Design and Applications of GHG Monitoring Networks:

Data Retrieval, Emissions Accounting, and Mitigation

2023 Yangtze River Delta Clean Air Forum

August 31, 2023

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Research Division

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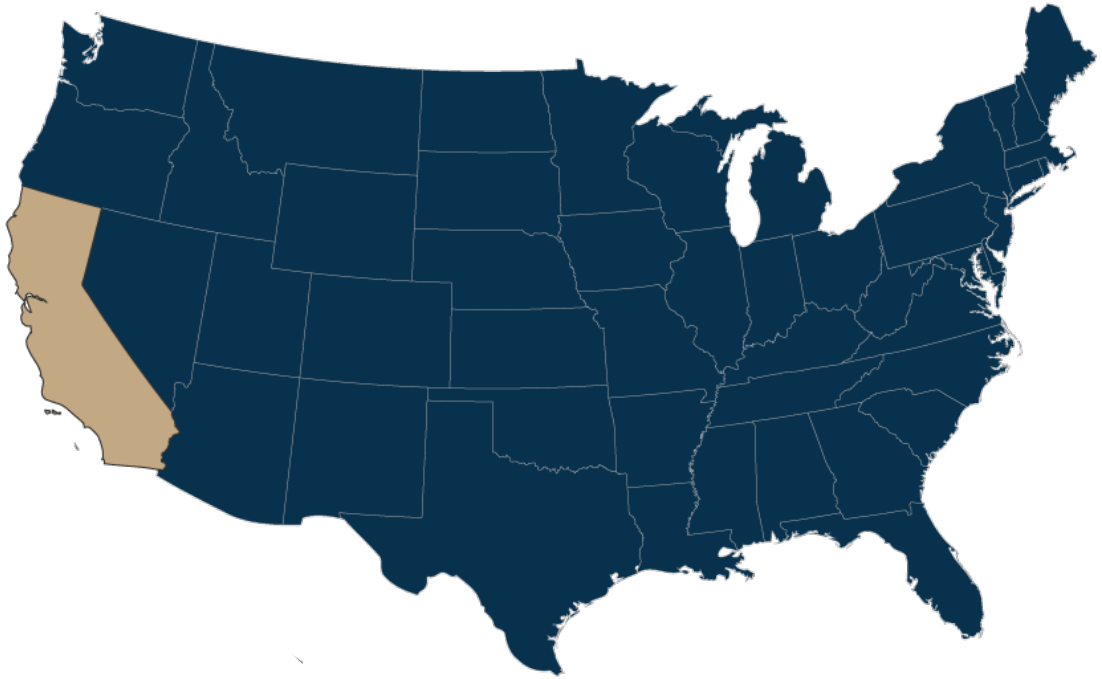
www.arb.ca.gov/cc/cc.htm

CALIFORNIA AIR RESOURCES BOARD

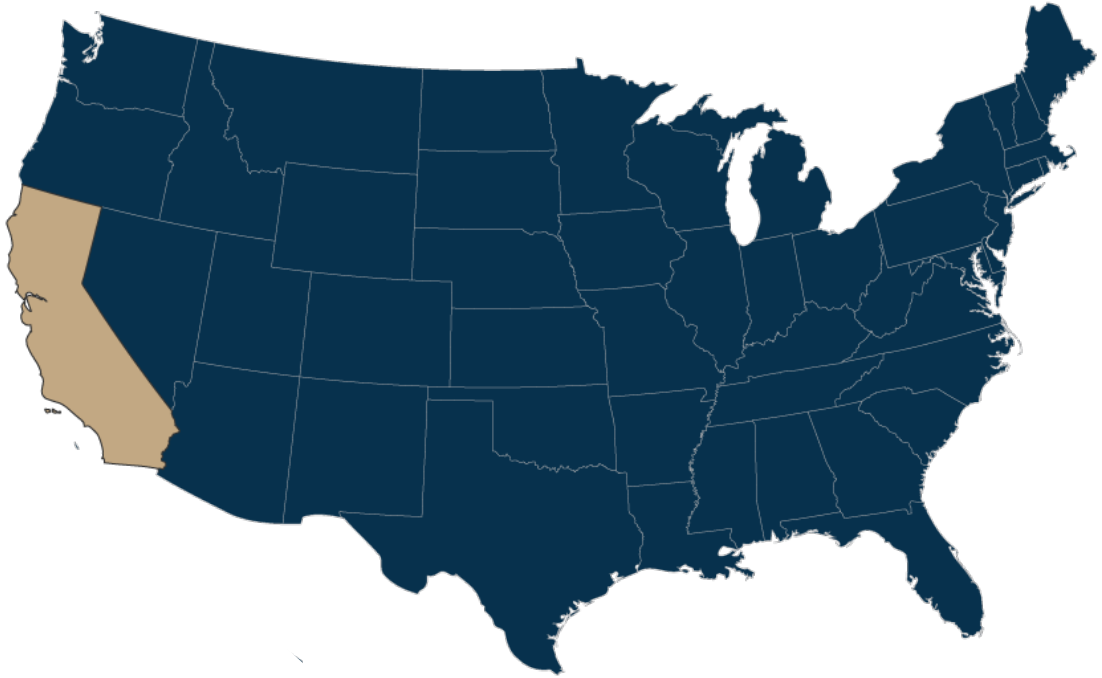
California



California is a collection of farmers, surfers, factory workers, outdoor enthusiasts, tech geeks, truckers, world-class researchers, celebrity actors, and many more—who come from all around the world to live and work in one of the most beautiful, vibrant, and ecologically and culturally diverse places on Earth. We are sustained, in more ways than one, by the mountains, deserts, rivers, streams, forests, farmlands, rangelands, coastline, and temperate climate that form our natural environment and characterize our great State.

California Scoping Plan 2013

California



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California Scoping Plan 2013

California's Air Pollution Problem

39 M people,
90 people per km^2
24 M gasoline cars
1.3 M diesel vehicles
1.4 B km per day
18 M off-road engines
3 large container ports

Geography and meteorology confine air pollutants, so necessary per capita pollution reduction needed to meet air quality standards are much greater than elsewhere, such as Atlanta, Houston, New York City, etc.

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California in the 1960’ties

no stranger to poor air quality

Dr. Arie J. Haagen-Smit 1900 – 1977

- The “father” of air pollution control
- Professor of bioorganic chemistry at California Institute of Technology
- Linked smog in southern California to automobiles
- ARB’s first Chairman in 1968
- Awarded the National Medal of Science in 1973

California Air Resources Board

On August 30, 1967, California's elected leaders came together to unify statewide efforts to address severe air pollution. Governor Ronald Reagan approved the Mulford-Carrell Air Resources Act to create the State Air Resources Board, committing California to a unified, statewide approach to aggressively address the serious issue of air pollution in the state.

In 2006, Assembly Bill 32, also known as the Global Warming Solutions Act of 2006, was signed by Gov. Arnold Schwarzenegger, giving CARB this new role. AB 32 established a first-in-the-world comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective reductions in greenhouse gases

California's Climate Requirements

Reduce Total Greenhouse Gas Emissions

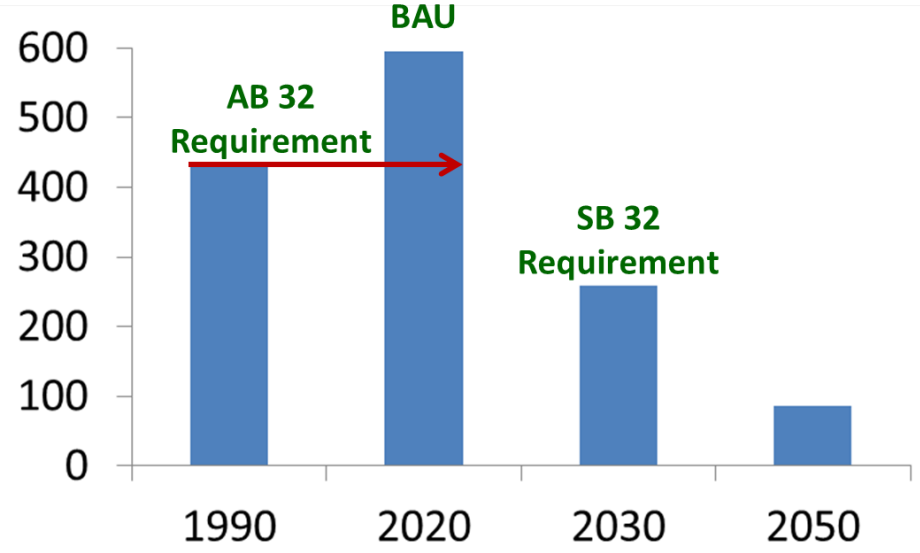
- 1990 Levels by 2020
- 40% below 1990 levels by 2030
- 80% below 1990 levels by 2050

Reduce Short Lived Climate Pollutants

- 40% below 2013 levels by 2030 for CH4 and HFCs
- 50% below 2013 levels by 2030 for BC

Electricity

- 50% renewables by 2030
- Carbon Free by 2045



Transportation

- Zero Emission Requirements for both cars and trucks
- By 2035 a*ll new cars and passenger trucks sold in California must be zero-emission vehicles*

Carbon Neutrality by 2045

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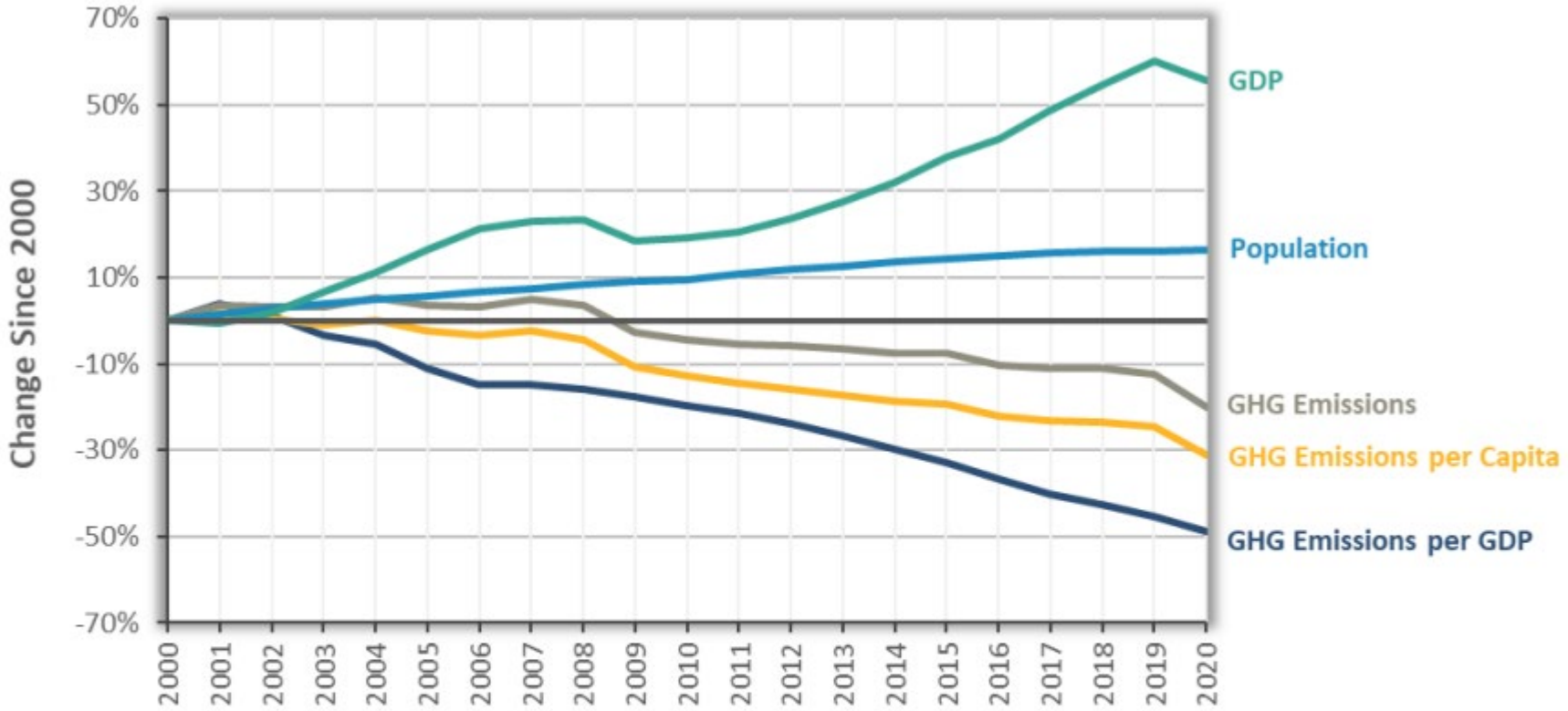
Progress to Date - Decoupling



Metric	Associated 2020 Value
GDP	2.7 trillion (2012 $)
Population	39.5 million
GHG Emissions	369.2 $MMTCO_2e$
GHG Emissions per Capita	9.3 metric tons CO_2e per person
GHG Emissions per GDP	139 metric tons CO_2e per million $

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The California Climate Program

Scoping Plans

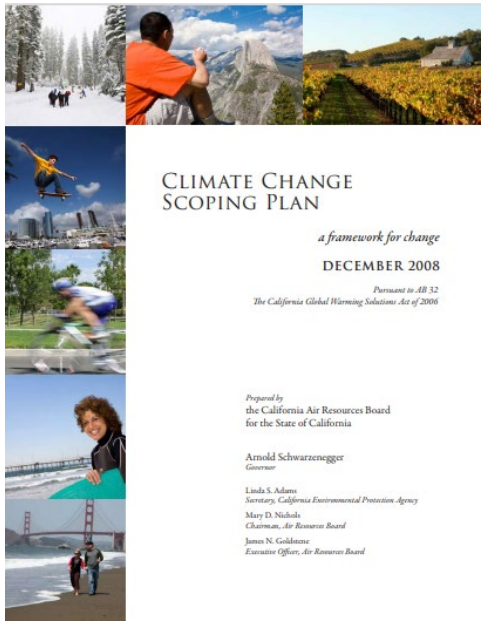
AB 32 required the California Air Resources Board to develop a **Scoping Plan** that describes the approach California will take to reduce GHGs to achieve the goal of reducing emissions to 1990 levels by 2020. The Scoping Plan was first approved by the Board in 2008 and must be updated at least every five years.

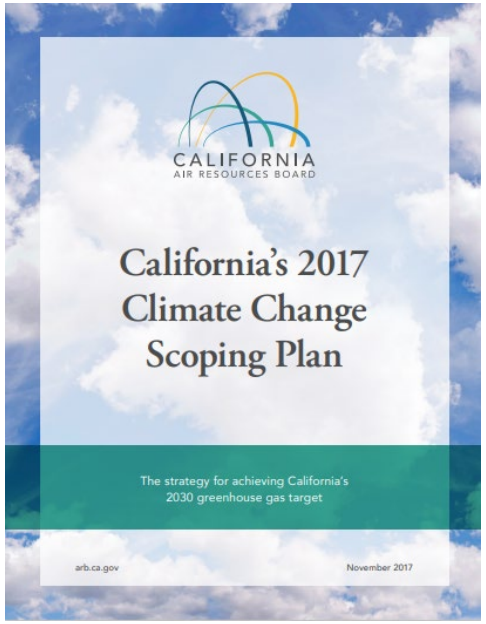
2008 – Achieving the 2020 target

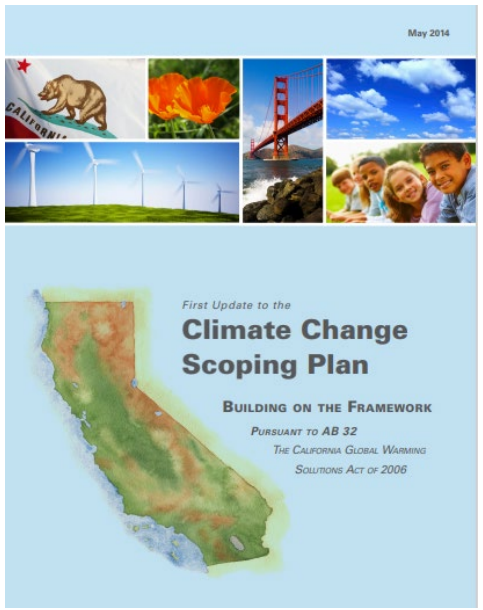
2013 – Building on the Framework

2017 – Achieving the 2030 target

2023 – Achieving Carbon Neutrality by 2045







Scoping Plans available here: https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan

Greenhouse Gas Monitoring In California

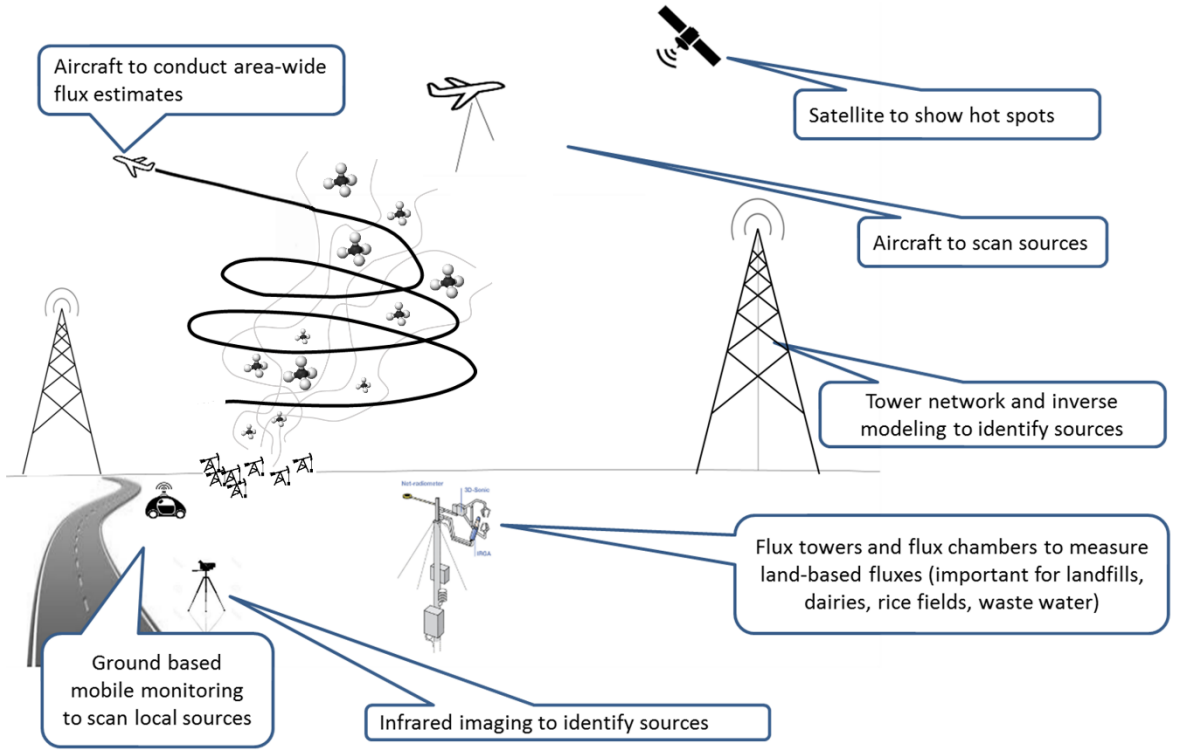
You Can't Manage What You Don't Measure

- Peter Drucker

Each measurement has its own purpose and limitations

- For detecting plumes or informing emissions
- Point in time or space

Need to consider all measurements for complete understanding



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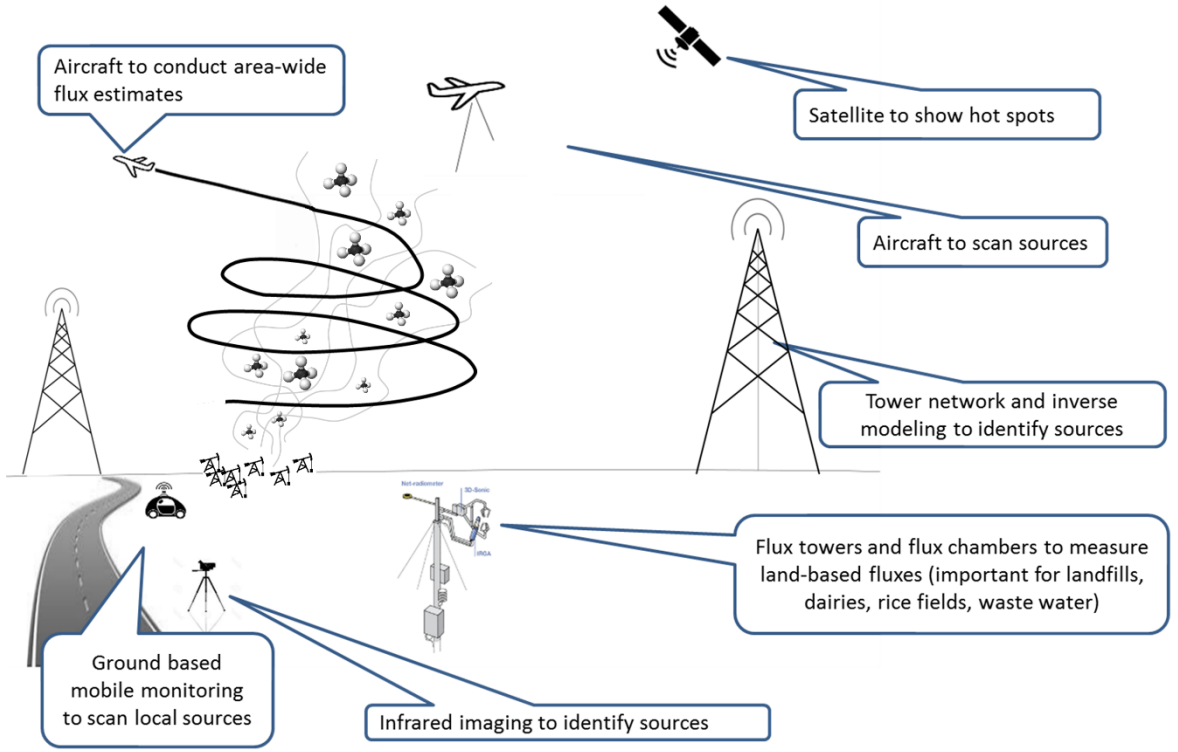
Need to consider all measurements for complete understanding

- Measurements to quantify emissions - stocktake
- Measurements to locate and fix leaks - mitigation



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GHG Monitoring - Stocktake

- Focused on non CO2 pollutants such as methane, HFCs, N2O
  - Using fixed sites such as mountain tops and monitoring networks
    - Gives you continuous measurements but is not sector or source specific
  - Using mobile platforms such as vehicles and planes
    - Gives sector or source specific information but are snapshots in time
  - Starting to use satellites as more data become available

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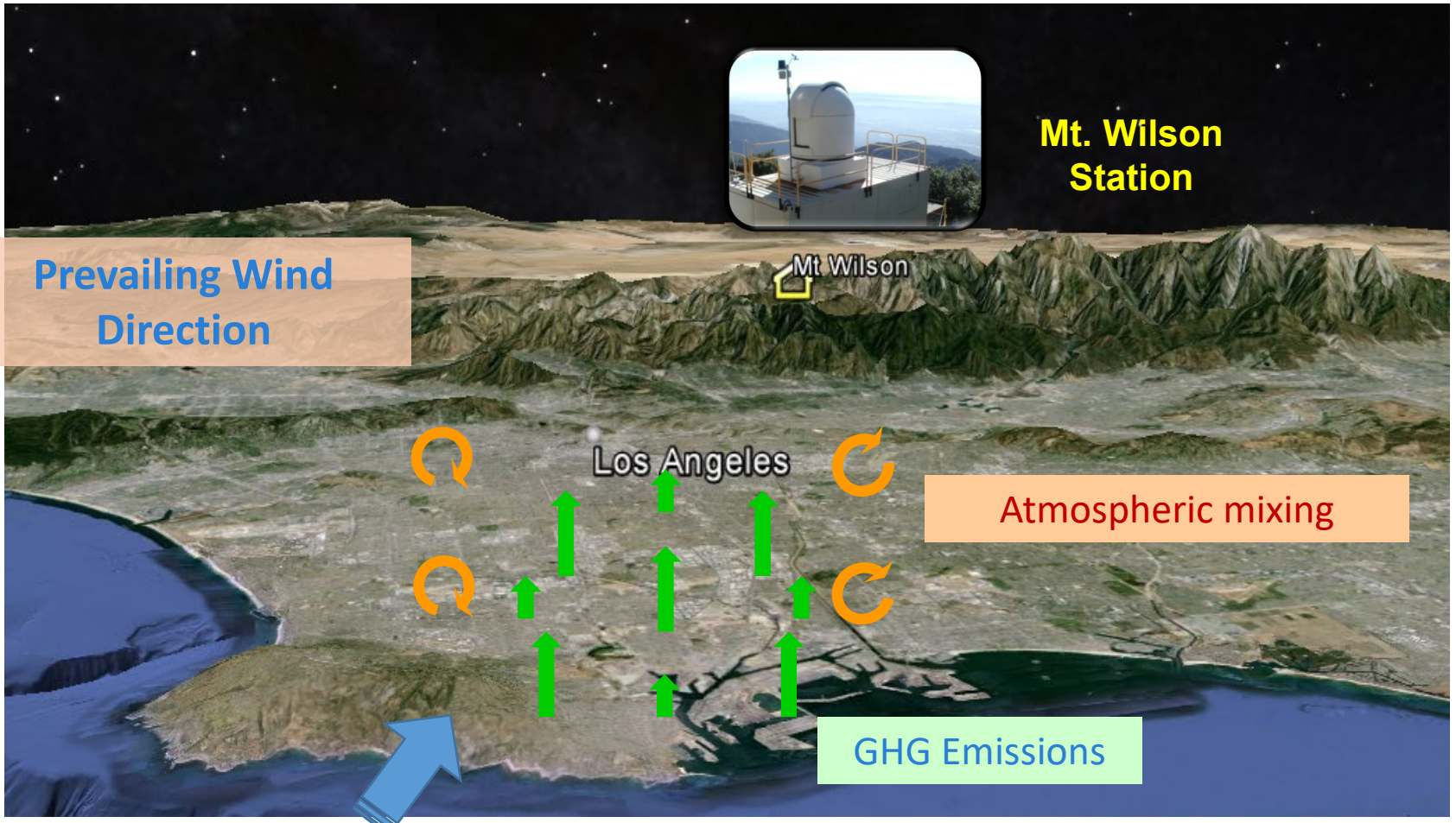
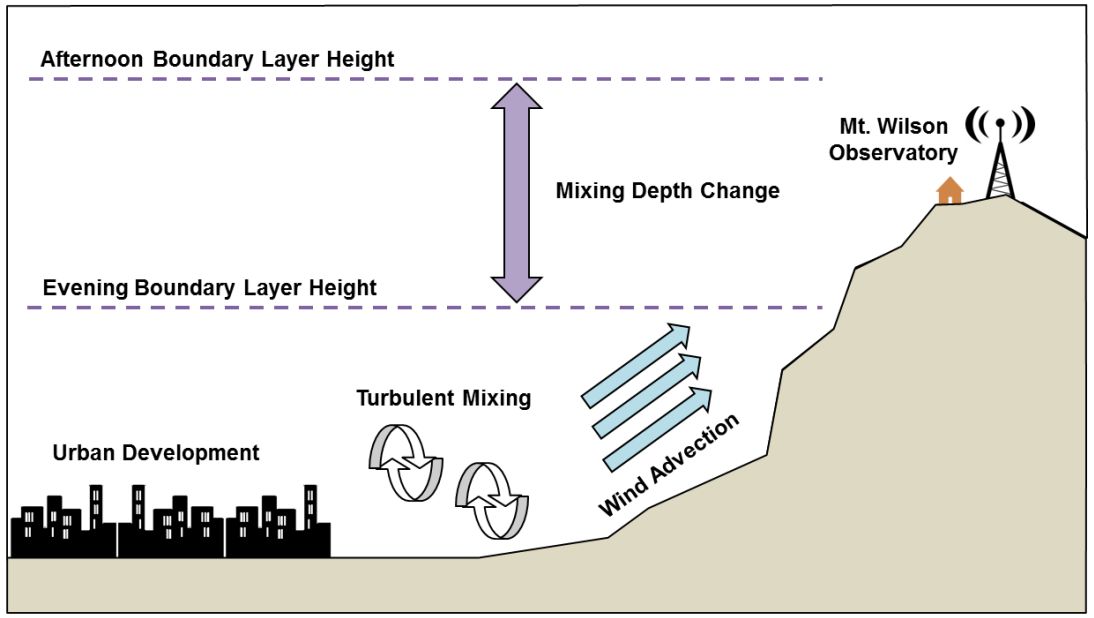
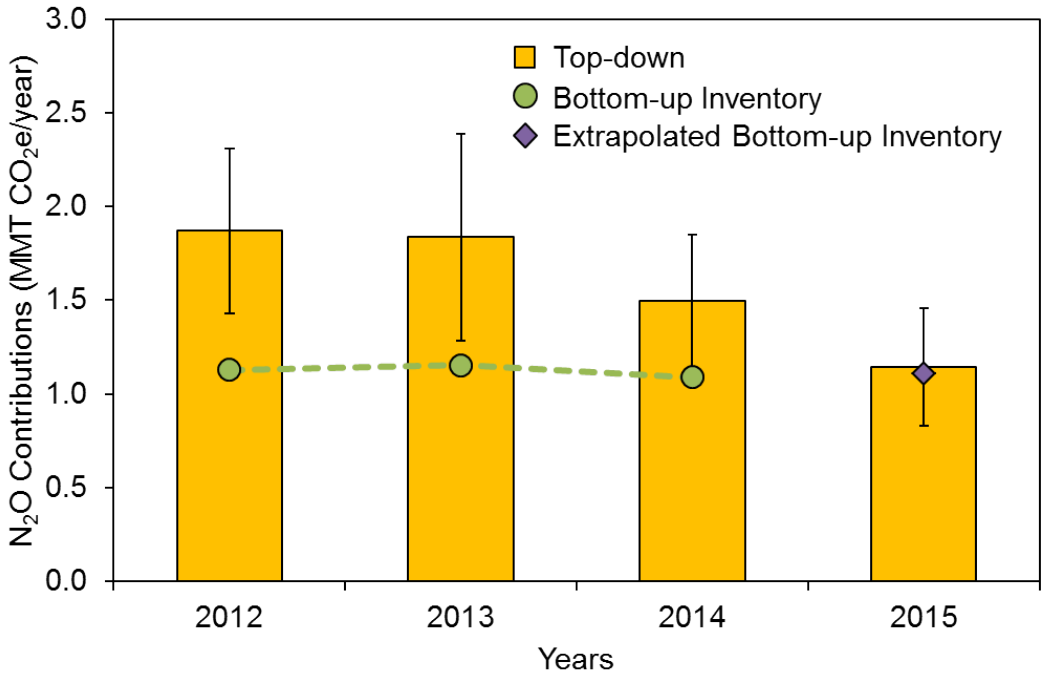
Mt. Wilson Observatory Station
Los Angeles County



Super site in Los Angeles



*Illustrated depiction of air mass transport to Mt. Wilson Observatory

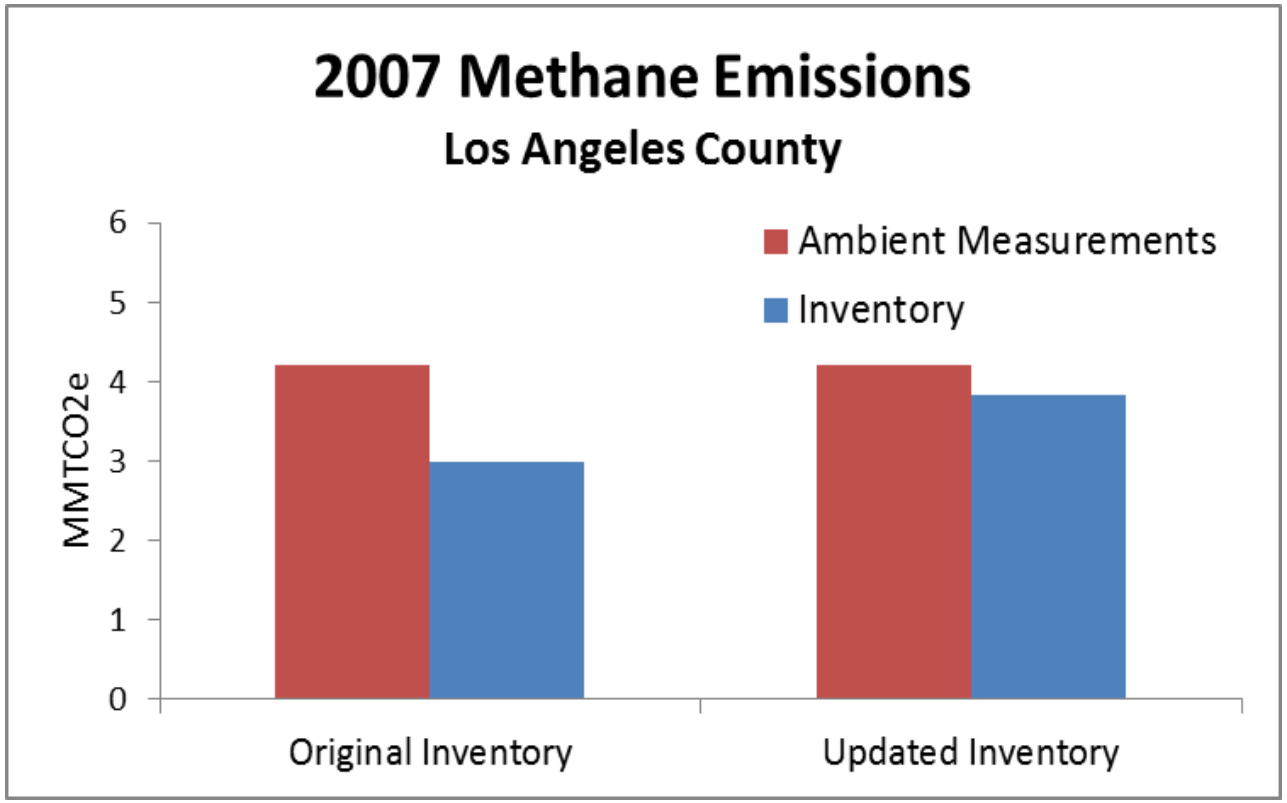


Ideal for tracking long-term trends in urban emissions

Source: Kuwayama, et al. 2018 manuscript in preparation

Super site in Los Angeles

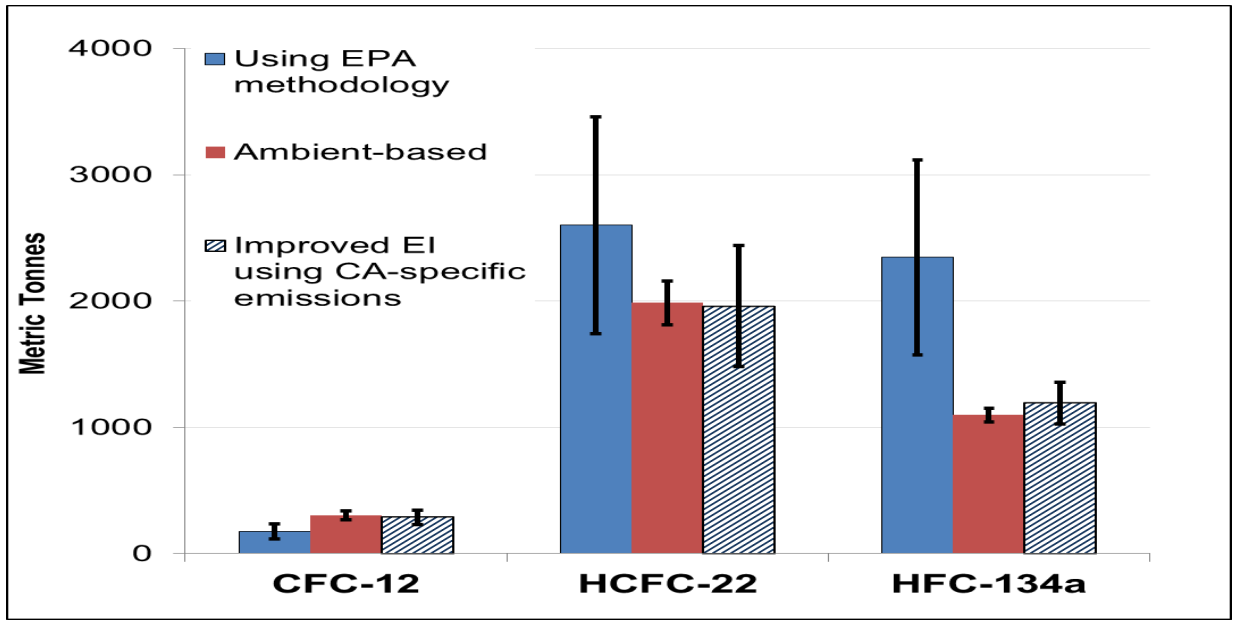
Spatial disaggregation of inventory improved



Reference: Hsu, et al. (2010) *Atmospheric Environment*, pp. 1–7

Super site in Los Angeles

Additional research improved models and inventory



Reference: Gallagher, et al. (2014) *Environmental Science & Technology*, pp. 1084-1093

- Results from national EPA-based method differed significantly from 2007 Mt. Wilson measurements
- New California-specific emissions inventory is consistent with 2007 Mt. Wilson measurements

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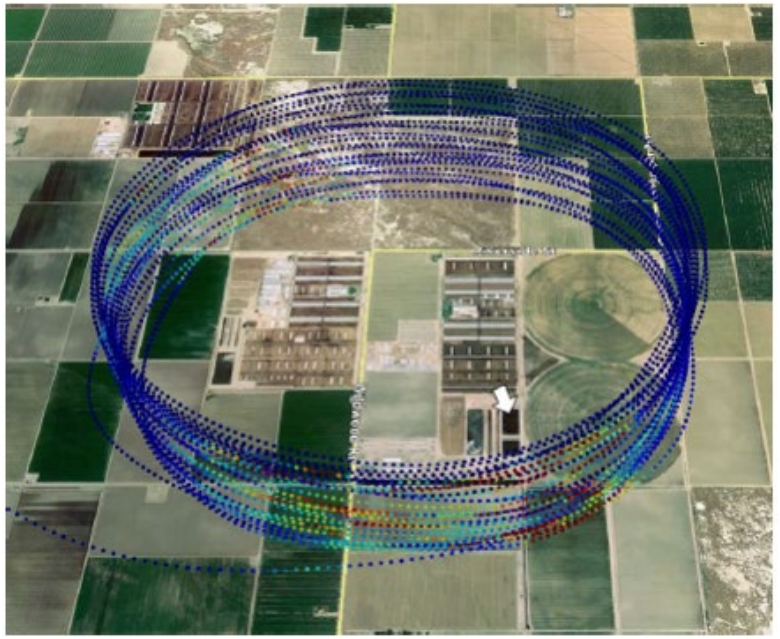
Individual Point Source Characterization



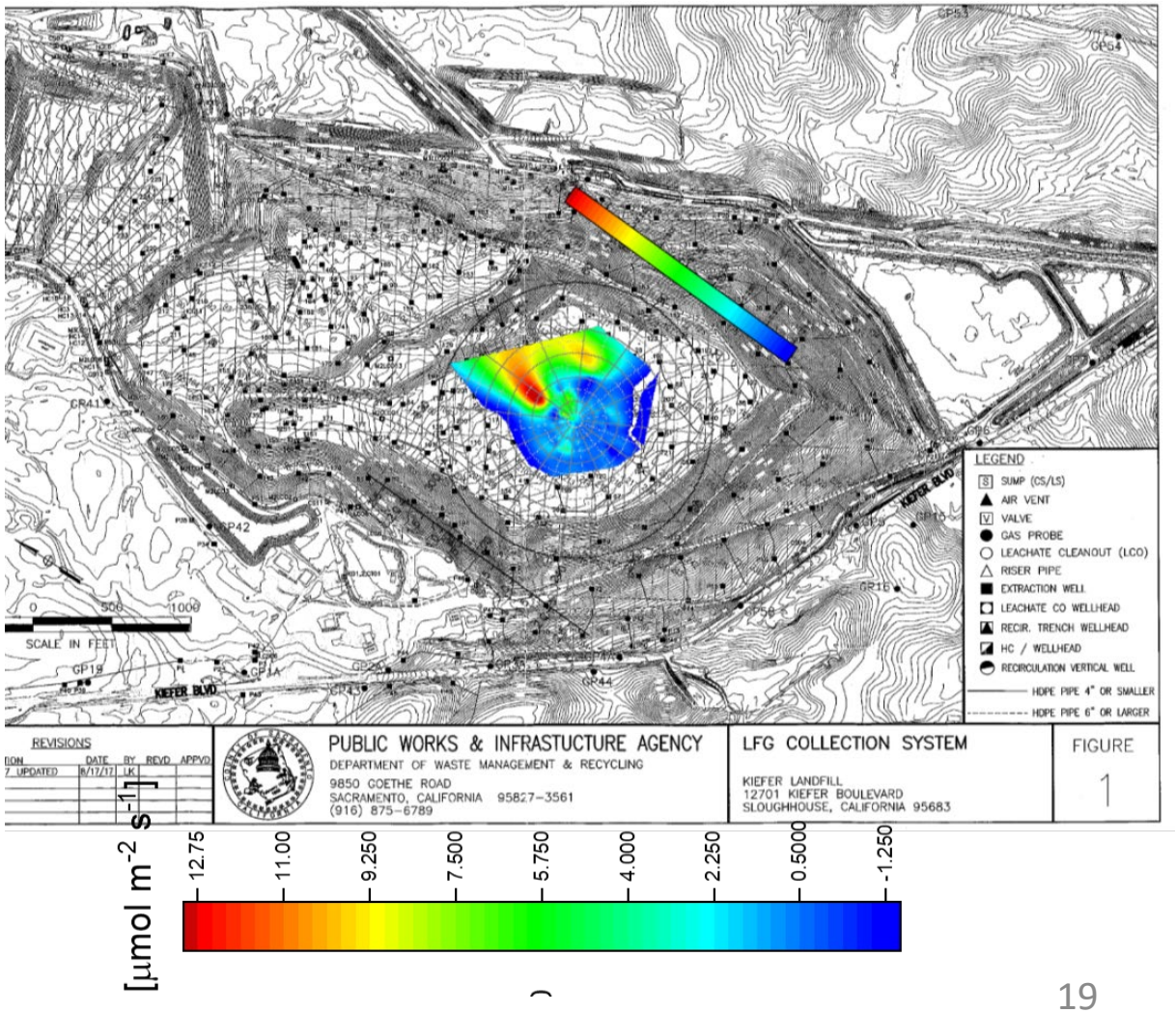
Facility Name	Latitude	Longitude	Air Basin	Sector	Facility Type	Date	CH4 Emission (kg/hr)	Uncertainty (kg/hr)	Data Status
Zero Waste + San Jose Wastewater + Zanker Landfill	37.4313	-121.9478	San Francisco Bay	Waste Management	Wastewater Treatment	10/05/2017	630.5	139.8	Final
Newby Island Landfill	37.4585	-121.9413	San Francisco Bay	Waste Management	Landfill	10/05/2017	2075.4	586.7	Final
Altamont Landfill	37.7539	-121.6517	San Francisco Bay	Waste Management	Landfill	10/06/2017	2976.8	653.2	Final
Keller Canyon Landfill	38.0039	-121.9365	San Francisco Bay	Waste Management	Landfill	10/06/2017	639.6	208.8	Final
Potrero Hills Landfill	38.2134	-121.9819	San Francisco Bay	Waste Management	Landfill	10/06/2017	2292.2	385.0	Final
Toland Landfill	34.4015	-118.9907	South Central Coast	Waste Management	Landfill	10/16/2017	3200.3	767.2	Final
Sunshine Canyon Landfill	34.3273	-118.5149	South Coast	Waste Management	Landfill	10/16/2017	1434.6	282.8	Final
Chiquita Canyon Landfill	34.4295	-118.6466	South Coast	Waste Management	Landfill	10/17/2017	2153.3	679.2	Final
Simi Valley Landfill	34.2945	-118.7954	South Central Coast	Waste Management	Landfill	10/17/2017	489.4	88.0	Final
Scholl Canyon Landfill	34.1560	-118.1937	South Coast	Waste Management	Landfill	11/09/2017	70.7	15.5	Final
Olinda Alpha Landfill	33.9416	-117.8331	South Coast	Waste Management	Landfill	11/09/2017	1698.6	327.8	Final
BKK West Covina Landfill	34.0364	-117.8995	South Coast	Waste Management	Landfill	11/09/2017	93.0	9.9	Final
Puente Hills Landfill	34.0161	-118.0146	South Coast	Waste Management	Landfill	11/09/2017	360.9	55.3	Final
Foothill Landfill	38.0378	-120.9372	San Joaquin Valley	Waste Management	Landfill	11/18/2017	680.1	146.0	Final

https://ww2.arb.ca.gov/our-work/programs/methane/ab1496-research

Area Source Characterization

Flux Towers

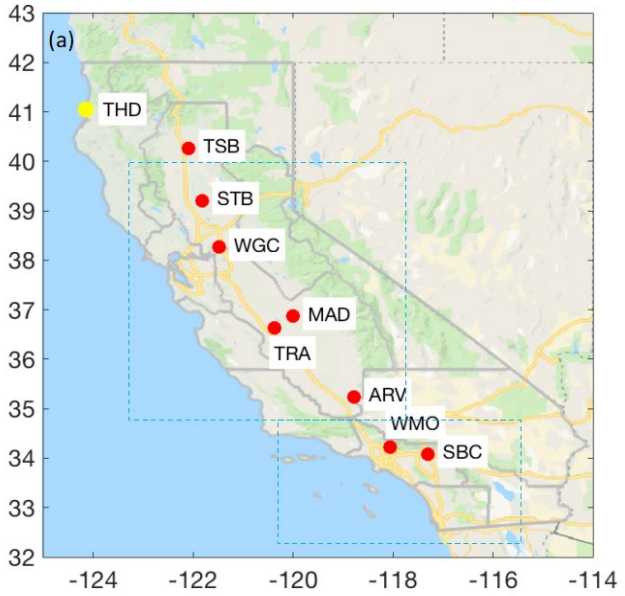
- Landfills
- Dairies

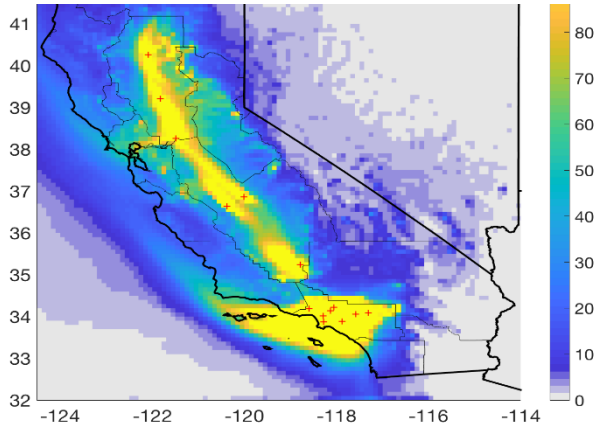


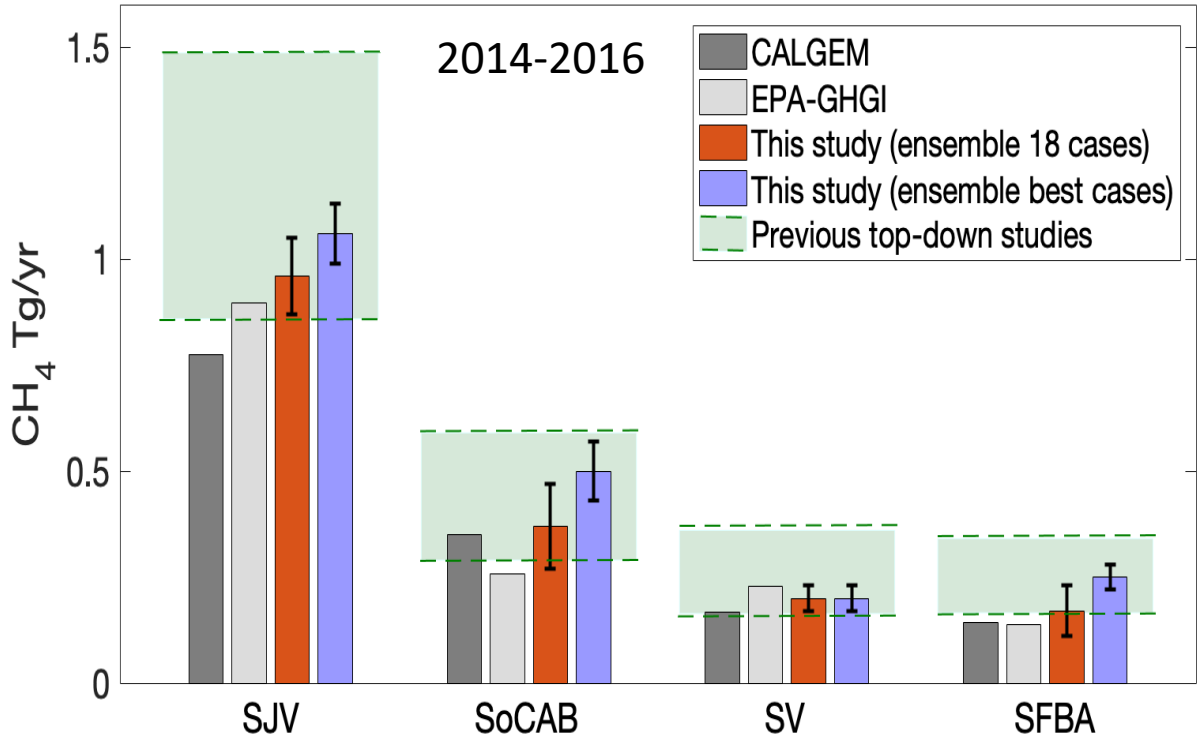
California GHG Monitoring Network

- Network started in 2010
- Current network
  - 7 CARB-managed stations (more coming)
  - Additional collaborated sites
- Measurements
  - Picarro CH_4, CO_2, H_2O
  - LGR N_2O, CO, H_2O
  - BC, F-gases, VOC (Mt. Wilson)
  - PBLH/wind profilers (red circles)
  - Adding real-time GC/MS at selected sites
- CARB data available to research community
  - https://www.arb.ca.gov/aqmis2/res/aqdselect.php

CARB Inverse Modeling Program







Source: Cui, et al. 2018 manuscript in preparation

Top down approximately 30-50% > Bottom up in California

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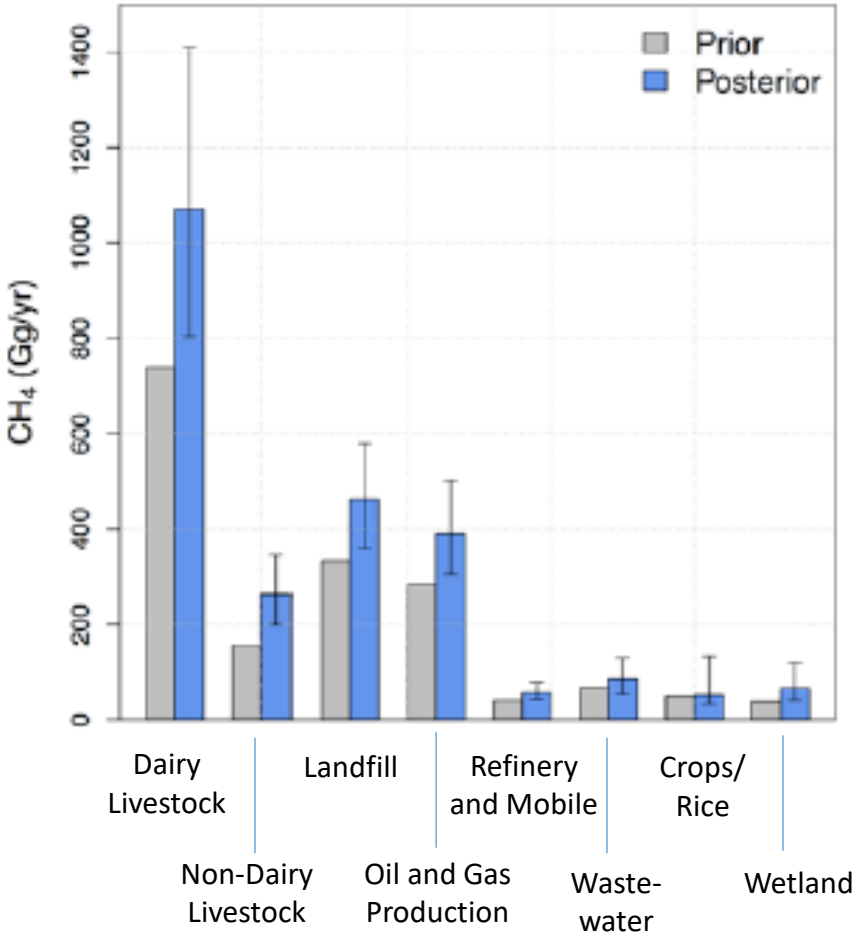
Top down inventory comparisons

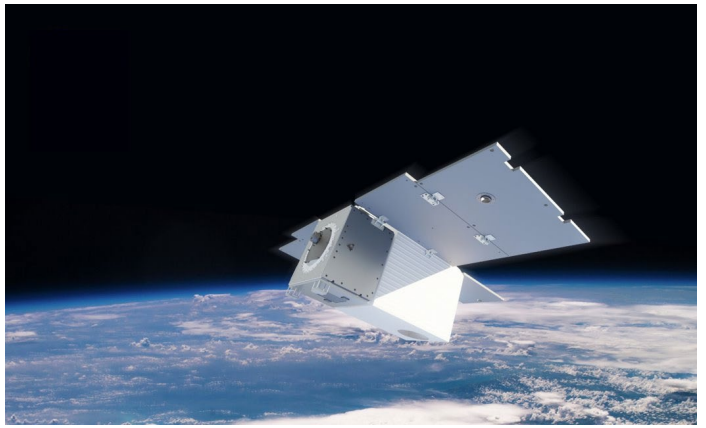
- Based on geography of emissions ⟶
- Working on adding VOC observations
- Initiated research to characterize methane emissions at dairies and develop California specific manure management and enteric fermentation emission factors and to develop mitigation options



Source: Marc Fischer, Final Report ARB research contract 11-306, https://www.arb.ca.gov/research/apr/past/11-306.pdf

GHG Monitoring - Mitigation

- Mature program to identify individual plumes of **methane** using remote sensing
  - Informing operators who take action
  - Demonstration using airplanes, will launch satellites in the next six months



- California already has methane regulations for oil and gas and landfills that require quarterly leak detection and repair of leaks

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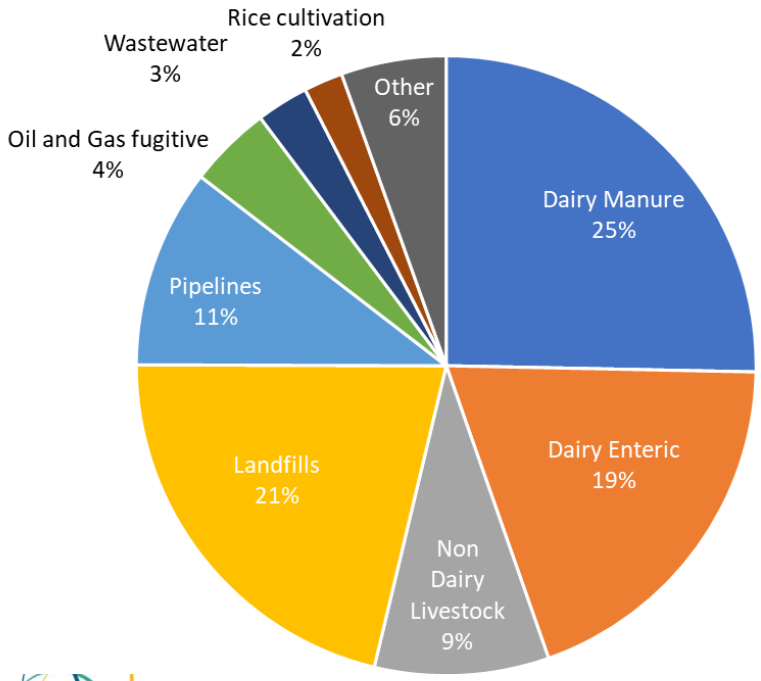
Why Methane?

California 2019 Methane

39 MMTCO$_2$e



Methane is an important GHG, and a Short Lived Climate Pollutant

- About 11% of both California and US total GHG emissions
- But has accounted for 30% of global warming since pre-industrial times

Global Warming Potentials (GWPs):

- 100 year – 25
- 20 year – 86

Atmospheric removal times:

- Methane – 50% removed every 8 years
- Carbon Dioxide – 50% removed every 53 years

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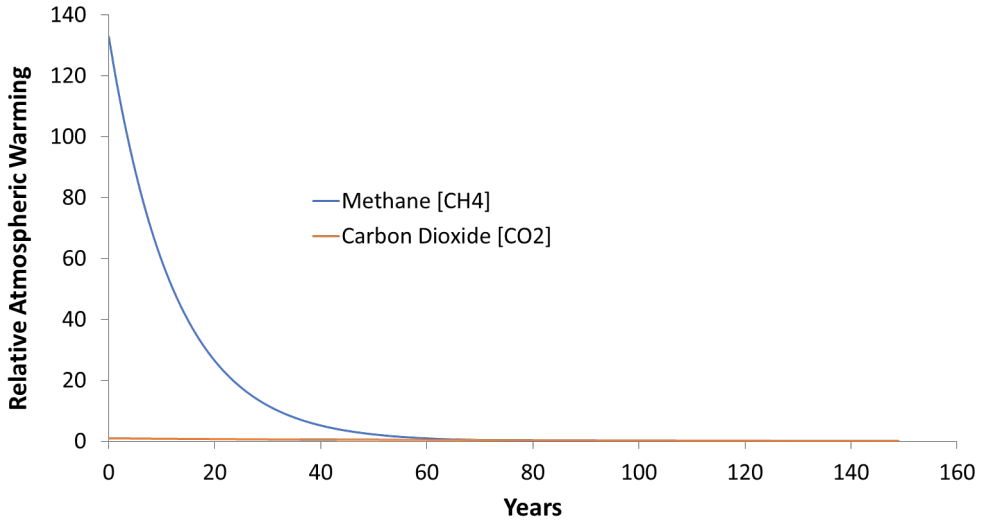
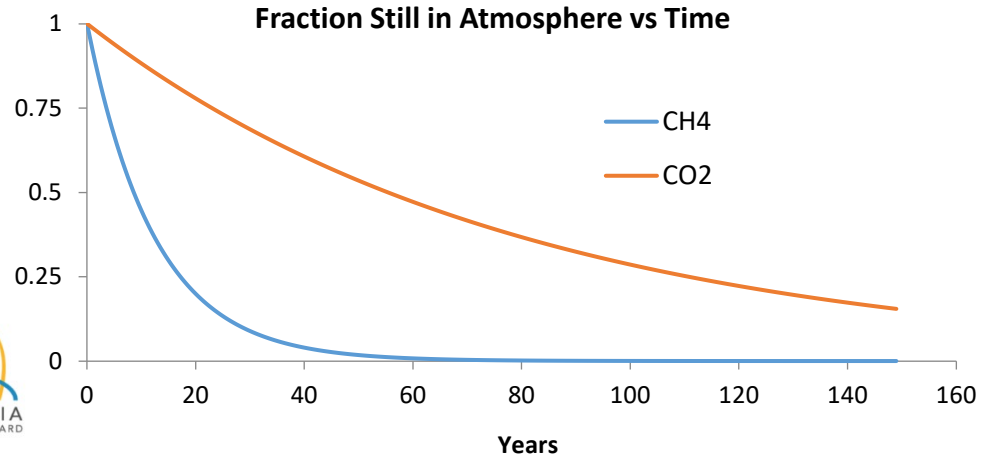
How much heat does CH_4 absorb compared to CO_2 and when





Implications:

- Reductions in methane will lead to relatively quick reduction in warming, especially compared to reductions in CO_2
- Reducing methane will allow measures for reducing effect of CO_2 to take effect

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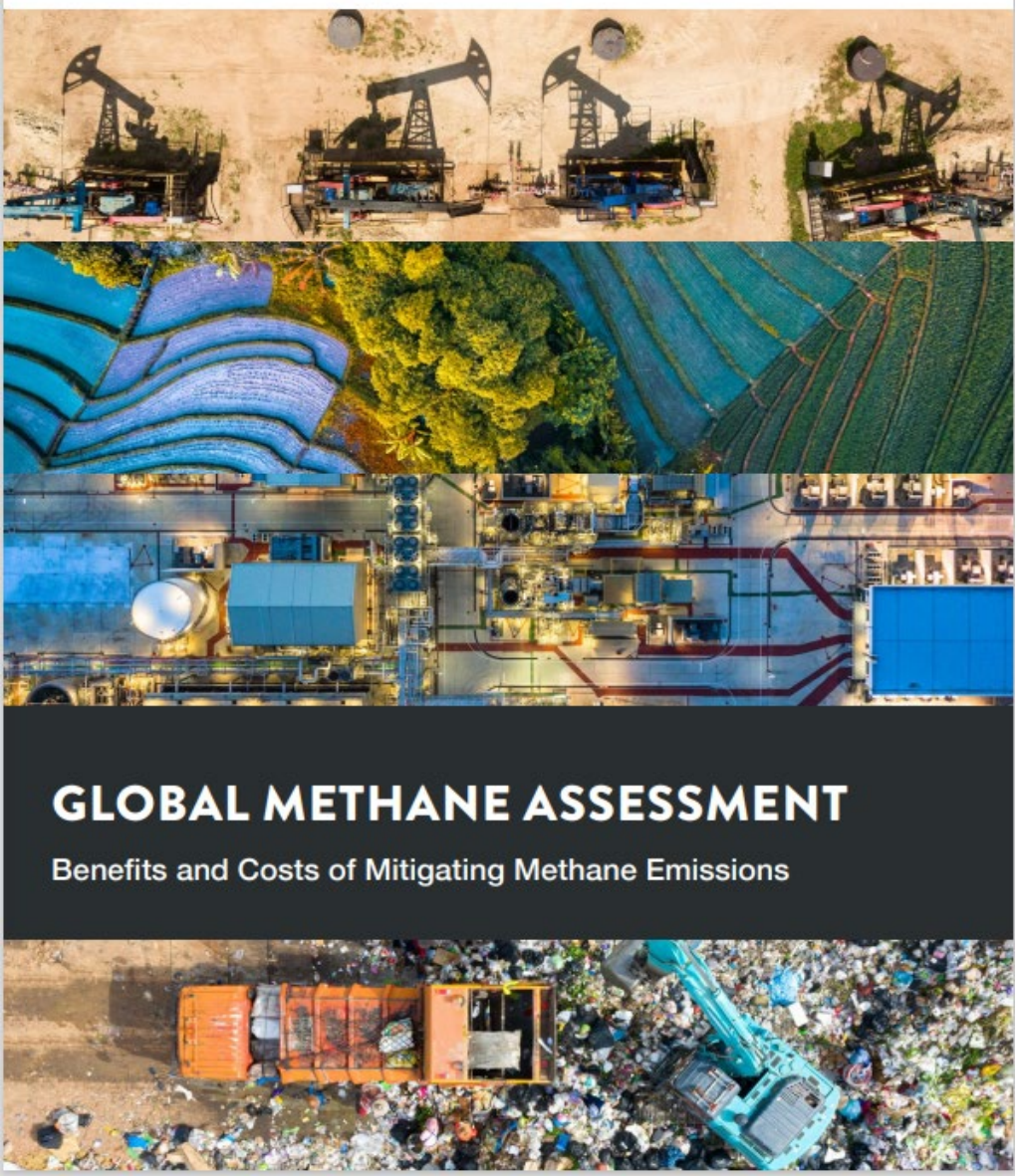


Fast and ambitious methane mitigation is one of the best strategies available today to deliver immediate and long-lasting multiple benefits for climate, agriculture, human and ecosystem health. (UN Global Methane Assessment)

THE WHITE HOUSE

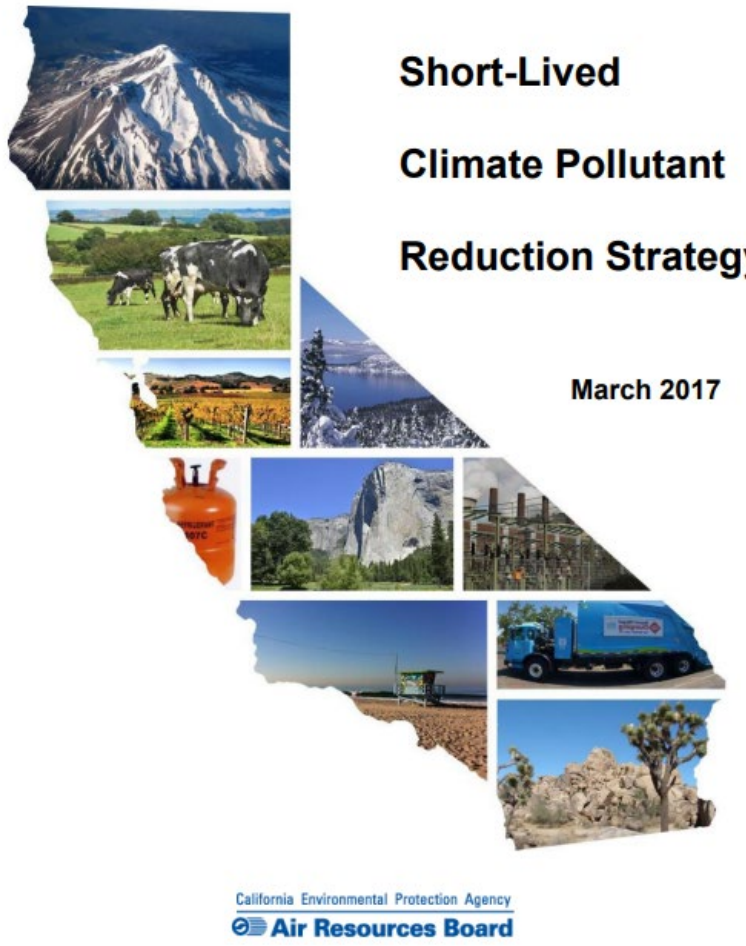
SEPTEMBER 18, 2021

Joint US-EU Press Release on the Global Methane Pledge

BRIEFING ROOM › STATEMENTS AND RELEASES

The United States and European Union announced today the Global Methane Pledge, an initiative to reduce global methane emissions to be launched at the UN Climate Change Conference (COP 26) in November in Glasgow. President Biden and European Commission President Ursula von der Leyen urged countries at the U.S.-led Major Economies Forum on Energy and Climate to join the Pledge and welcomed those that have already signaled their support.

California Methane Policy



Senate Bill 1383 (2016) – Requires reductions in SLCPs

- 40% reduction from 2013 levels by 2030 for CH_4 and HFCs
- 50% reduction from 2013 levels by 2030 for BC
- For landfills it requires 75% organic waste diversion
- Requirements for leak detection and repair in oil and gas and waste sectors

Methane Technology Assessment

In the mid 2010's, new research demonstrated the ability of *hyperspectral imagers* to detect localized sources of methane

Retrieval techniques for airborne imaging of methane concentrations using high spatial and moderate spectral resolution: application to AVIRIS

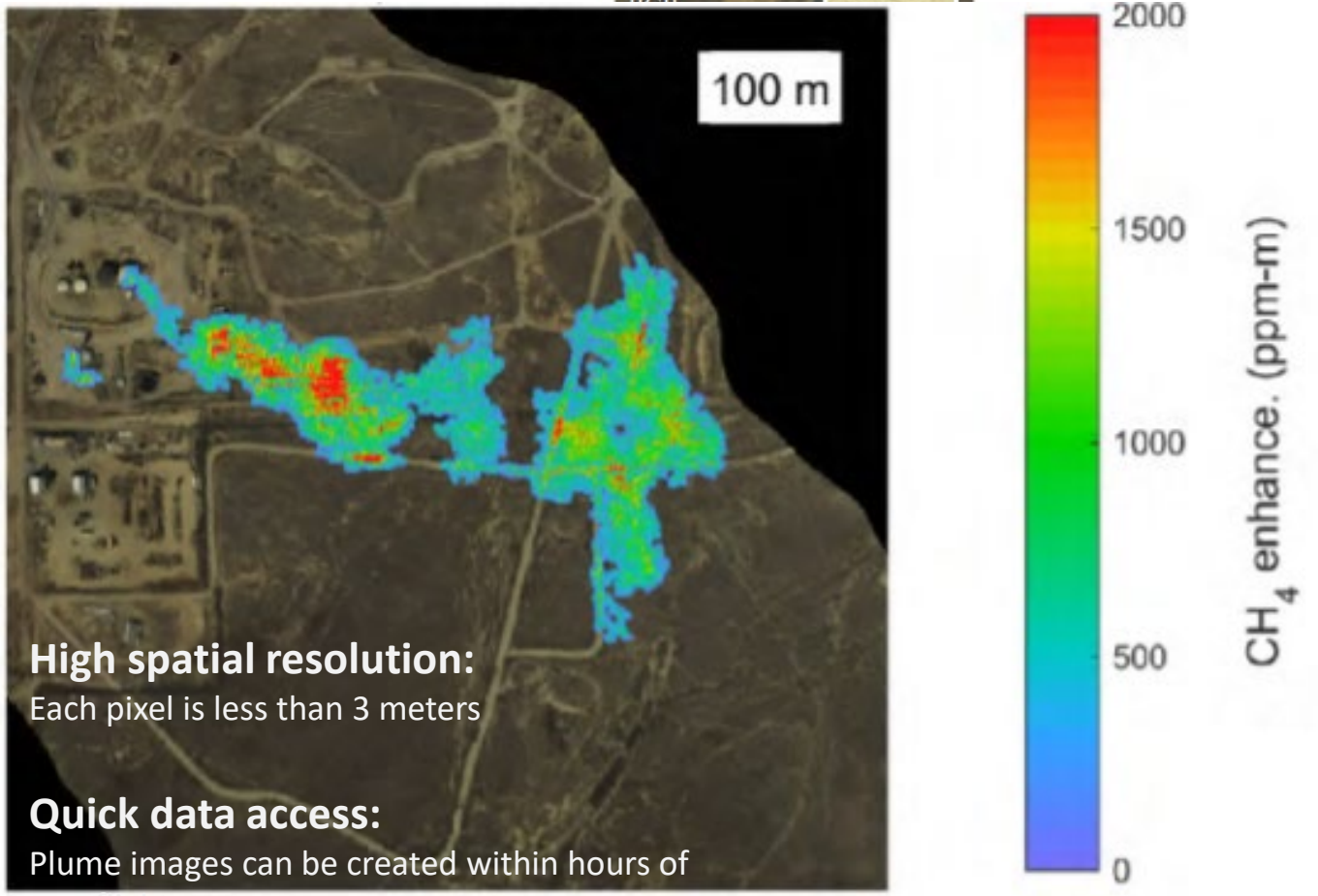
A. K. Thorpe[1,2], C. Frankenberg[2], and D. A. Roberts[1]

[1]Department of Geography, University of California, Santa Barbara, Santa Barbara, California, USA
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane

D. R. Thompson[1], I. Leifer[2], H. Bovensmann[3], M. Eastwood[1], M. Fladeland[4], C. Frankenberg[1], K. Gerilowski[3], R. O. Green[1], S. Kratwurst[3], T. Krings[3], B. Luna[4], and A. K. Thorpe[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[2]Bubbleology Research International, Solvang, CA, USA
[3]University of Bremen, Institute of Environmental Physics, P.O. Box 330440, 28334 Bremen, Germany.
[4]NASA Ames Research Center, Moffett Field, CA, USA



High spatial resolution:
Each pixel is less than 3 meters

Quick data access:
Plume images can be created within hours of overflight

“Large Localized Sources of Methane”

“Diffuse” or “area-wide” source:

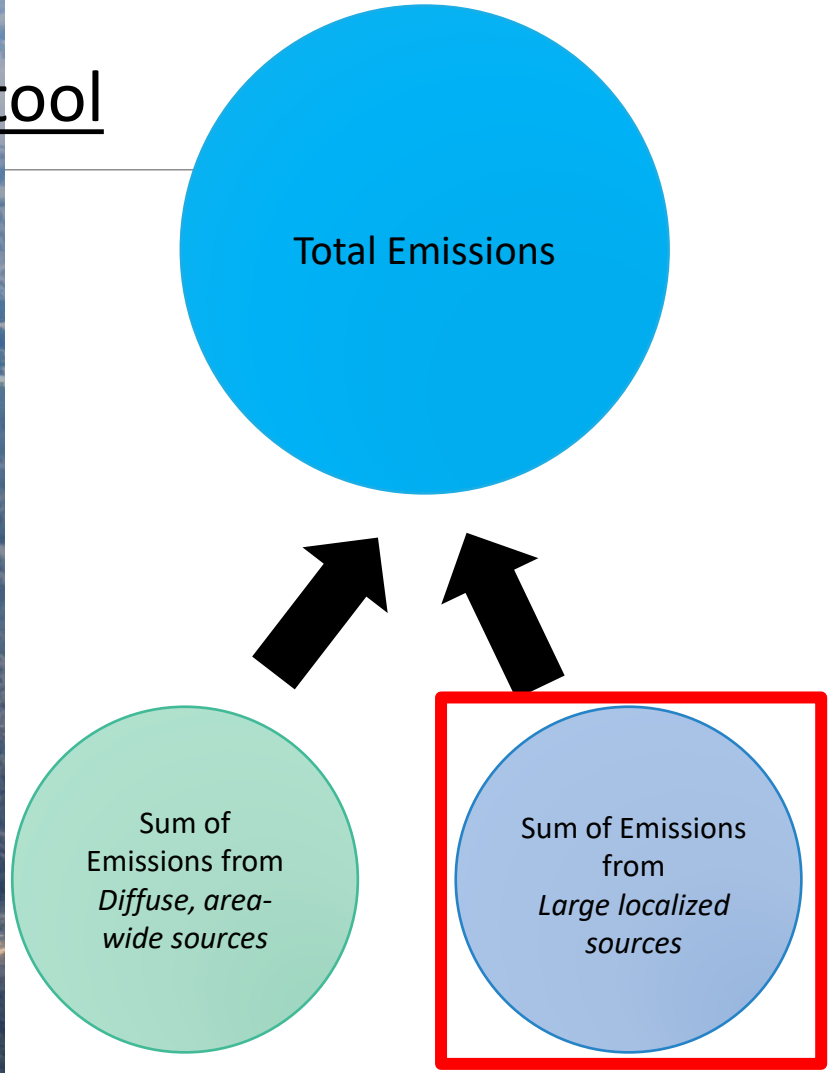
Small sources of emissions scattered over the landfill property

Large Localized Sources of Methane”

One plume detection

“Large Localized Sources of Methane”

Plume mapping is a *mitigation* tool, not an *inventory* tool

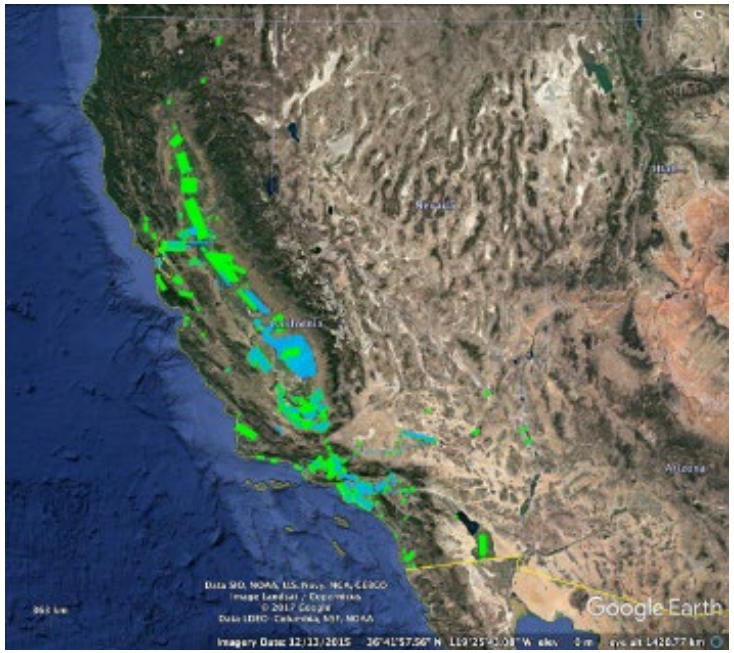


Airborne Research Surveys Conducted in California

Three airborne research campaigns that quantified emissions and demonstrated voluntary mitigation

<u>Campaign #1</u> - 2016-2018 – California Methane Survey

- Several months of flights in 5 campaigns. Cost $2m
- Surveyed 272,000 facilities and components with multiple revisits.
- Plumes were found in all sectors



The California Methane Survey was the first large-scale demonstration of this methane-detection technology

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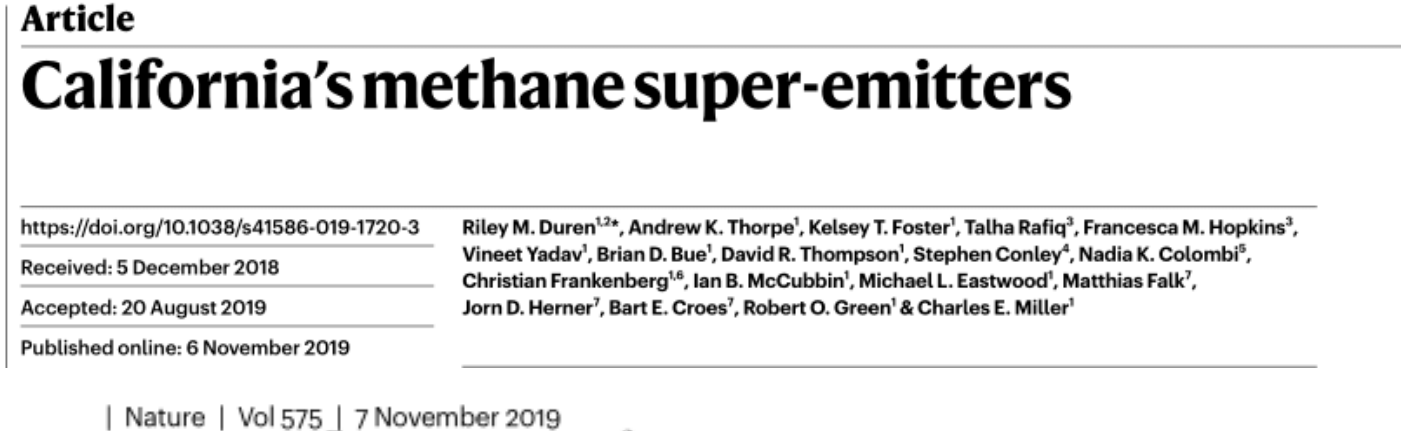


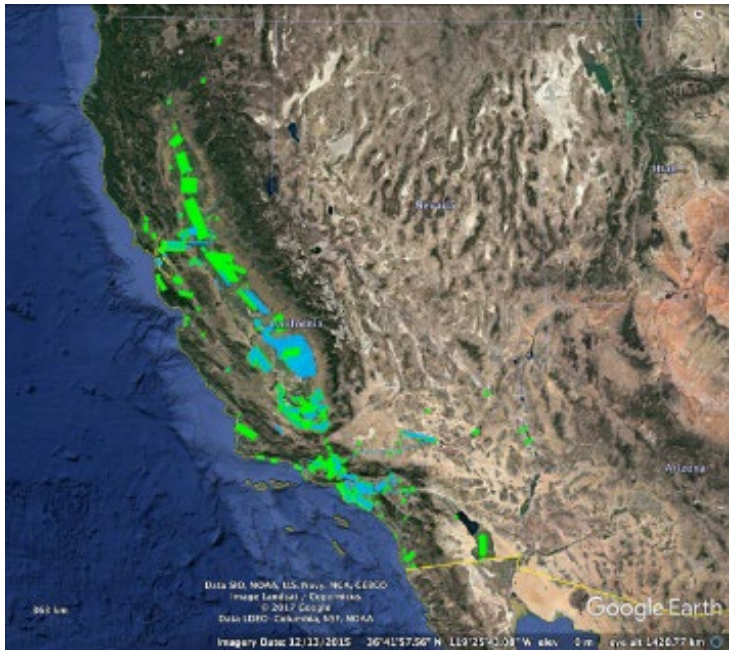
Article

California's methane super-emitters

https://doi.org/10.1038/s41586-019-1720-3
Received: 5 December 2018
Accepted: 20 August 2019
Published online: 6 November 2019

Riley M. Duren[1,2*], Andrew K. Thorpe[1], Kelsey T. Foster[1], Talha Rafiq[3], Francesca M. Hopkins[3], Vineet Yadav[1], Brian D. Bue[1], David R. Thompson[1], Stephen Conley[4], Nadia K. Colombi[5], Christian Frankenberg[1,6], Ian B. McCubbin[1], Michael L. Eastwood[1], Matthias Falk[7], Jorn D. Herner[7], Bart E. Croes[7], Robert O. Green[1] & Charles E. Miller[1]

| Nature | Vol 575 | 7 November 2019



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Airborne Research Surveys Conducted in California

Simulating Satellite Data Using the same instrument on airplanes – allows for pilot studies

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<u>Campaign #1</u> - 2016-2018 – California Methane Survey

- Several months of flights in 5 campaigns. Cost $2m
- Surveyed 272,000 facilities and components with multiple revisits.
- Plumes were found in all sectors

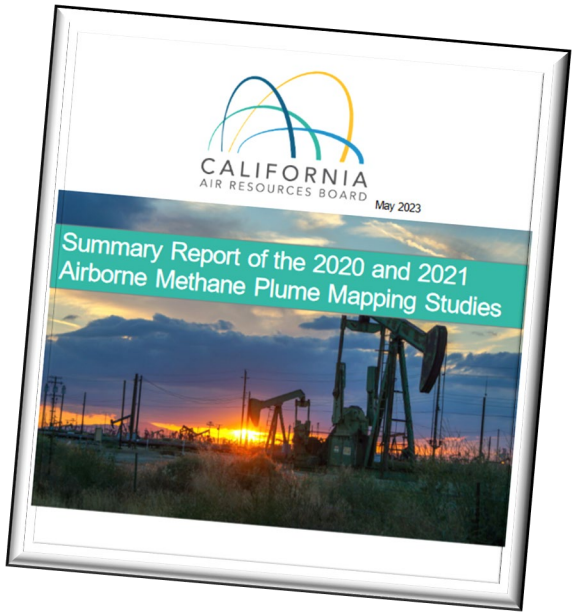
<u>Campaign #2</u> – 2020

- 15 days of flight. Cost $550k
- Worked with industry prior to voluntarily 'enroll' their infrastructure
- Industry voluntarily provided feedback on what was leaking and why
- About half of sources found could be mitigated

<u>Campaign #3</u> - 2021

- 11 days of flight. Funded by Carbon Mapper
- Let industry know we were flying but did not 'enroll' volunteers.
- Automated identification of infrastructure owner and some of the communication
- Worked closely with non-research CARB staff for communication and other actions

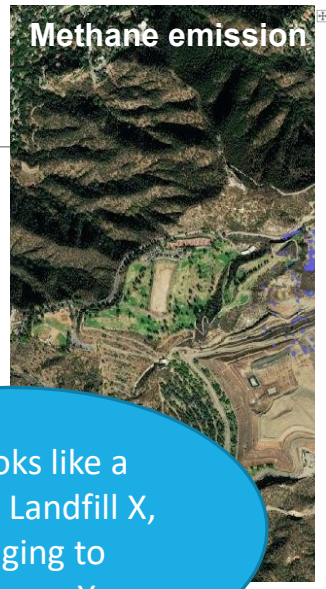
<u>Campaign #4</u> – June 2023 – data available later in 2023



Campaigns #2 and #3 were the first large-scale demonstrations of this technology being used to support methane mitigation

https://ww2.arb.ca.gov/resources/documents/summary-report-2020-and-2021-airborne-methane-plume-mapping-studies

Example of Voluntary Action from Nov 2021



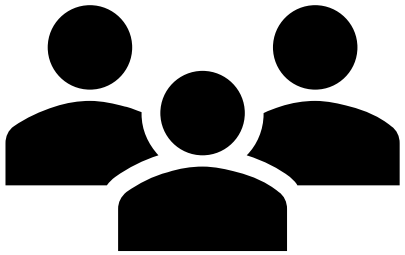
CARB Methane Satellite Dry Run – Landfill Follow-up

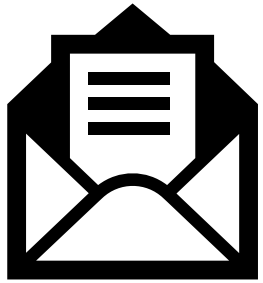
Fill out this form for each notification from CARB of a plume identified from the plane. Complete all fields if possible. *Items in italics are optional but preferred.*

Facility/Flight Survey Info	
Name of Facility:	[redacted]
Contact information (name, phone number, email address):	[redacted]
Plume ID (provided by CARB):	GAO20211111t203239p0000-A_r208_c692
Lat/Lon coordinates (provided by CARB):	34.1595/-118.1932
Date of follow-up ground survey	11/19/21
Follow-up Ground Survey	
Instrument used to locate the leak (e.g., Method 21 instrument like TVA2020):	TVA2020
Was an emission source identified?	Yes
What was the nature of the emission source (well, surface crack etc.)?	In response to the aerial survey, vertical PVC pipe markers were found to be compromised due to bird activity (see additional comments below).
Was this location included in the previous quarterly/annual Landfill Methane Regulation (LMR) surface emission monitoring?	Yes
If not please state why the area was not monitored (construction, active working face, steep slope, etc.)	
Is this location planned for inclusion in the next quarterly/annual LMR monitoring?	Yes
If not please state why the area will not be monitored (construction, active working face, steep slope, etc.)	
Was the source of emissions a leak (unintentional) or a vent (intentional)?	Unintentional
Concentration of the leak:	1,862 ppm methane
Follow-up Actions	
Mitigation actions taken (if it was a leak):	The vertical PVC pipe markers were removed, and the new gas trenches were connected to vacuum on 11/18/21.
Concentration of the leak after repair:	28.6 ppm methane (maximum instantaneous reading)

This looks like a plume at Landfill X, belonging to Company Y

Wed	Thurs	Fri	Sat	Sun	Mon	Tues
10	11 Plume Detected	12	13	14	15	16 Operator Notified
17	18	19	20	21	22	23

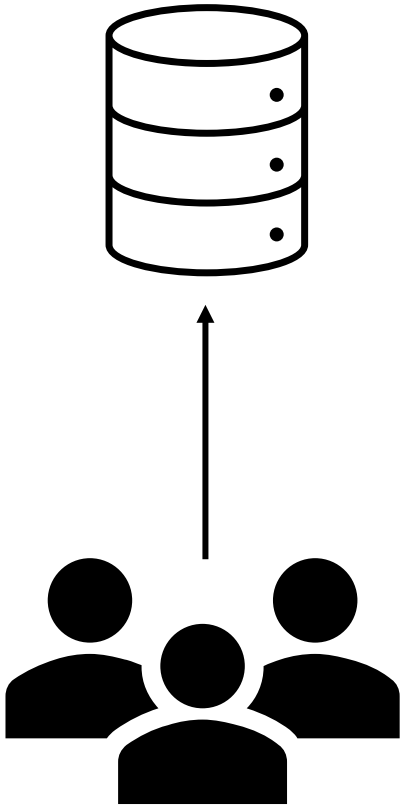




CARB+Collaborators

Example of Voluntary Action from Nov 2021

Wed	Thurs	Fri	Sat	Sun	Mon	Tues
10	11 Plume Detected	12	13	14	15	16 Operator Notified
17 Operator inspected	18 Operator repaired source	19	20	21	22	23

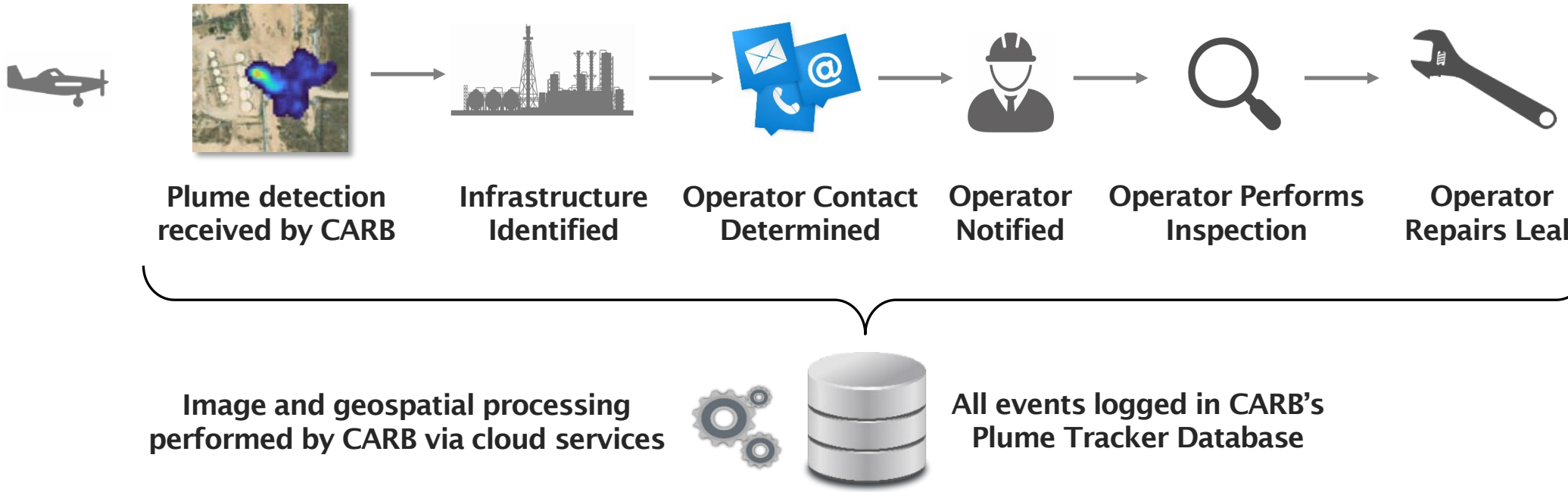


CARB+Collaborators

We found the source of the plume. We found damaged PVC pipe markers, which were repaired

Mitigation

This allows the identification of methane leaks in California such that operators can be notified and mitigate these GHG emissions



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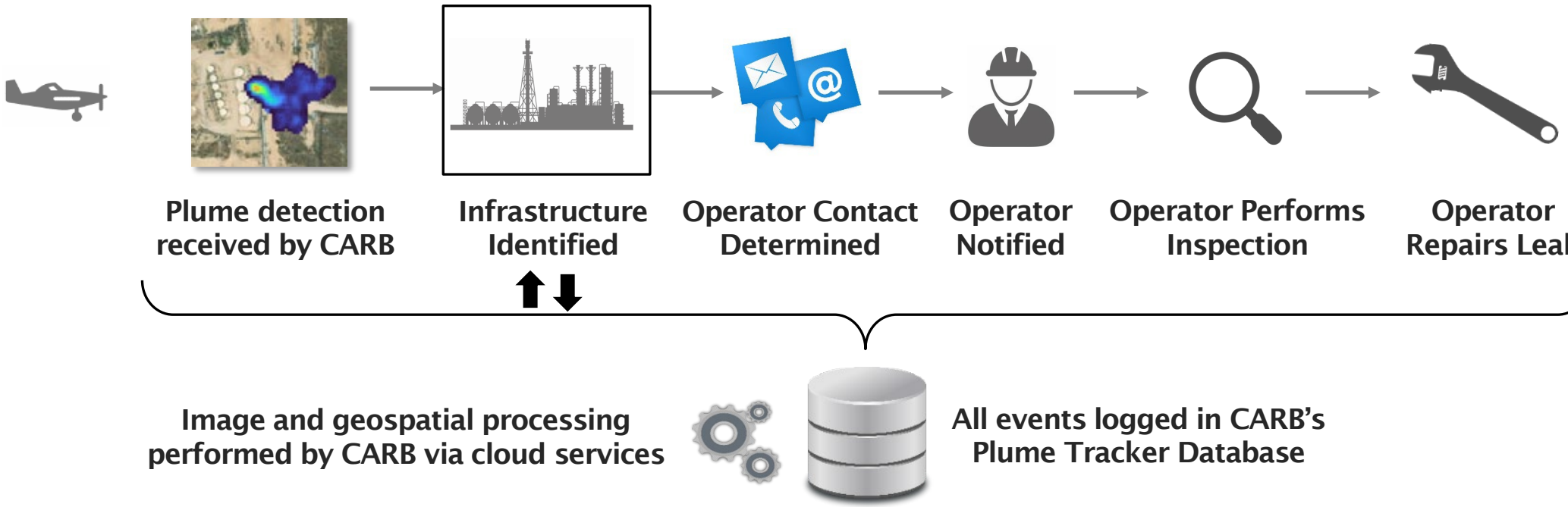

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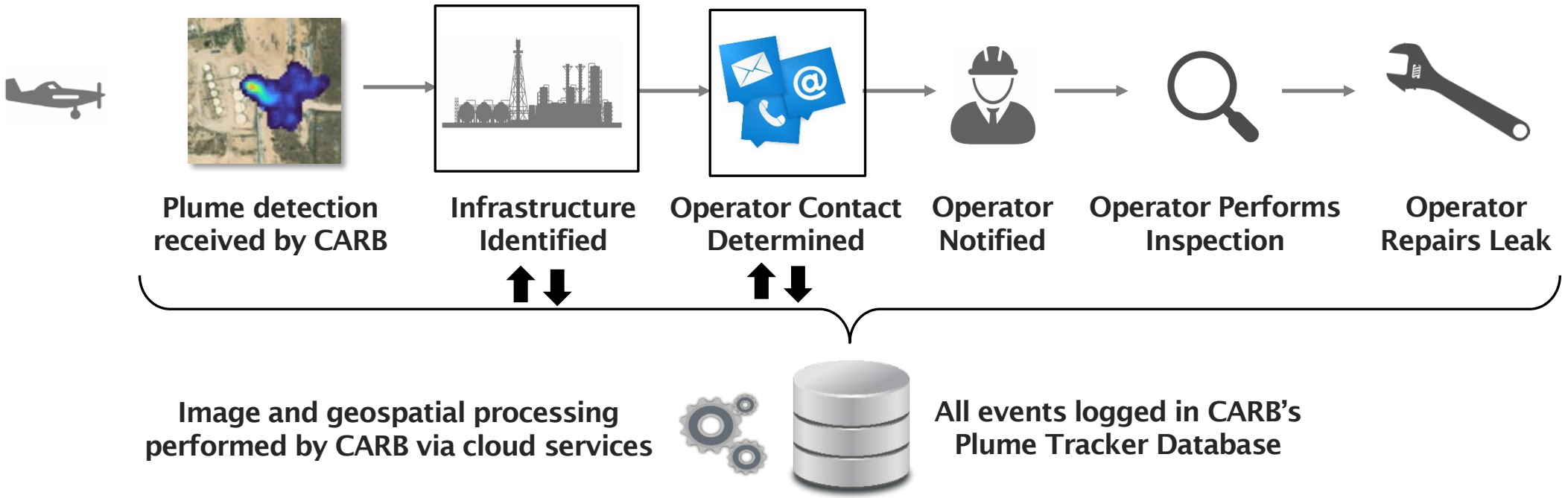

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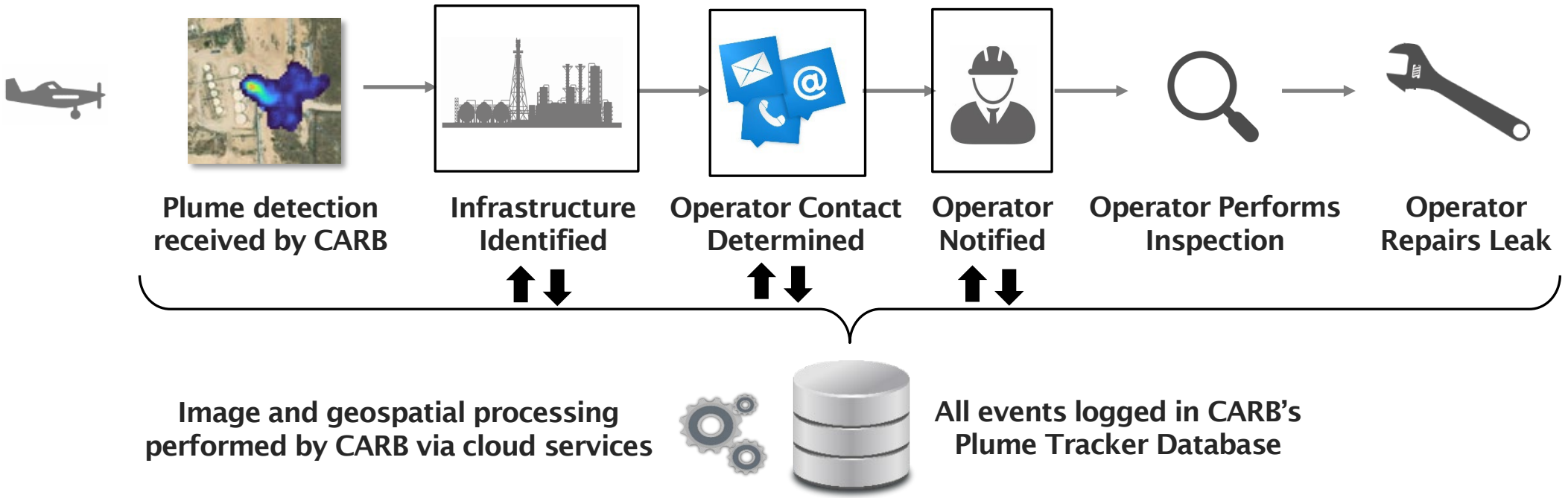

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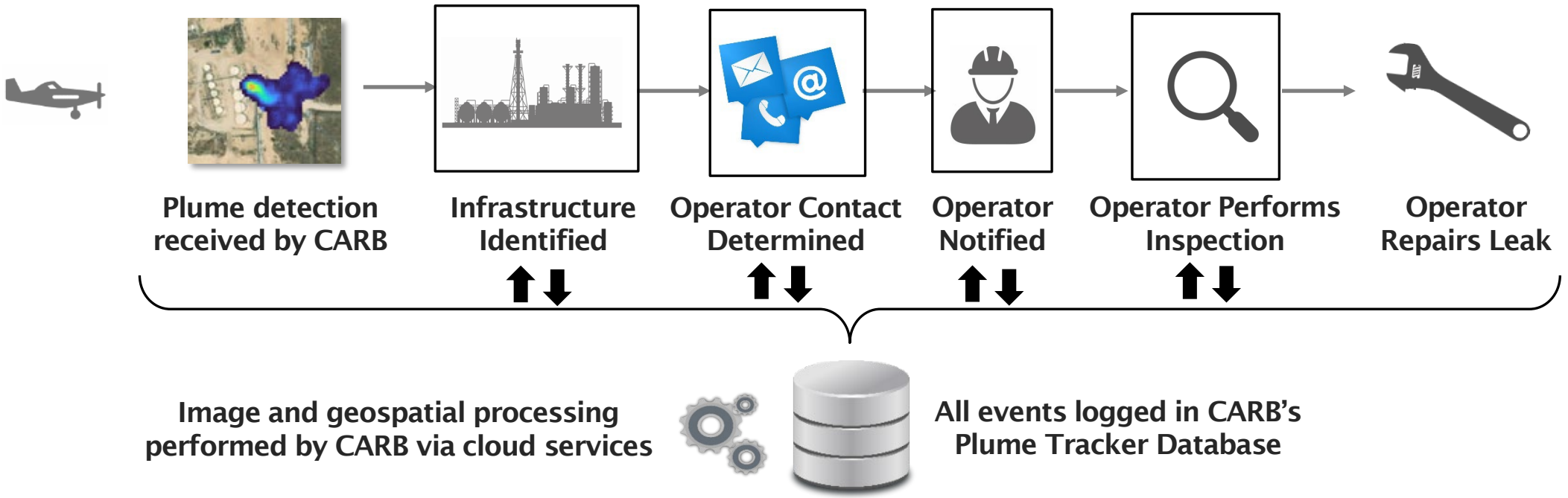

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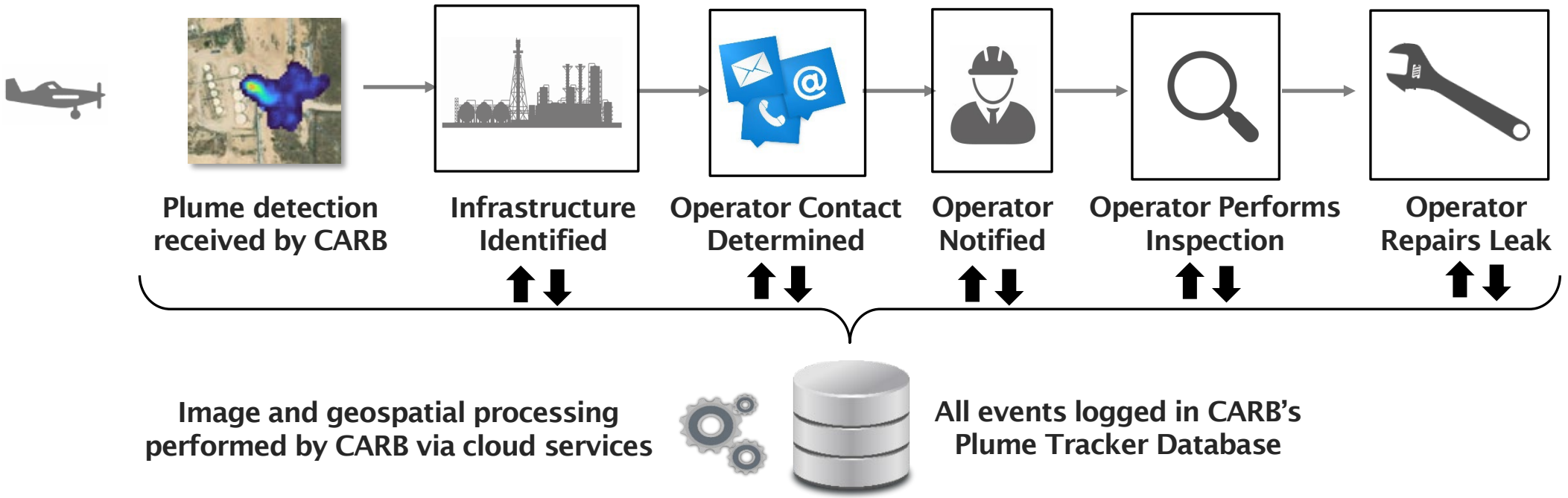
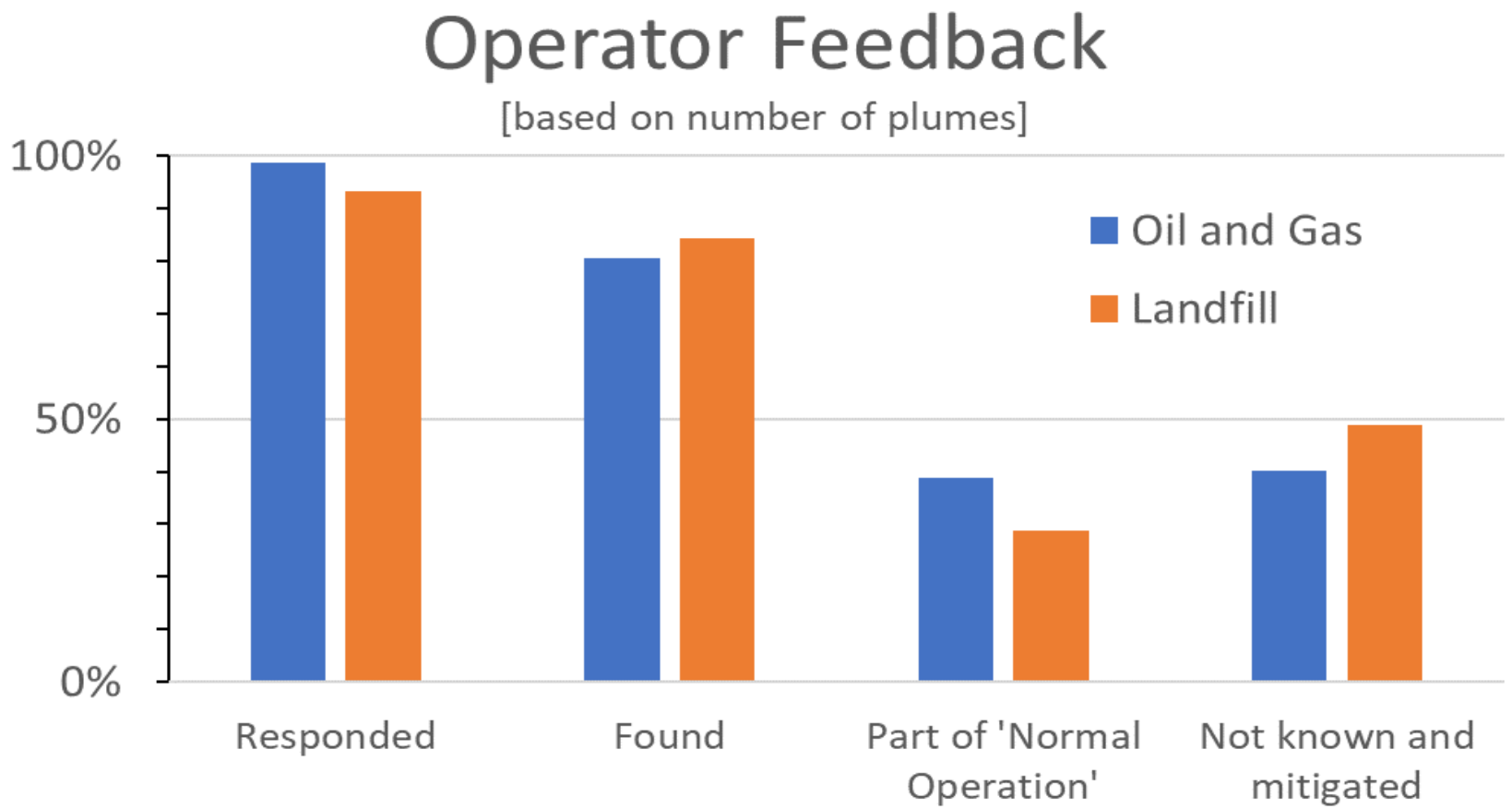


Combined Results –

high response rate and significant mitigation potential



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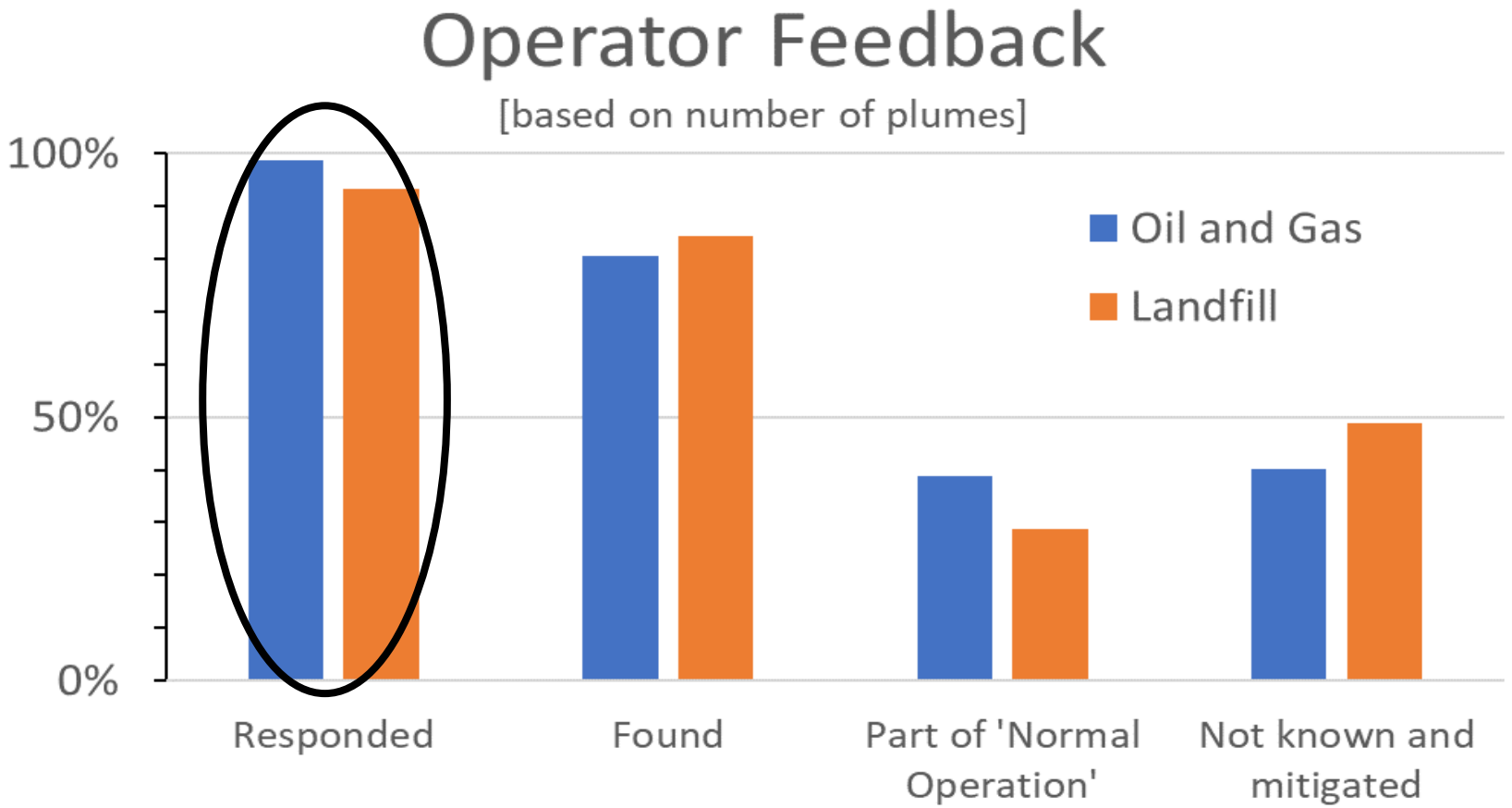

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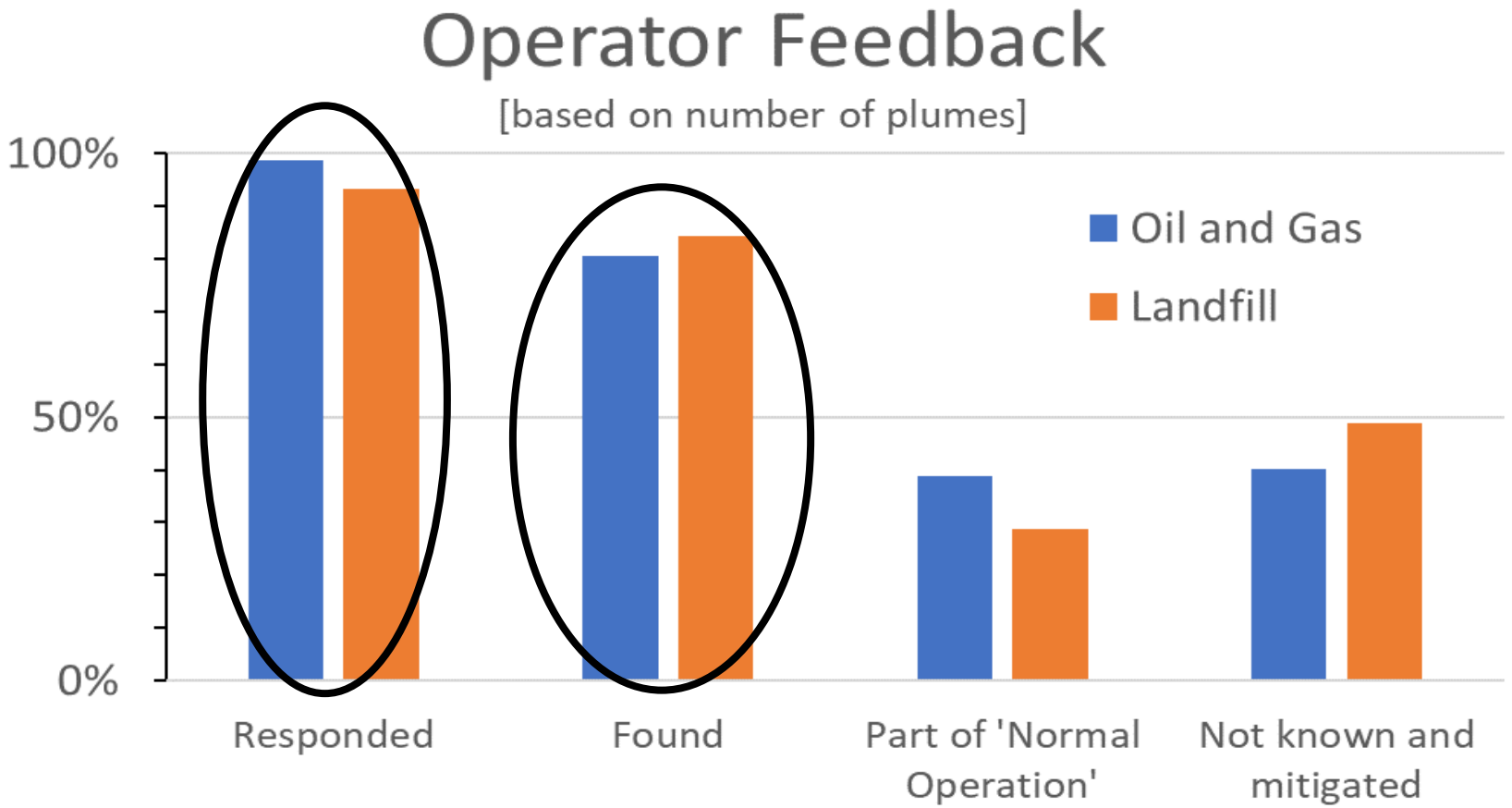

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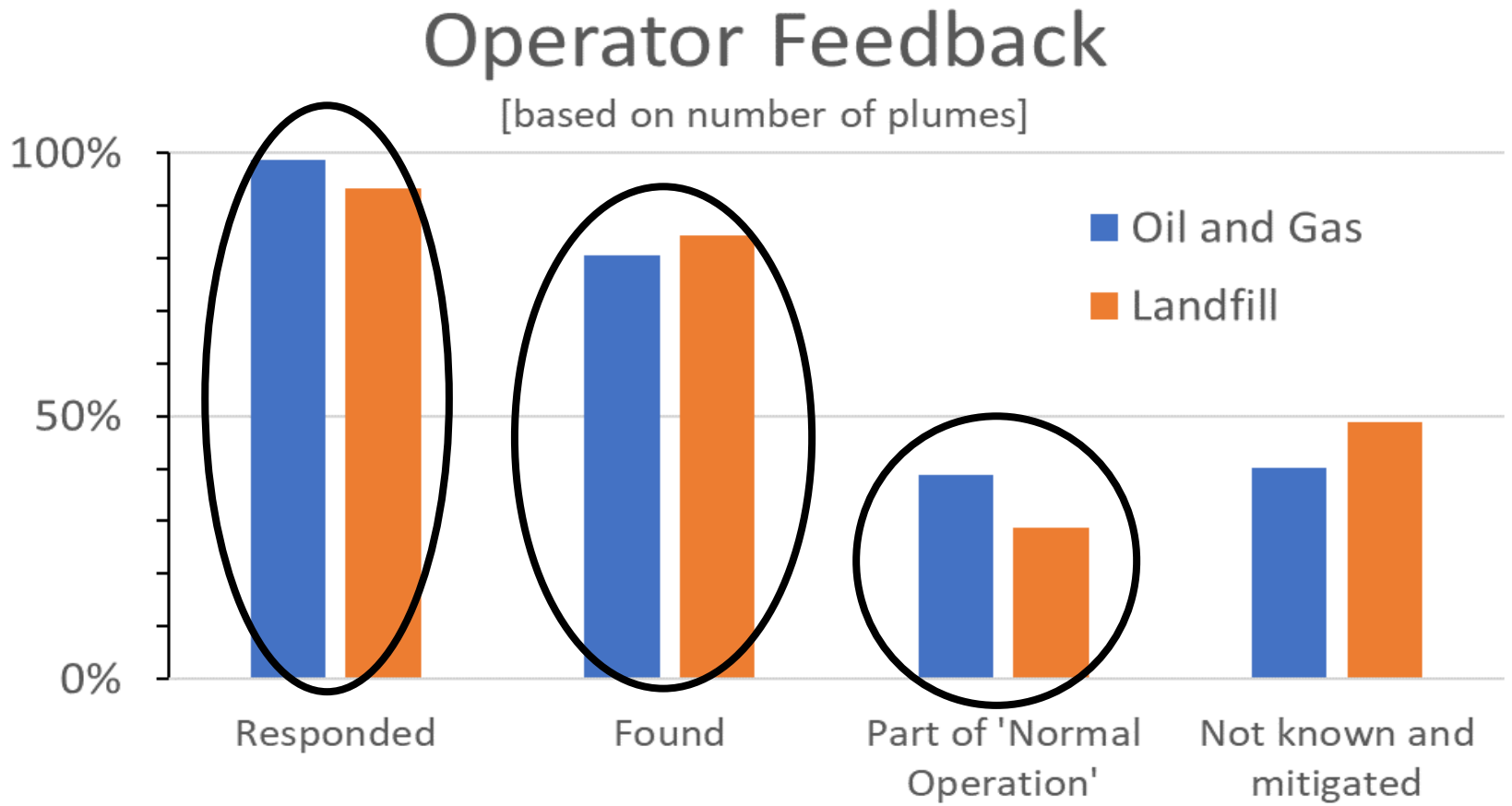

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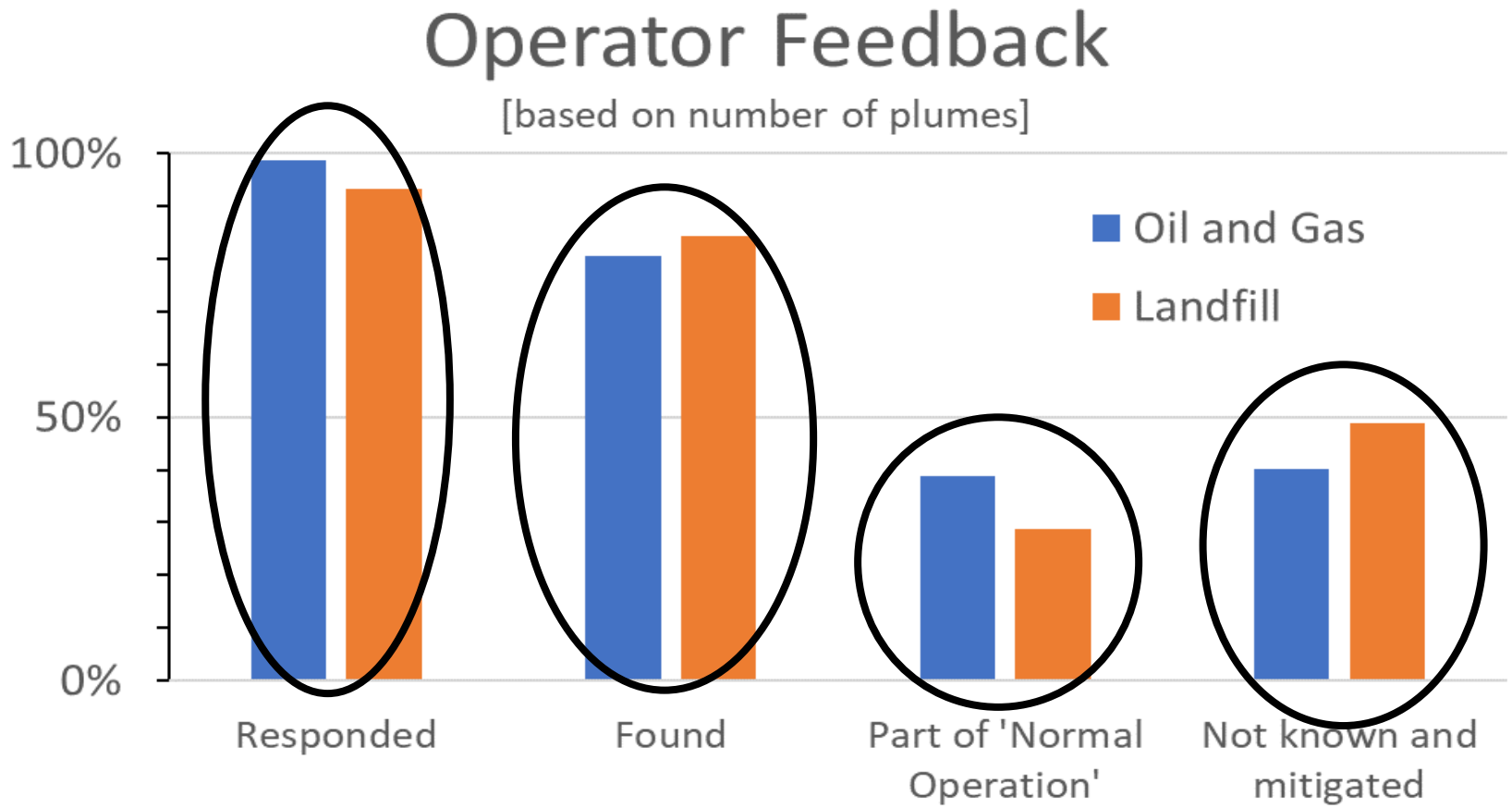
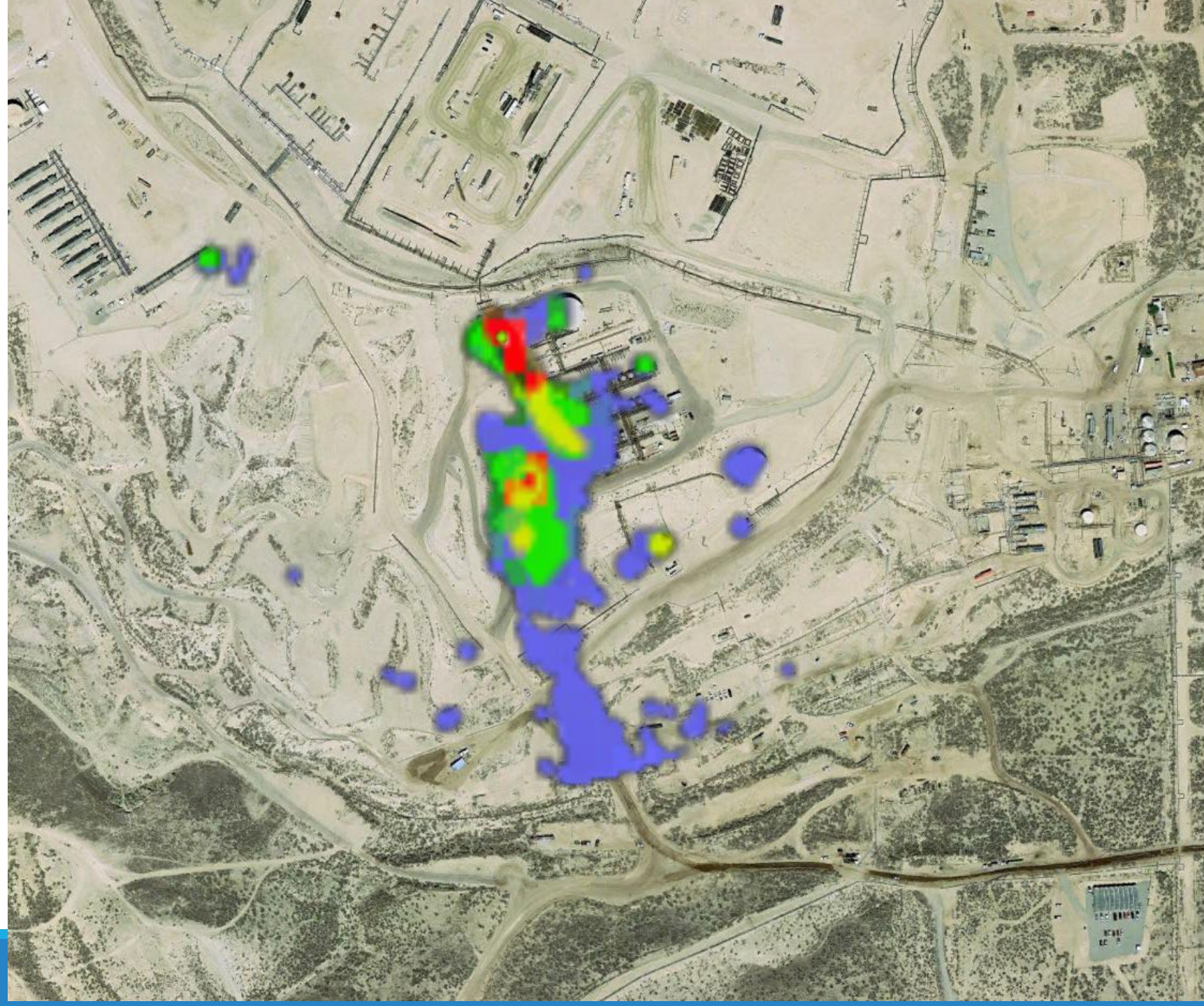


Example of images shared with operators

Sector:	Oil and Gas
Emissions:	97 kgCH4/hr
Mitigated:	Yes
Response:	Tank Valve



001_GAO20201109t182655p0000-3

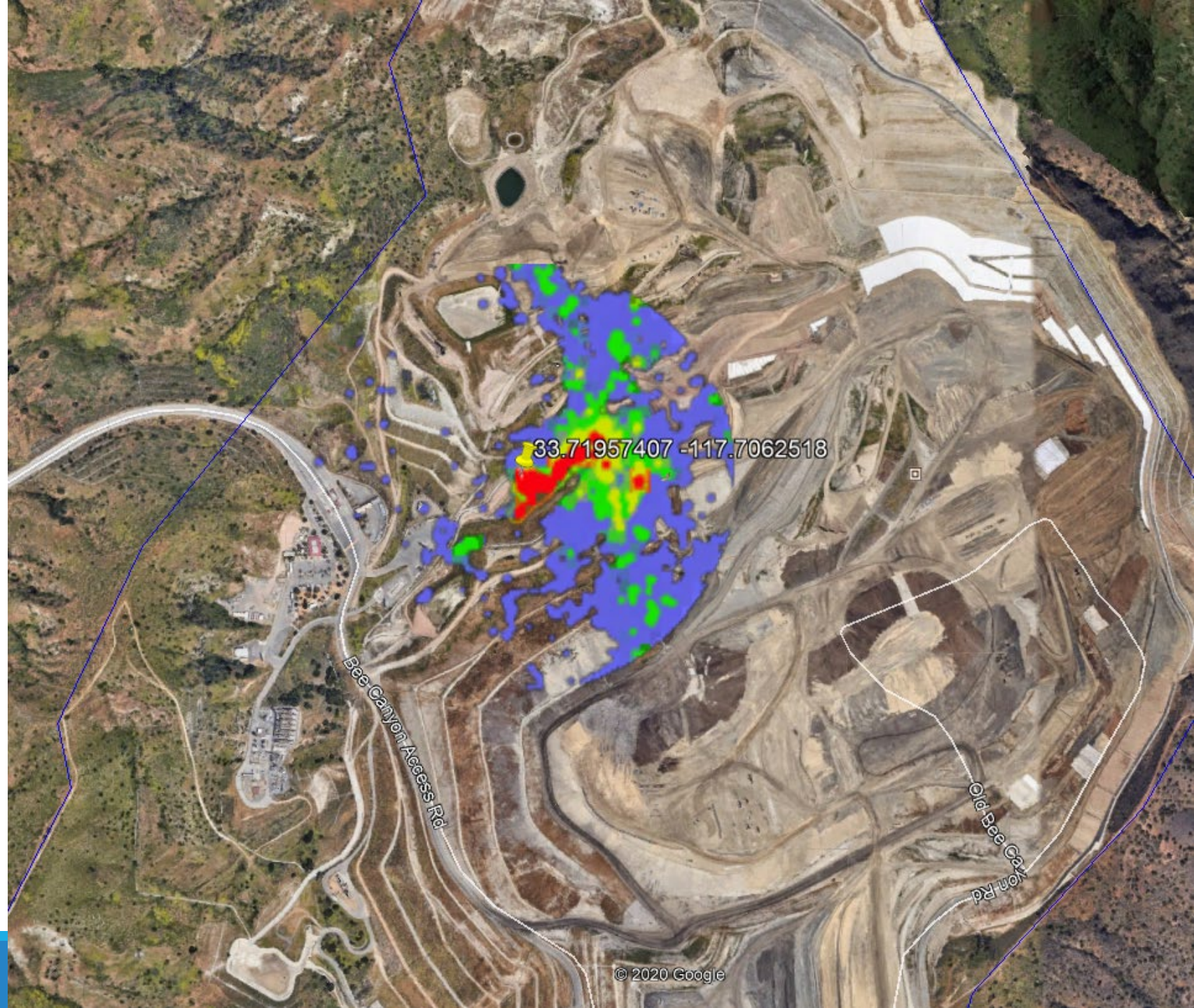
Example of images shared with operators

Sector: Utilities
Emissions: 190 kgCH4/hr
Mitigated: Yes
Response: Solenoid valve on NG compressor

030_GAO20201119t182156p0000-1

Example of images shared with operators

Sector:	Waste
Emissions:	907 kgCH4/hr
Mitigated:	?
Response:	None
received	



028_GAO20201111t190435p0000-1(FRB)

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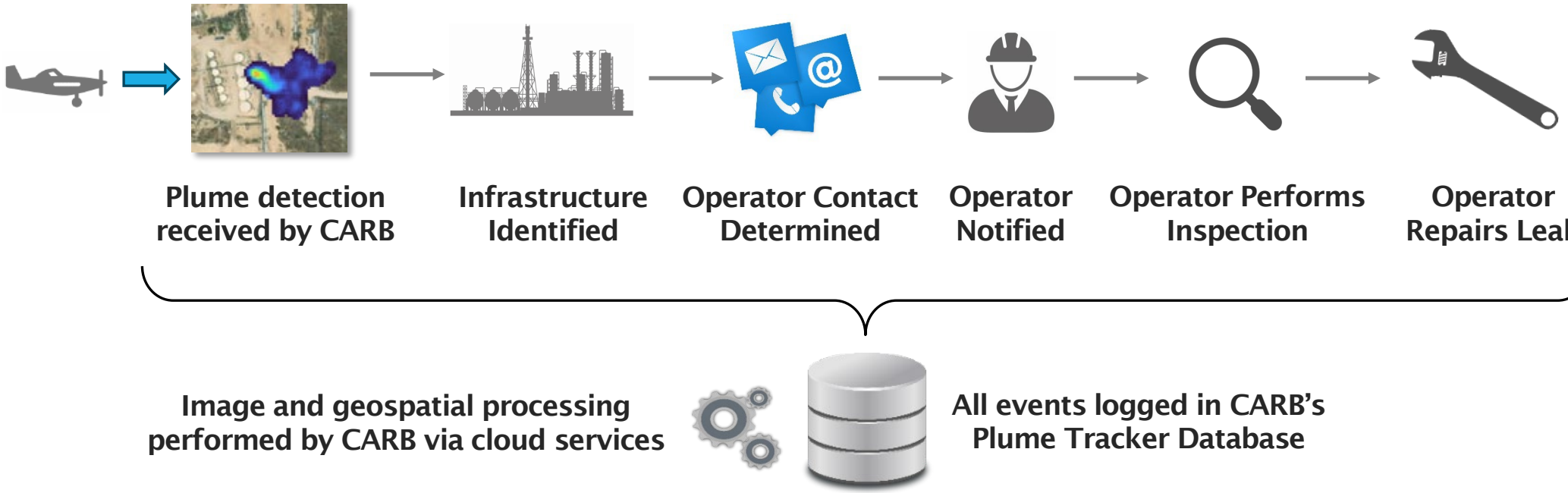

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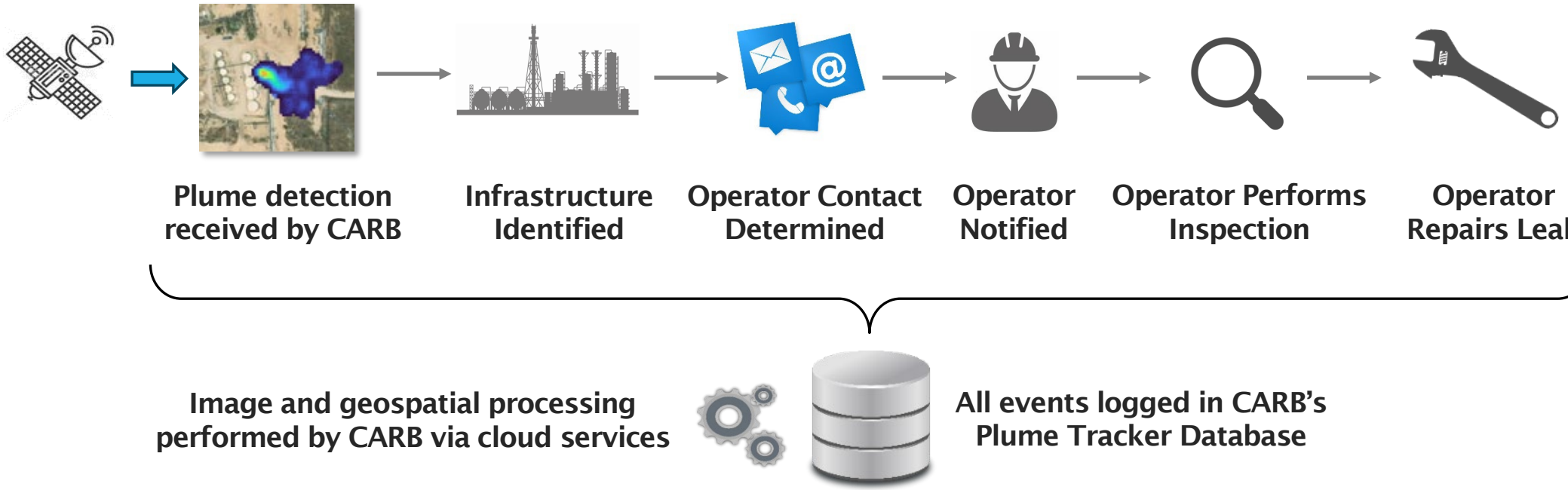

Operator Engagement: Complementary to regulations

Notification typically happens 3-5 days after observation

- Many sources are subject to State and Local regulations that limit methane emissions
  - This work complements quarterly LDAR surveys that landfill operators and oil and gas are already required to do.

Satellites enable routine coverage of large spatial areas; ideal platform for routine monitoring

CARB

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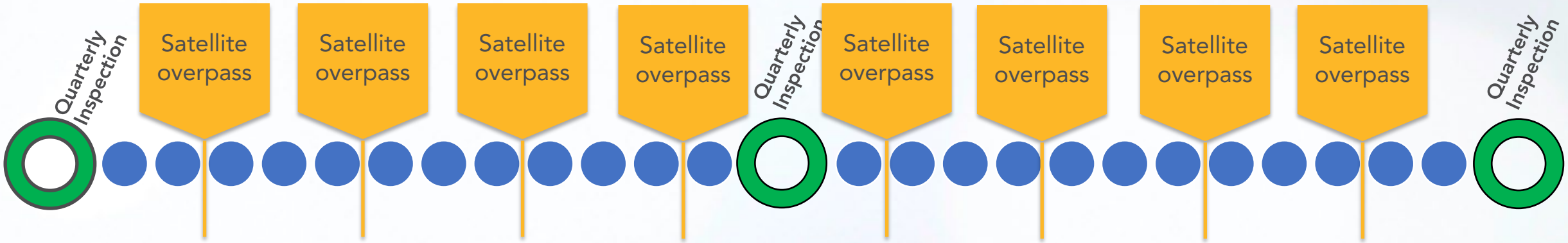

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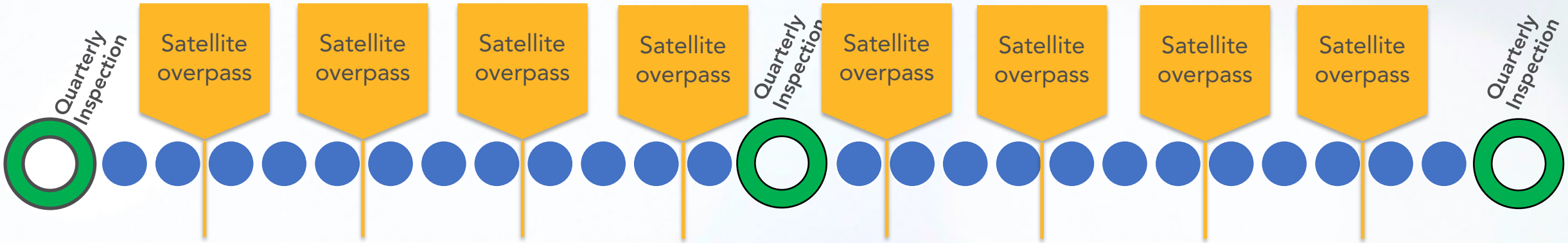
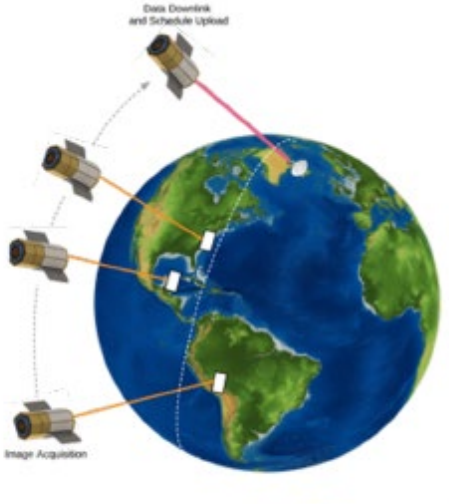


Satellites enable routine coverage of large spatial areas; ideal platform for routine monitoring

In June 2023 CARB staff presented proposed changes to the California Oil and Gas methane regulations that included the requirement from operators to inspect and fix leaks identified with remote sensing when supplied with such information from CARB. Similar regulatory action is being considered for other sectors

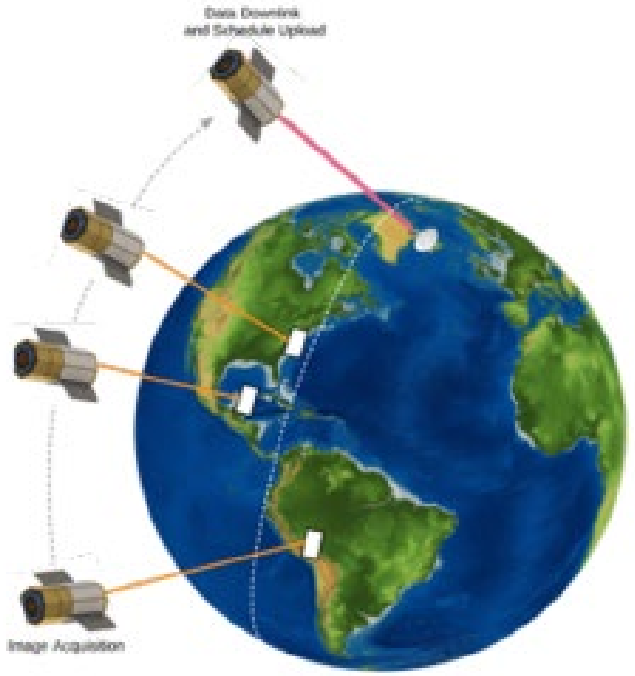
CARB

From Airborne Research Flights to Satellites



- Airborne campaigns are great for research studies and to pilot potential mitigation strategies. For sustained monitoring satellites will be needed.
- Two satellites to be launched in late 2023/early 2024 funded by philanthropy through Carbon Mapper, Inc.
- $100 million in last years California budget to purchase additional satellite data
  - *Will be awarded through a competitive RFP process*
- Traditional regulatory approaches, such as leak detection and repair for methane, can be augmented based on remote sensing observations

Satellites as Observation Platform



Engineering not final, but specifications will approximate:

- Satellite in a polar orbit – about 400 km above earth
- Can 'nod' approximately 30 degrees left to right
- Can also 'back-nod' to dwell in a single location
- Two collection modes:
  - Strip collect, individual 18x50 km tiles
  - Push broom, 18x500 km, less sensitivity, high detection limits
- Goes around the planet 15 times per day, or every 95 min
- Each satellites can collect approximately 45 tiles per day

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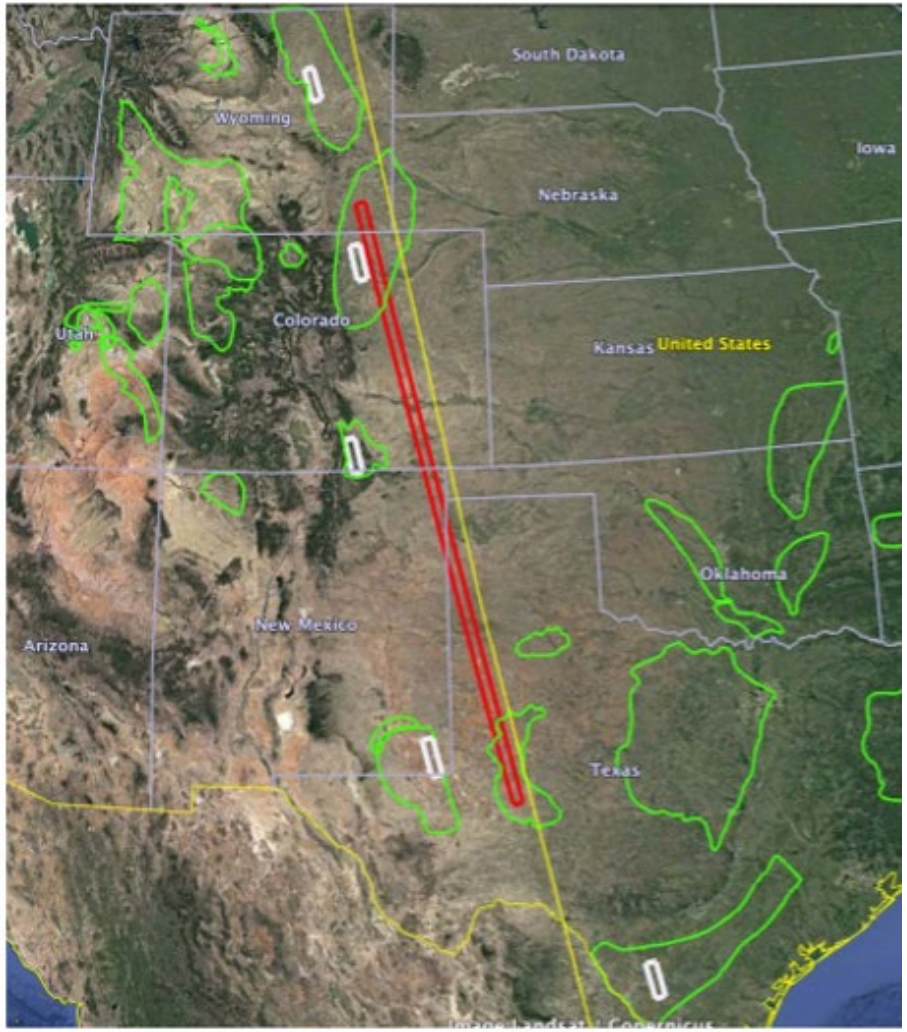

Coverage figure: comparing coverage between Carbon Mapper pushbroom (red) and strip-collect (white) observing modes in selected US gas basins (green). Basemap source: Google Earth

Thank you