California's methane super-emitters

California's Methane Super-Emitters

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Abstract

Methane is a powerful greenhouse gas and is targeted for emissions mitigation by the US state of California and other jurisdictions worldwide[1, 2]. Unique opportunities for mitigation are presented by point-source emitters—surface features or infrastructure components that are typically less than 10 metres in diameter and which emit plumes of highly concentrated methane[3]. However, data on point-source emissions are sparse and typically lack sufficient spatial and temporal resolution to guide their mitigation and to accurately assess their magnitude[4]. Here we survey more than 272,000 infrastructure elements in California using an airborne imaging spectrometer that can rapidly map methane plumes[5, 6, 7]. We conduct five campaigns over several months from 2016 to 2018, spanning the oil and gas, manure- management and waste-management sectors, resulting in the detection, geolocation and quantification of emissions from 564 strong methane point sources. Our remote sensing approach enables the rapid and repeated assessment of large areas at high spatial resolution for a poorly characterized population of methane emitters that often appear intermittently and stochastically. We estimate net methane point-source emissions in California to be 0.618 teragrams per year (95 per cent confidence interval 0.523–0.725), equivalent to 34–46 per cent of the state's methane inventory[8] for 2016. Methane 'super-emitter' activity occurs in every sector surveyed, with 10 per cent of point sources contributing roughly 60 per cent of point-source emissions—consistent with a study of the US Four Corners region that had a different sectoral mix[9]. The largest methane emitters in California are a subset of landfills, which exhibit persistent anomalous activity. Methane point-source emissions in California are dominated by landfills (41 per cent), followed by dairies (26 per cent) and the oil

and gas sector (26 per cent). Our data have allowed the identification of the 0.2 per cent of California's infrastructure that is responsible for these emissions. Sharing these data with collaborating infrastructure operators has led to the mitigation of anomalous methane-emission activity[10].

Methane (CH_4) is being increasingly prioritized for near-term climate action given its relatively short atmospheric lifetime and the potential for rapid, focused mitigation that can complement economy-wide efforts to reduce carbon dioxide emissions. Efforts to mitigate California's methane emissions are complicated by large inconsistencies between estimates of methane emissions derived from atmospheric measurements and greenhouse gas inventories. Past studies using atmospheric measurements report methane emissions that are higher than those reported by inventories for California both statewide [11-13] and for key regions and sectors [14-15]. Other studies indicate that methane emissions from the oil and gas supply chain are about 60% higher than currently reported in the national greenhouse gas inventory [16] and that there is a heavy-tail distribution of methane emission sources in the US natural gas supply chain where typically fewer than 20% of sources (so-called super-emitters) contribute more than 60% of total emissions from that sector [17]. Scientists and policymakers have emphasized rapid identification and mitigation of methane super-emitters, particularly those due to leaks and abnormal operating conditions [18].

In addition to California, there remain large uncertainties regarding the distribution of methane emissions in other key regions and emission sectors globally[19]. There is a dearth of available observational studies of other sectors such as livestock manure management and landfills, both of which are predicted to be significantly larger contributors to California's methane budget than the oil and gas sector [8]. Additionally, spatially sparse and infrequent field studies can over- or under-estimate important methane sources that are intermittent and/or highly unpredictable. Finally, the relative contributions of methane point sources and area sources have not been well studied in California. We define "point source" to be a condensed surface feature or infrastructure component < 10 meters across that emits plumes of highly concentrated methane. This is in contrast to an "area source" or the combined effect of many small emitters distributed over a large area (typically 1 – 100 km across) that releases methane in a more diffuse fashion including anaerobic decomposition from rice cultivation and enteric fermentation from ruminant animals, both of which are better addressed with other measurement methods and not included in this study.

The California Methane Survey was designed to provide the first systematic survey of methane point sources across the State with a focus on detecting, geolocating and quantifying super-emitters. This survey fills an important scale gap and complements other observational systems that provide aggregate constraints on emissions from regions and area sources [20-22] and short-duration field campaigns limited to a small number of facilities [23-24]. It was conducted with the Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG). AVIRIS-NG measures ground-reflected solar radiation from 380 to 2,510 nm with 5 nm spectral sampling and has a 1.8 km field of view and 3 m pixel resolution at typical survey altitudes of 3 km [5]. This class of instrument is unique in terms of its high signal to noise ratio, calibration accuracy and response uniformity [25]. The methane retrieval is based on absorption spectroscopy [6-7,26] and can reliably detect and quantify methane point sources with emissions typically as small as 2-10 kg CH_4 h^{-1} for typical surface winds of 5 m s^{-1}, depending on surface brightness and aircraft altitude and ground speed. See Supplementary Information (SI) section for detailed description of data sets, estimation methods and validation.

The spatial and sectoral scope of this survey included key methane point source emission sectors in California including oil and gas production, processing, transmission, storage and distribution; refineries; dairy manure management; landfills and composting facilities; waste water treatment plants; gas fired power plants; and liquified and compressed natural gas facilities. Multiple overflights were conducted for the same infrastructure over several years to assess source persistence.

AVIRIS-NG flights for this study were conducted during five campaigns: August – November 2016, March 2017, June 2017, August-November 2017, and September-October 2018. The survey imaged approximately 59,000 km^2 including revisits (Fig 1). The survey was designed to cover at least 60% of methane point source infrastructure in California guided by a Geographic Information System (GIS) data set known as Vista-CA, described in Supplemental Information. Approximately 272,000 infrastructure elements were covered by the survey, most of which were observed multiple times to assess emission source persistence. The survey included over 200,000 oil and gas wells and related production infrastructure – representing a sample size over 500 times larger than previous point source persistence studies [27].

The AVIRIS-NG flights conducted during this survey detected 1,181 individual methane plumes that were each attributed to a Vista-CA infrastructure element (Fig. 1). Average emission rates and 1σ uncertainties were estimated for 564 distinct sources at 250 facilities using observed methane enhancements and surface wind speed data from weather reanalysis products. The sum of our measured source emissions is 0.511 Tg CH_4 y^{-1} and we apply a non-parametric bootstrap analysis to the population of observed sources to calculate a 95% confidence interval of 0.433 - 0.601 Tg CH_4 y^{-1}. The population has a heavy-tail distribution indicating that 10% of the point sources are responsible for 60% of the detected point source emissions (Fig. 2 and SI) spanning every surveyed sector

The repetitive, high spatial resolution plume imagery allowed us to characterize point source behavior and controlling processes, particularly for sectors that have not been as well studied as the oil and gas production sector. Many of the sources were highly intermittent – with a median persistence of 0.20 for the entire population (mean 0.33, range 0.02 – 1.0). In some cases, the intermittent emissions can be explained by normal operations (e.g., periodic waste flushing at large dairies). In other cases, more persistent activity is apparently due to sustained venting at a small number of anaerobic digesters at dairies and waste water treatment plants or leaking bypass valves at natural gas compressor stations. We find a similar distribution of persistence (20-35% on average) and emissions in the manure management, waste water treatment and oil and gas sectors. Solid waste management is the largest methane point source emission sector in California (Table 1) with persistent plumes only observed at 32 of 436 surveyed landfills and composting facilities. Our imagery of landfills identified methane plumes associated with construction, gaps in intermediate cover and leaking gas capture wells – indicating a sub-population of anomalous emitters (see SI section). The fact that we did not detect a larger population of smaller methane point sources across the landfill sector suggests the majority of those facilities emit methane as area sources that are not detectable with this method.

Since we surveyed a significant fraction (32-100%) of every point source emission sector in California we can upscale our measurements to estimate statewide point source emissions. resulting in 0.618 (95% confidence 0.523-0.725) $TgCH_4\ yr^{-1}$, equivalent to 34 - 46% of the California Air Resources Board (CARB) methane inventory for 2016 [8]. We find that solid waste management contributes 41% of observed point source emissions followed by 26% from manure management and 26% from oil and gas (in contrast to 32%, 39% and 25% of total methane emissions for those sectors according to the CARB inventory). We estimate that upstream oil and gas production contributes about 79% of the total oil and gas methane point source emissions in California. Spatially, 85% of point source emissions from upstream production are concentrated in the southern San Joaquin Valley (the highest oil- and associated-gas producing region in the State), 14% in Los Angeles and Ventura counties, and 1% in the Sacramento Valley.

In addition to solid waste management, other emission sectors may be significantly underestimated in the CARB inventory. When comparing our estimates of point source emissions for those sectors in the CARB inventory most likely to include methane point sources our sectoral estimates account for ~38% of emissions from the wastewater treatment sector, 42% of manure management sector, and ~366% of the CARB inventory for the energy industries sector. The latter is likely associated with most refineries and a small number of high emitting power plants (SI section). Large discrepancies are observed between many of the self-reported emissions from participating facilities and AVIRIS-NG and independent airborne estimates (Figure 3 and SI). We also find that our population of point source emissions in California and that of the EPA's Greenhouse Gas Reporting Program (GHGRP) for the entire US [28] both indicate that 99% of those emissions come from facilities emitting at least 25 kg h^{-1} (SI section). This is significant considering that manure management and oil and gas production contribute over half of the point source emissions in our study but those sectors are mostly not included in the GHGRP for California and are only partially represented in the total US GHGRP.

We shared preliminary findings from our surveys, including methane plume images, with collaborating facility operators, who provided verification with surface observations and/or explained the underlying mechanisms for the observed emissions and persistence. Many of these collaborative efforts directly led to mitigation of the methane sources detected by the survey. For example, we discovered four cases of leaking natural gas distribution lines and one leaking liquified natural gas storage tank (Fig. 1) that the operators confirmed and repaired and then requested verification by follow up AVIRIS-NG flights (10). The prevalence of methane super-emitter activity observed across multiple sectors in California suggests significant mitigation potential. We find that 30 facilities are potentially responsible for ~20% of the 2016 CARB methane inventory including many that exhibit large discrepancies between reported and measured emissions (Figure 3 and SI). Our survey in California and a previous study of the Four Corners region in the US exhibit consistent heavy-tail distributions of methane point source emissions (Figure 2) despite the different sectoral mixes for the two regions; the Four Corners emissions are primarily associated with oil, gas, and coal production [9]. If similar distributions of methane point source emissions occur in other key regions around the world that could translate to as much as much as 8-11% of global greenhouse gas forcing, assuming a100 year warming potential of 32 and 350 $TgCH_4\ y^{-1}$ total anthropogenic methane emissions for 2016 [19, 29]. Testing this hypothesis would require additional aircraft surveys and satellite observations that can provide the necessary combination of high spatial resolution, sensitivity and wide area coverage for other key regions globally. Those broader studies would also improve understanding of waste and manure management emissions which like California may dominate the emission budgets of other regions [19].

Methane point source detection limits could be relaxed by a factor of 10 compared to the system described in this study and still net 90% of super-emitters if applied frequently over large areas with emission distributions similar to those observed in California (Figure 2). Since detection scales linearly with spatial resolution [30], mature technologies such as the one described in this study could be deployed for more efficient point source monitoring across larger regions on high altitude aircraft and satellites. The high-performance infrared imaging spectroscopy demonstrated here would translate to a robust detection limit of 100 kgCH_4 h^{-1} for a satellite in low earth orbit depending on spatial resolution (assuming $\leq$ 5 m s^{-1} wind speed). Widespread and sustained deployment of point source remote sensing methods like the ones described here when combined with near-continuous regional monitoring of distributed area sources by surface observations and other satellites could significantly advance scientific understanding of methane budgets and efforts to manage them. Complete methane budget closure and effective mitigation will likely require a multi-tiered observational strategy, of which the methods demonstrated in this study can play a key role.

Data Availability

AVIRIS-NG calibrated radiance and reflectance products can be ordered from the AVIRIS-NG data portal https://avirisng.jpl.nasa.gov/alt_locator/. Retrieved methane images from flight lines in this study are available for download at https://doi.org/10.3334/ORNLDAAC/1727. Vista-CA infrastructure spatial layers are available for download at https://doi.org/10.3334/ORNLDAAC/1726. Methane plumes images, Vista-CA layers, and regional scale methane emission products for California can be viewed at https://methane.jpl.nasa.gov/. Tables of methane plume and source characteristics reported in this study are provided as Extended Data.

Code Availability

Custom computer code or algorithms used to generate results in this paper can be made available to researchers upon request.

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Author contributions: R.M.D., A.K.T., F.M.H. and C.E.M conceived the study. R.M.D., A.K.T., F.M.H., T.R., I.B.M, M.L.E. and S.C. conducted flight planning. Each author contributed to the collection, analysis or assessment of one or more data sets necessary to perform this study. R.M.D., A.K.T., K.T.F., F.M.H. and T.R performed the analysis with contributions from B.D.B., D.R.T., C.F., N.K.C., M.F., J.D.H, B.E.C, R.O.G. and V.Y. R.M.D., A.K.T., K.T.F. and F.M.H. wrote the manuscript with input from all authors.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to R.D. (riley.m.duren@jpl.nasa.gov).

Supplementary Information

Detailed Materials and Methods

Figs S.1 – S.13

Tables S.1 – S.3

Supplementary Tables

Supplementary Table S.4: Methane Plume List

Supplementary Table S.5: Methane Source List

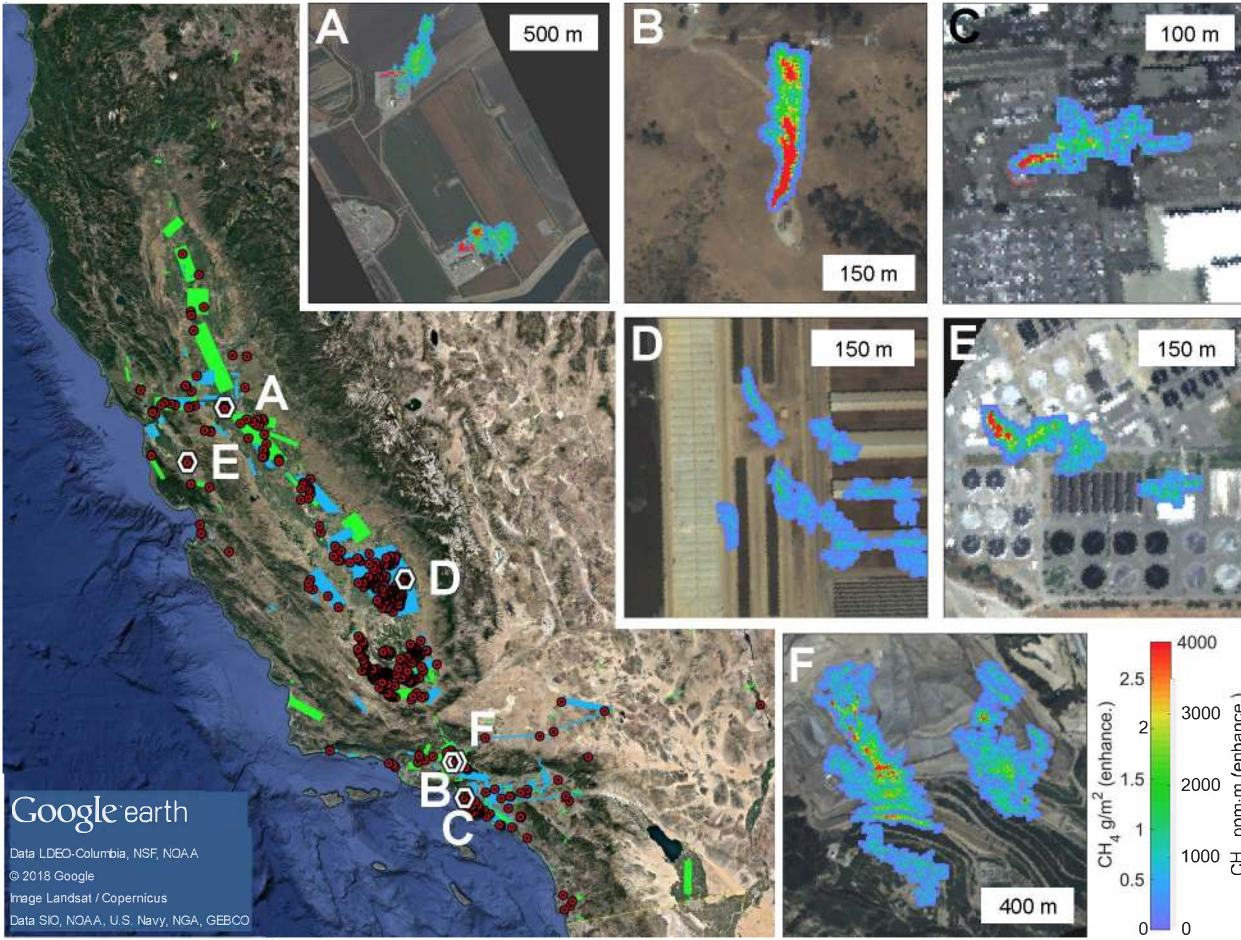
Table 1: Summary of persistence (frequency) adjusted point source emissions by IPCC sector from this study and estimated total emissions derived with population scalars. Most of the scalars are simply the ratio of the number Vista-CA infrastructure elements to the number of surveyed elements with three exceptions highlighted in blue font (other oil and gas production equipment, landfills and industrial wastewater treatment) where we further constrain or eliminate scaling. See Supplementary Information (S2) for details.

IPCC Source Category	Vista-CA infrastructure element	# of Vista-CA infrastructure elements	# of surveyed elements	% surveyed	Sectoral Scalar	N sources detected	Measured emissions ($TgCH_4\ y^{-1}$)	State Total Emissions ($TgCH_4\ y^{-1}$)	State total 95% confidence intervals ($TgCH_4\ y^{-1}$)	% of total emissions
1A1 Energy Industries	Gas fired power plants	435	238	55	1.83	7	0.007	0.013	0.007, 0.021	2.1%
	Refineries	26	26	100	1.00	37	0.015	0.015	0.008, 0.023	2.4%
	sub-totals	*461*	*264*	*57*	*1.27*	*44*	*0.022*	*0.028*	*0.015, 0.044*	*4.6%*
1B2 Oil and Natural Gas	CNG/LNG Fueling Stations	208	132	63	1.58	6	0.002	0.003	0.003, 0.004	0.5%
	NG Stations (non-storage compressor, metering, etc)	1,131	538	48	2.10	5	0.005	0.010	0.009, 0.012	1.6%
	NG Pipeline (transmission, distribution)	216,774	68,548	32	3.16	5	0.004	0.012	0.010, 0.014	1.9%
	NG Processing Plants	26	23	88	1.13	5	0.004	0.004	0.004, 0.005	0.7%
	NG Storage Fields	12	12	100	1.00	11	0.009	0.009	0.008, 0.010	1.4%
	Oil & Gas: Wells	225,766	198,231	88	1.14	107	0.048	0.054	0.046, 0.063	8.8%
	Oil & Gas: Other Production Equipment	3,356	2,872	86	1.00	120	0.066	0.066	0.056, 0.076	10.7%
	sub-totals	*447,273*	*270,356*	*60*	*1.16*	*259*	*0.137*	*0.158*	*0.135, 0.184*	*25.6%*
3A2 Manure Management	Dairy Confined Animal Feeding Operations	620	443	71	1.40	215	0.115	0.161	0.137, 0.187	26.1%
4A1 Managed Waste Disposal	Landfills & composting facilities	1,146	436	38	1.11	32	0.229	0.255	0.175, 0.345	41.3%
4D1, 4D2 Wastewater Treatment & Discharge	Domestic & industrial wastewater treatment	148	57	39	2.60	12	0.004	0.012	0.005, 0.020	1.9%
	Industrial wastewater treatment: beef processing	n/a	n/a	n/a	1.00	2	0.004	0.004	0.004, 0.005	0.6%
	totals	*449,648*	*271,556*	*60*	*1.21*	*564*	*0.511*	*0.618*	*0.523, 0.725*	*100.0%*

Figure 1 Approximately 2000 individual AVIRIS-NG flight lines flown in 2016 (blue) and 2017 (green) covered over 272,000 individual facilities and infrastructure elements. Detected sources are indicated by red points with the densest clusters in the San Joaquin Valley (dairies and oil fields). The inset images show examples of representative methane plumes from different sectors: A. compressor stations at a natural gas storage facility, B. oil well, C. liquified natural gas tank, D. dairy manure management, E. wastewater treatment plant, F. landfill. The color scales indicate the methane concentration-length enhancement in each pixel in units parts per million-meter (ppm-m). Inset images are from AVIRIS-NG. The basemap image is from Google Earth, LDEO-Columbia, NSF, NOAA, Landsat/Copernicus, SIO, US Navy, GEBCO.

Figure 2 Distribution of point source emissions are consistent between two different regions. (A) 564 California methane point sources from all sectors (red) and 250 coal, oil and gas sources (blue) from the Four Corners region (9). The California numbers have not been adjusted for persistence here since that step wasn't possible for the brief Four Corners study. (B) Histogram showing the density of point source emissions with lognormal fits. The Four Corners region includes some large emitters associated with coal production that do not occur in California. The vertical lines indicate typical detection limits for this class of infrared imaging spectrometer: ranging from 2-10 $kgCH_4\ h^{-1}$ for the typical 3km flight altitudes used in this study through 100 $kg\ CH_4\ h^{-1}$ for an equivalent satellite in low earth orbit.

Figure 3. Independent airborne measurements of emissions (in $kgCH_4\ h^{-1}$) for representative facilities from (a) simultaneous flights and (b) average emissions from multiple non-simultaneous flights over several months. AVIRIS-NG estimates of point source emissions (orange bars) and Scientific Aviation estimates (31) of facility net emissions (blue bars). Error bars indicate 1 s.d. AVIRIS-NG estimates are lower for facilities having significant non point source activity. The 14 estimates here correlate with an R^2 of 0.86 (see SI). The R^2 for the 8 facilities in panel (a) is 0.99. The estimated total emissions here are 11,228 ± 4,981 $kg\ h^{-1}$ and 13,900 ± 3,593 $kg\ h^{-1}$ for AVIRIS-NG and Scientific Aviation, respectively. Diamonds indicate available self-reported emissions [28].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Data LDEO-Columbia, NSF, NOAA
© 2018 Google
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
CH4 g/m2 (enhance.)
CH4 ppm·m (enhance.)
4000
3000
2000
1000
0
2.5
2
1.5
1
0.5
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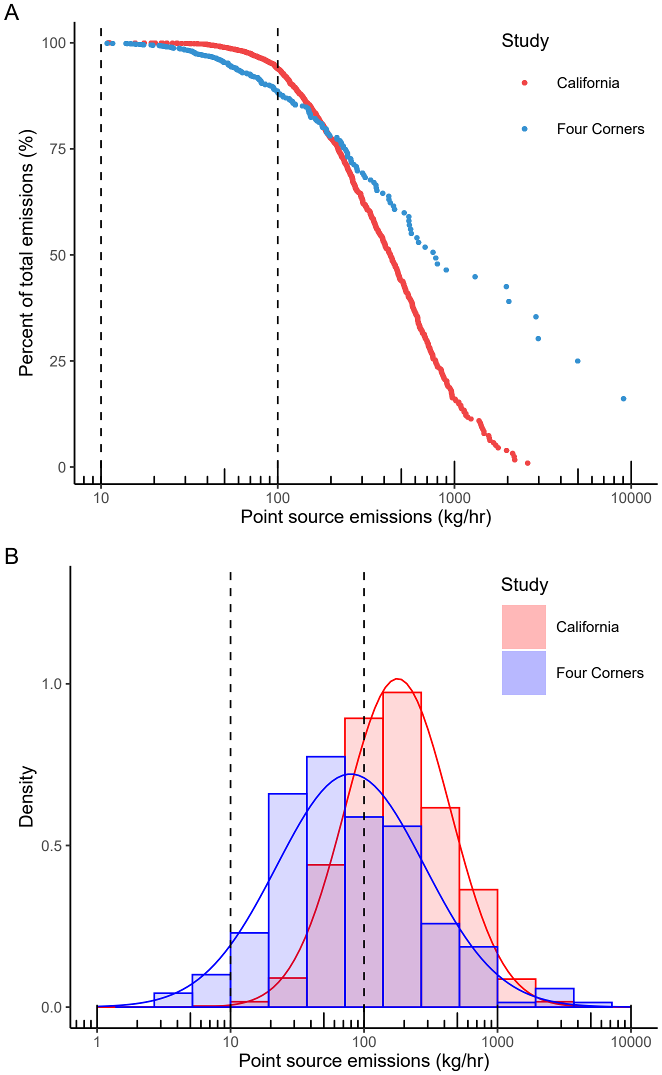
A
Percent of total emissions (%)
100
75
50
25
0
10
100
1000
10000
Point source emissions (kg/hr)
Study
California
Four Corners
B
Density
1.0
0.5
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Point source emissions (kg/hr)
Study
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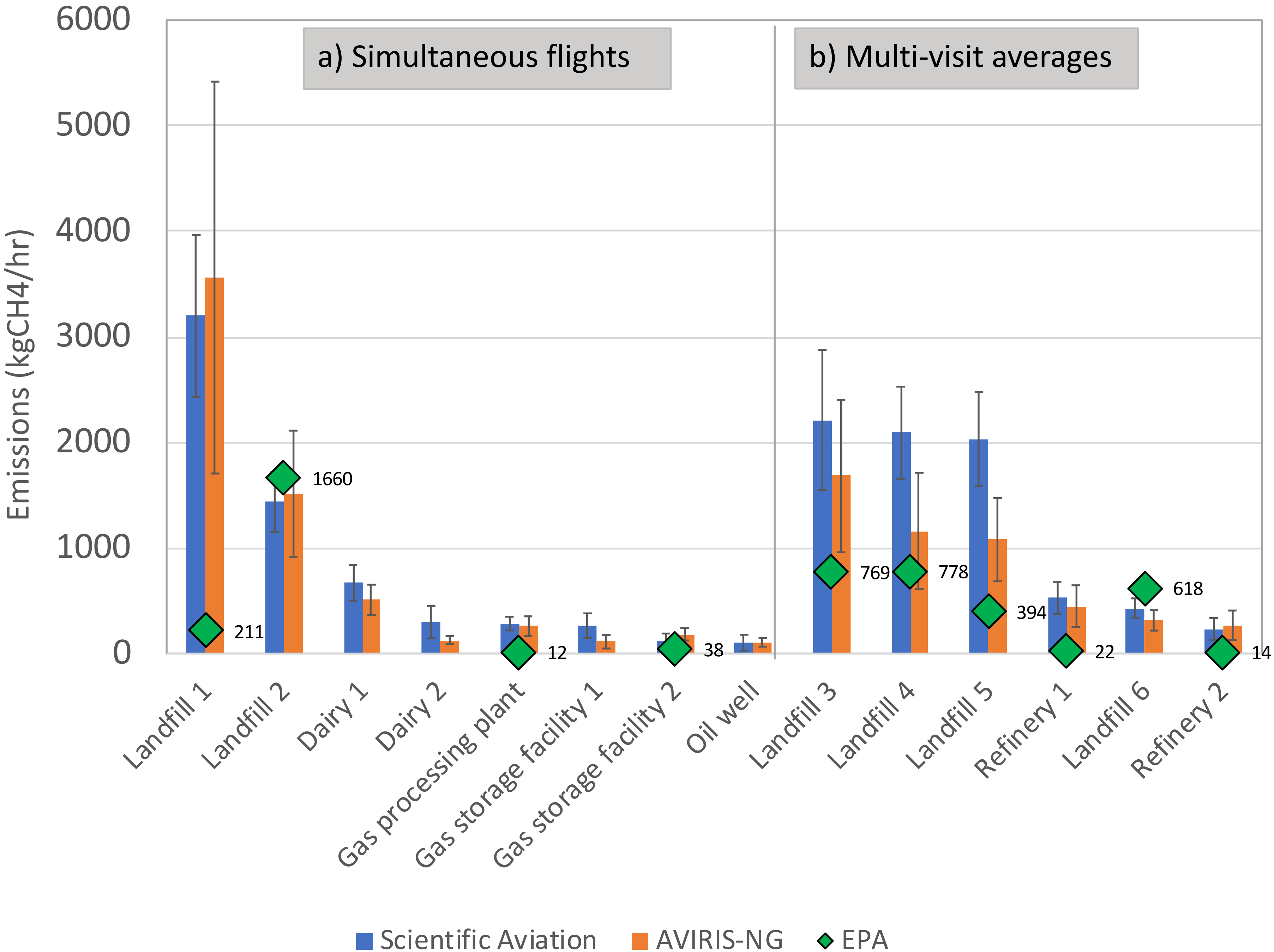
6000
5000
4000
3000
2000
1000
0
Emissions (kgCH4/hr)
a) Simultaneous flights
b) Multi-visit averages
211
1660
12
38
769
778
394
22
618
14
Landfill 1
Landfill 2
Dairy 1
Dairy 2
Gas processing plant
Gas storage facility 1
Gas storage facility 2
Oil well
Landfill 3
Landfill 4
Landfill 5
Refinery 1
Landfill 6
Refinery 2
Scientific Aviation
AVIRIS-NG
EPA