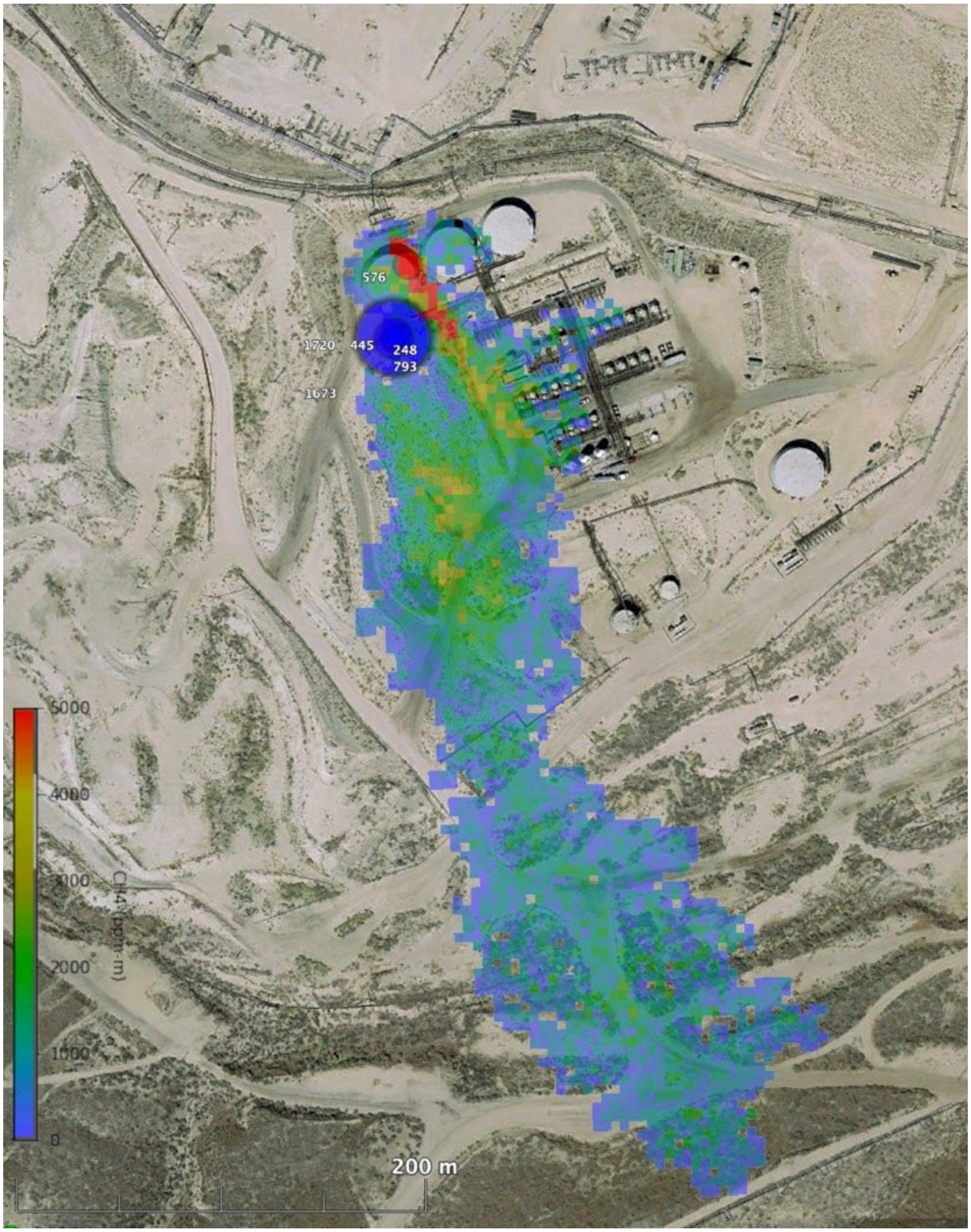

Figure 5 CH4 emissions detected repeatedly at a condensate storage tank during the Fall 2020 survey (as well as during prior overflights for another study in July 2020). The operator reported to CARB that the cause was a leaking 12" pressure relief valve that was subsequently repaired and verified by one of our follow-up overflights.

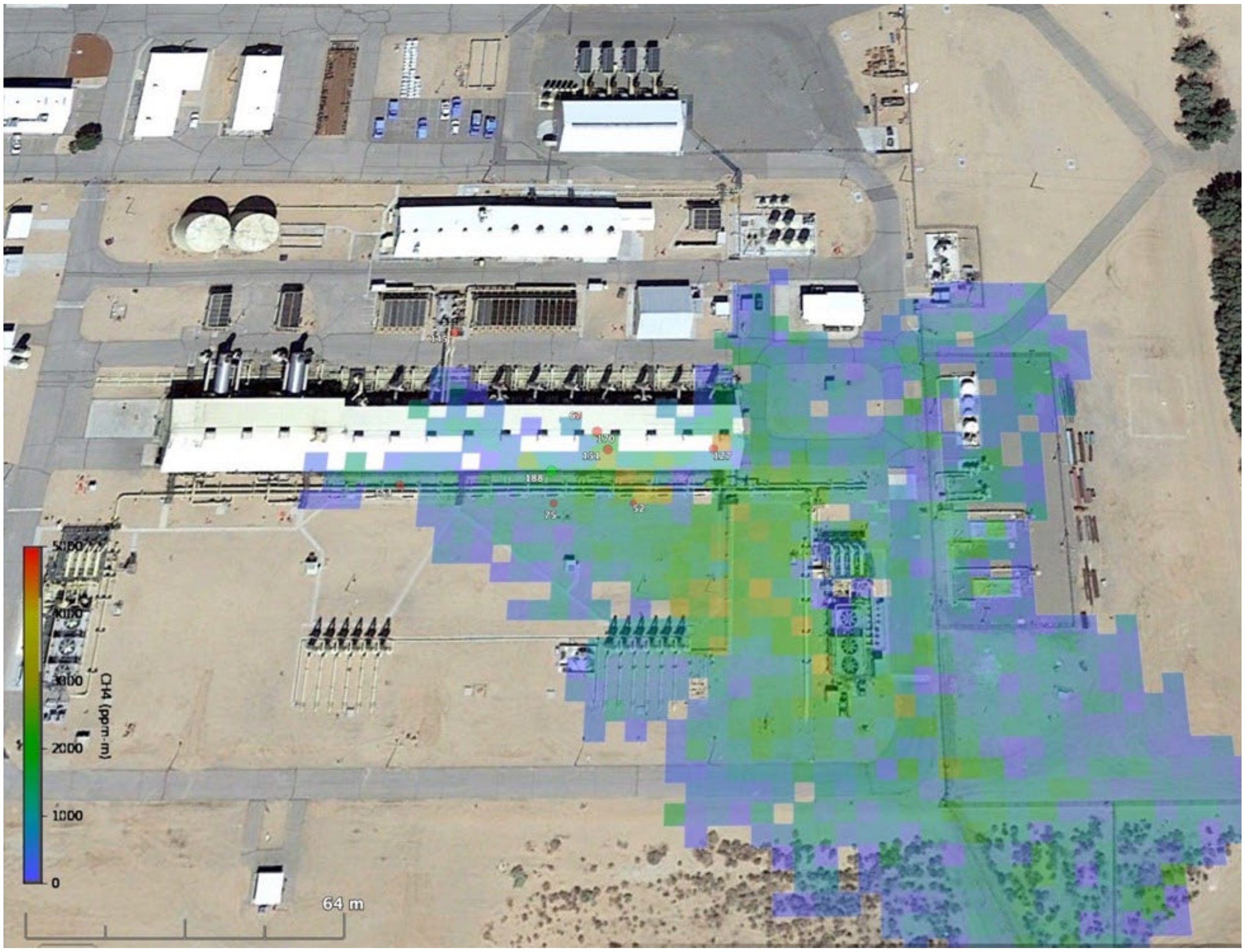

Figure 6 Persistent CH4 venting from Hinkley gas compressor station. The small dots indicate the best estimate of the plume origin on different overflights. The operator notified CARB that a leak had been verified and repairs were planned but not confirmed by the conclusion of the November 2020 overflights.

Figure 7 illustrates an example of one landfill (Newby Island) where emissions were significantly higher than the 2016-2017 California CH4 Survey. We do not have a robust hypothesis for why emissions appear to be increasing at some facilities while decreasing at others (Figure 4) however it is likely due to different management practices and/or retrofit programs.

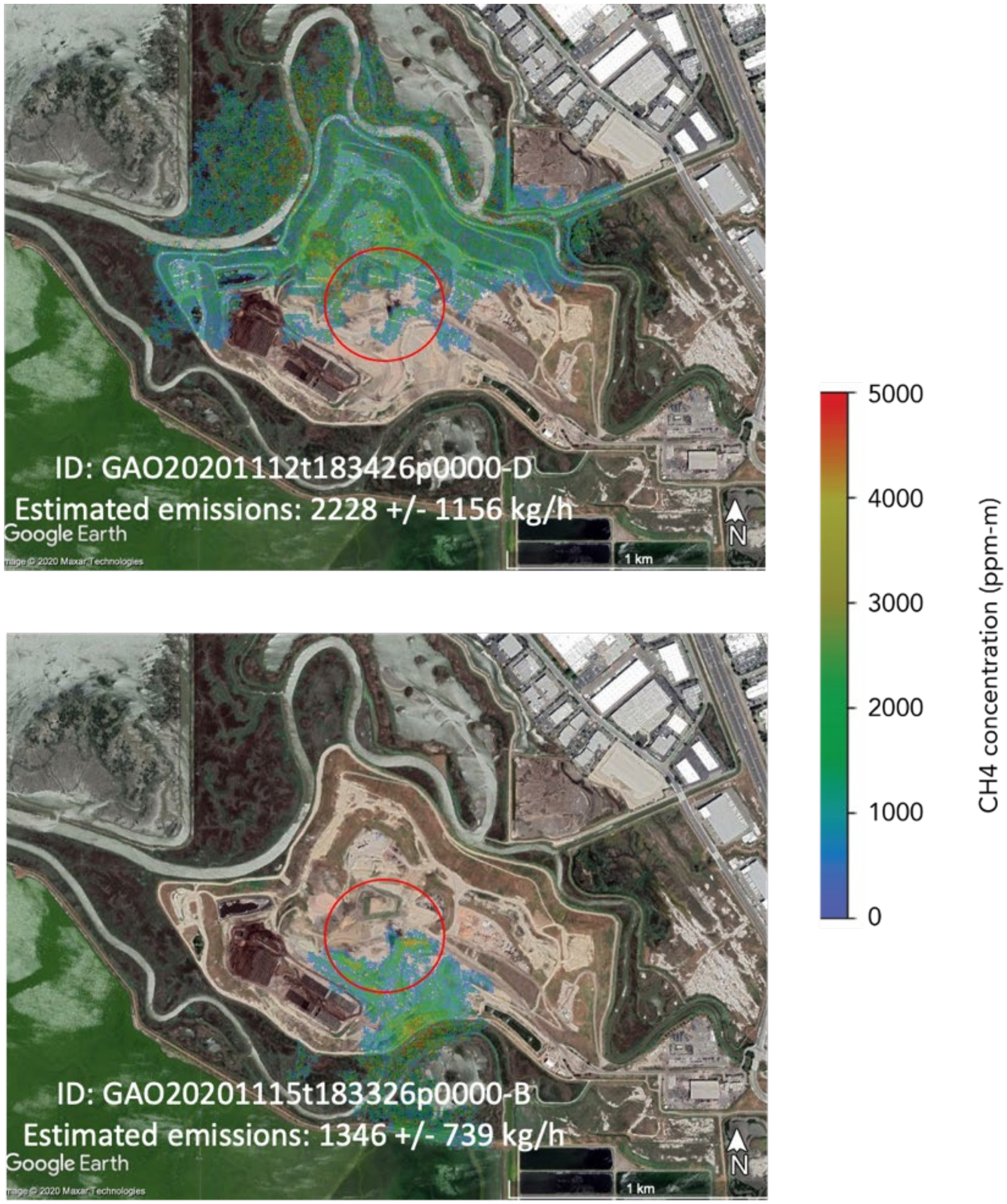

Figure 7 Example of persistent localized, elevated CH4 activity on two different days at Newby Island landfill in northern California. This facility's average emissions were significantly higher in Fall 2020 than during the 2016-2017 California CH4 Survey.

6. Recommendations for Future Projects

Given the degree of operator participation and potential for leak repairs during and following this campaign it is recommended that a follow-up airborne campaign be conducted using the same methods over the same facilities to assess the impact and permanence of those efforts.

Additionally, this study, the previous California CH4 Survey (Duren *et al.,* 2019), and our recently completed Permian basin study (Cusworth *et al.,* 2021) conclusively indicate that many localized elevated sources of CH4 are highly stochastic, variable and intermittent, and ubiquitous across many emission sectors. This indicates that accurate quantification and effective mitigation of CH4 point source emissions requires frequent, repeated sampling of large areas. It is for this reason that future satellites with sufficient sensitivity, spatial coverage, and revisit frequency such as the Carbon Mapper constellation should provide critical contributions, along with ongoing airborne and surface observations, in addressing these challenges.

7. References

California Greenhouse Gas Emission Inventory - California Air Resources Board, CH4 emissions for 2016, https://www.arb.ca.gov/cc/inventory/data/data.htm (2018).Cusworth, D.H., Duren, R.M., Thorpe, A.K., Tseng, E., Thompson, D., Guha, A., Newman, S., Foster, K.T. and Miller, C.E., 2020. Using remote sensing to detect, validate, and quantify CH4 emissions from California solid waste operations. Environmental Research Letters, 15(5), p.054012.

Cusworth, Daniel H.,Riley M. Duren, Andrew K. Thorpe, Winston Olson-Duvall, Joseph Heckler, John W. Chapman, Michael L. Eastwood, Mark C. Helmlinger, Robert O. Green, Gregory P. Asner, Philip E. Dennison, and Charles E. Miller., Intermittency of Large CH4 Emitters in the Permian Basin, *Environmental Science & Technology Letters* Article ASAP, DOI: 10.1021/acs.estlett.1c00173

Duren, R. M., Thorpe, A. K., Foster, K. T., Rafiq, T., Hopkins, F. M., Yadav, V., Bue, B. D., Thompson, D. R., Conley, S., Colombi, N. K., Frankenberg, C., McCubbin, I. B., Eastwood, M. L., Falk, M., Herner, J. D., Croes, B. E., Green, R. O., and Miller, C. E.: California's CH4 super-emitters, Nature, 575, 180–184, doi:10.1038/s41586-019-1720-3, URL https://doi.org/10.1038/s41586-019-1720-3, 2019

Elder, C.D., Thompson, D.R., Thorpe, A.K., Hanke, P., Walter Anthony, K.M. and Miller, C.E., 2020. Airborne mapping reveals emergent power law of arctic CH4 emissions. Geophysical Research Letters, 47(3), p.e2019GL085707.

Frankenberg, C., *et al.,* Airborne CH4 remote measurements reveal heavy-tail flux distribution in Four Corners region. *Proc. Nat. Academy Sci.* 113 (35) 9734-9739 (2016)

Guha, A., Newman, S., Fairley, D., Dinh, T.M., Duca, L., Conley, S., Smith, M.L., Thorpe, A., Duren, R.M., Cusworth, D. and Foster, K., 2020. Assessment of Regional CH4 Emissions Inventories through Airborne Quantification in the San Francisco Bay Area. Environmental Science & Technology.

Hamlin, L., *et al.,* Imaging spectrometer science measurements for terrestrial ecology: AVIRIS and new developments. *Aerospace Conference,* IEEE (2011).

Krautwurst, S., Gerilowski, K., Jonsson, H.H., Thompson, D.R., Kolyer, R.W., Iraci, L.T., Thorpe, A.K., Horstjann, M., Eastwood, M., Leifer, I. and Vigil, S.A., 2017. CH4 emissions from a Californian landfill, determined from airborne remote sensing and in situ measurements. Atmospheric Measurement Techniques, 10(9), p.3429.Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and natural radiative forcing, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Tech. Rep.

Nisbet, E.G., Manning, M.R., Dlugokencky, E.J., Fisher, R.E., Lowry, D., Michel, S.E., Myhre, C.L., Platt, S.M., Allen, G., Bousquet, P. and Brownlow, R., 2019. Very strong atmospheric CH4 growth in the 4 years 2014–2017: Implications for the Paris Agreement. Global Biogeochemical Cycles, 33(3), pp.318-342.

Thompson, D.R., *et al.,* Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with CH4. *Atmos. Meas. Tech., 8* (10), 4383-4397 (2015).

Thompson, D.R., *et al.,* Space-based remote imaging spectroscopy of the Aliso Canyon CH4 superemitter. *Geophy. Res. Let. 43*(12), pp.6571-6578 (2016).

Thorpe, A.K., *et al.,* Airborne DOAS retrievals of CH4, carbon dioxide, and water vapor concentrations at high spatial resolution: application to AVIRIS-NG. *Remote Sensing of Environment* 179, 104–115 (2016)

Thorpe, A.K., Duren, R.M., Conley, S., Prasad, K.R., Bue, B.D., Yadav, V., Foster, K.T., Rafiq, T., Hopkins, F.M., Smith, M.L. and Fischer, M.L., 2020. CH4 emissions from underground gas storage in California. Environmental Research Letters, 15(4), p.045005.

8. Acknowledgements

The views expressed here are those of the author and do not represent the positions of any institutions. This work benefited from analytic frameworks funded by NASA's Carbon Monitoring System and Advanced Information Systems Technology programs. RD's JPL affiliation is for unrelated programs and did not support this effort. The Global Airborne Observatory (GAO) is managed by the Center for Global Discovery and Conservation Science at Arizona State University. The GAO is made possible by support from private foundations, visionary individuals, and Arizona State University.

Appendix

Table A.1 – Facility List indicating all 56 facilities surveyed during the Fall 2020 survey (blue columns). Earlier results from the California CH4 Survey are offered for comparison (brown columns). The rightmost column indicates that 13 of the facilities covered in Fall 2020 were not covered in the previous survey.

			Fall 2020 survey			Cal Methane Survey (2016-2017)			
Facility Name	Facility type	IPCC Emission Sector	Num plumes	Persistence adjusted emissions (kg/hr)	Persistence adjusted uncertainty (kg/hr)	Num plumes	Persistence adjusted emissions (kg/hr)	Persistence adjusted uncertainty (kg/hr)	Surveyed during Cal Methane?
Hinkley PG&E Compressor Station	gas compressor	1A1 Energy Industries	8	211	88	1	63	10	Y
Maricopa-Wheeler Ridge Compressor	gas compressor	1B2 Oil & Natural Gas	0	0	0	1	537	139	Y
Topock compressor station	gas compressor	1A1 Energy Industries	3	310	86	0	0	0	N
Honor Rancho Gas Storage Facility	gas storage facility	1B2 Oil & Natural Gas	1	139	82	2	320	107	Y
MacDonald Island Gas Storage Facility	gas storage facility	1B2 Oil & Natural Gas	6	635	196	3	288	121	Y
Altamont Landfill	landfill	4A1 Managed Waste Disposal Sites	1	380	198	1	1163	550	Y
Azusa Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	Y
Badlands Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Barstow Sanitary Landfill	landfill	4A1 Managed Waste Disposal Sites	1	40	13	0	0	0	N
Bradley Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	Y
Central Disposal Site (Sonoma county)	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Chiquita Canyon Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	1	934	293	Y
Corinda Los Trancos/Ox Mountain Lar	landfill	4A1 Managed Waste Disposal Sites	1	1569	892	1	2673	1135	Y
El Sobrante Landfill	landfill	4A1 Managed Waste Disposal Sites	1	428	224	0	0	0	N
Forward Landfill	landfill	4A1 Managed Waste Disposal Sites	1	913	392	1	3009	1261	Y
Frank R. Bowerman Landfill	landfill	4A1 Managed Waste Disposal Sites	1	2752	1054	1	1962	1022	Y
Keller Canyon Landfill	landfill	4A1 Managed Waste Disposal Sites	1	1098	353	0	0	0	Y
Kirby Canyon Landfill	landfill	4A1 Managed Waste Disposal Sites	1	141	69	1	261	144	Y
Lamb Canyon Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Lancaster Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Midvalley Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Monterey Peninsula Landfill	landfill	4A1 Managed Waste Disposal Sites	1	400	191	1	1390	326	Y
Newby Island Landfill	landfill	4A1 Managed Waste Disposal Sites	1	3024	1586	1	1922	826	Y
Olinda Alpha Landfill	landfill	4A1 Managed Waste Disposal Sites	1	103	64	1	264	101	Y
Potrero Hills Landfill	landfill	4A1 Managed Waste Disposal Sites	1	191	82	1	1259	424	Y
Recology Hay Road Landfill	landfill	4A1 Managed Waste Disposal Sites	1	256	67	0	0	0	N
Redwood Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	1	301	90	Y
Sacramento County/Kiefer Landfill	landfill	4A1 Managed Waste Disposal Sites	1	699	282	1	2131	564	Y
San Timoteo	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Scholl Canyon Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	Y
Shafter Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	2	328	120	Y
Simi Valley Landfill and Recycling Cen	landfill	4A1 Managed Waste Disposal Sites	1	29	18	0	0	0	Y
Sonoma County Transfer Station	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Sunshine Canyon Landfill	landfill	4A1 Managed Waste Disposal Sites	1	36	25	1	1457	599	Y
Toland Road Landfill	landfill	4A1 Managed Waste Disposal Sites	1	124	71	1	1195	637	Y
Victorville Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	1	103	61	Y
Yolo County Central Landfill	landfill	4A1 Managed Waste Disposal Sites	0	0	0	0	0	0	N
Belgian Anticline Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	1	139	39	4	478	222	Y
Belridge North Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	2	30	12	0	0	0	Y
Belridge South Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	1	91	39	5	485	142	Y
Buena Vista Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	6	469	218	1	88	27	Y
Coles Levee South Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	2	45	23	0	0	0	Y
Cymric Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	29	1384	457	8	570	101	Y
Elk Hills Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	15	814	255	41	1569	478	Y
Kern Front Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	14	420	174	22	802	235	Y
Kern River Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	0	0	0	12	294	64	Y
Lost Hills Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	7	223	83	4	341	89	Y
McKittrick Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	2	152	42	7	450	135	Y
Midway Sunset Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	18	673	239	25	1446	392	Y
Poso Creek Oil and Gas Field	oil and gas field	1B2 Oil & Natural Gas	11	504	216	39	1302	345	Y
Round Mountain Oil and Gas Field	oil and gas field	1A1 Energy Industries	1	61	28	7	289	90	Y
Berry Cogen Tanne Hills (Midway Sur	powerplant	1A1 Energy Industries	1	32	10	0	0	0	Y
Mt Poso Cogeneration	powerplant	1A1 Energy Industries	1	26	11	2	78	24	Y
Valley power plant	pwerplant	1A1 Energy Industries	0	0	0	1	96	25	Y
Baker Commodities rendering	wastewater treatmen	4D2 Industrial Wastewater Treatment & Discharge	4	270	106	0	0	0	N
San Jose Waste Treatment	wastewater treatmen	4D1 Domestic Wastewater Treatment & Discharge	0	0	0	1	193	98	Y

The detailed Plume List, persistence adjusted Source List, and plume image files are delivered to CARB as separate documents.