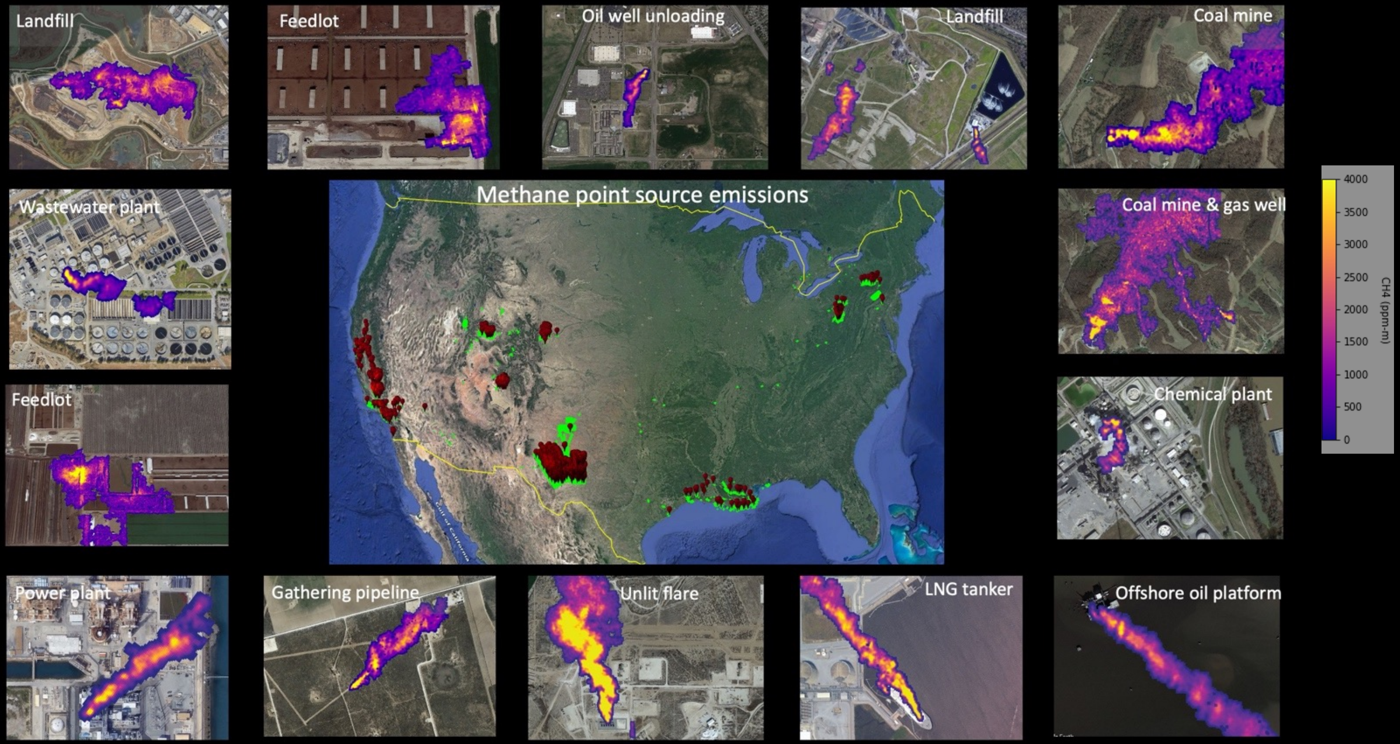
The role of (remote-sensing) measurements: what have we learned?



Riley Duren, Daniel Cusworth

Carbon Mapper, University of Arizona

carbonmapper.org

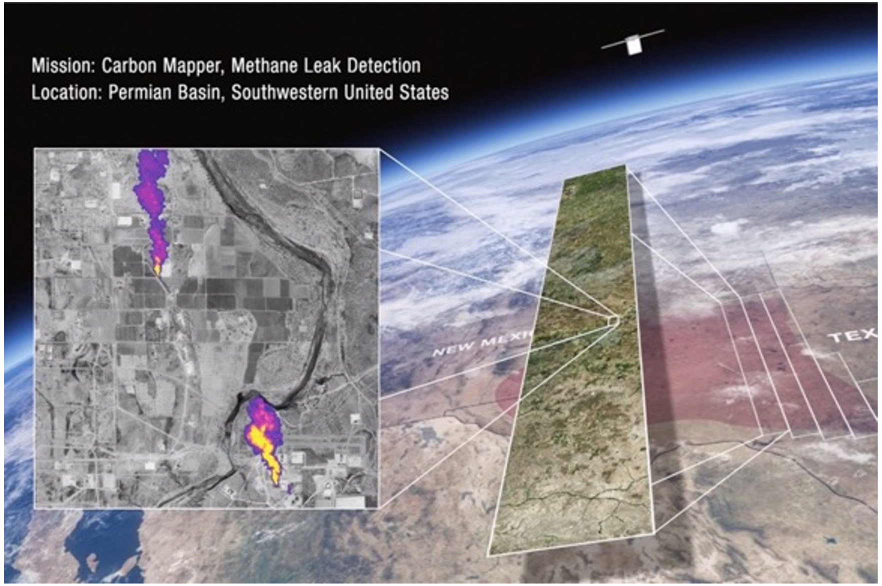
acknowledgements: contributions from collaborators at Carbon Mapper, JPL, CARB, U. Arizona, ASU, WMO IG^{3}IS, Planet; funding from NASA CMS, ACCESS, and AIST programs, NIST, CARB, CEC, U. Arizona, RMI, EDF, Joey Irwin Memorial Public Projects Fund, High Tide Foundation, Bloomberg Philanthropies, Grantham Foundation other philanthropic donors

Carbon Mapper

- Carbon Mapper the non-profit: public good mission to deliver actionable CH_4 and CO_2 data
- Carbon Mapper satellite program: public-private partnership to build and operate satellite constellation
- Phase 1: Launch first 2 satellites in 2023 – operate through at least 2024
- Phase 2: Goal to expand constellation to enable daily to bi-weekly monitoring in coming years
- Track 90% of high emitting CH_4 & CO_2 point sources at facility scale globally
- Rapid leak detection service from Planet
- All quantitative CH_4 & CO_2 emissions data publicly available from Carbon Mapper
- Continuing airborne surveys prepare for and support satellites

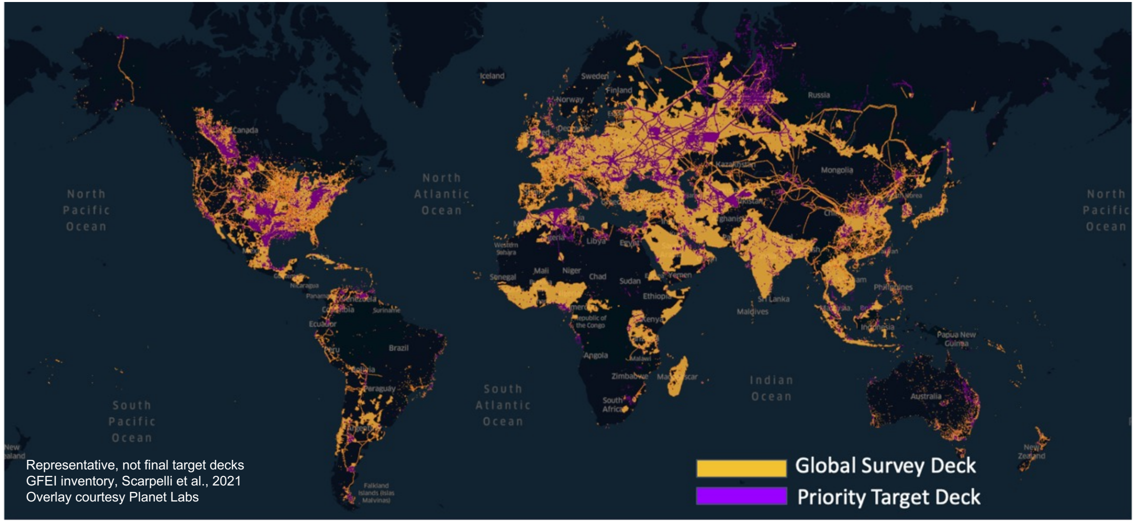
Integration

Policy | Technology | Technology | Science | Policy



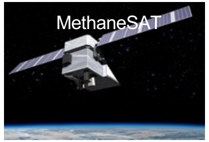
Carbon Mapper observing strategy

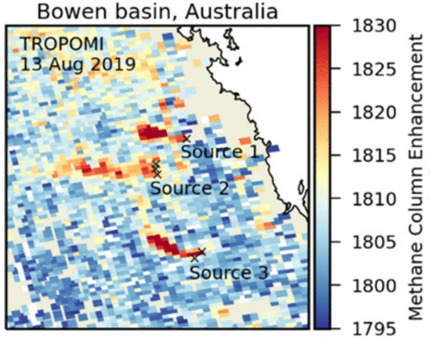
Carbon Mapper: (1) periodic global surveys and (2) sustained frequent monitoring of priority areas



Includes wide-area monitoring of offshore O&G platforms and ships using ocean glint tracking

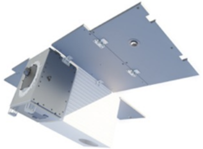
Regional CH_4 hotspots detected by other satellites (area flux mappers)

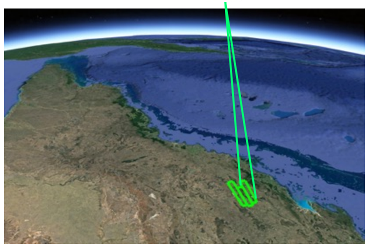




Sadavarte *et al.* 2021

(3) Carbon Mapper: agile tip & cue tasking



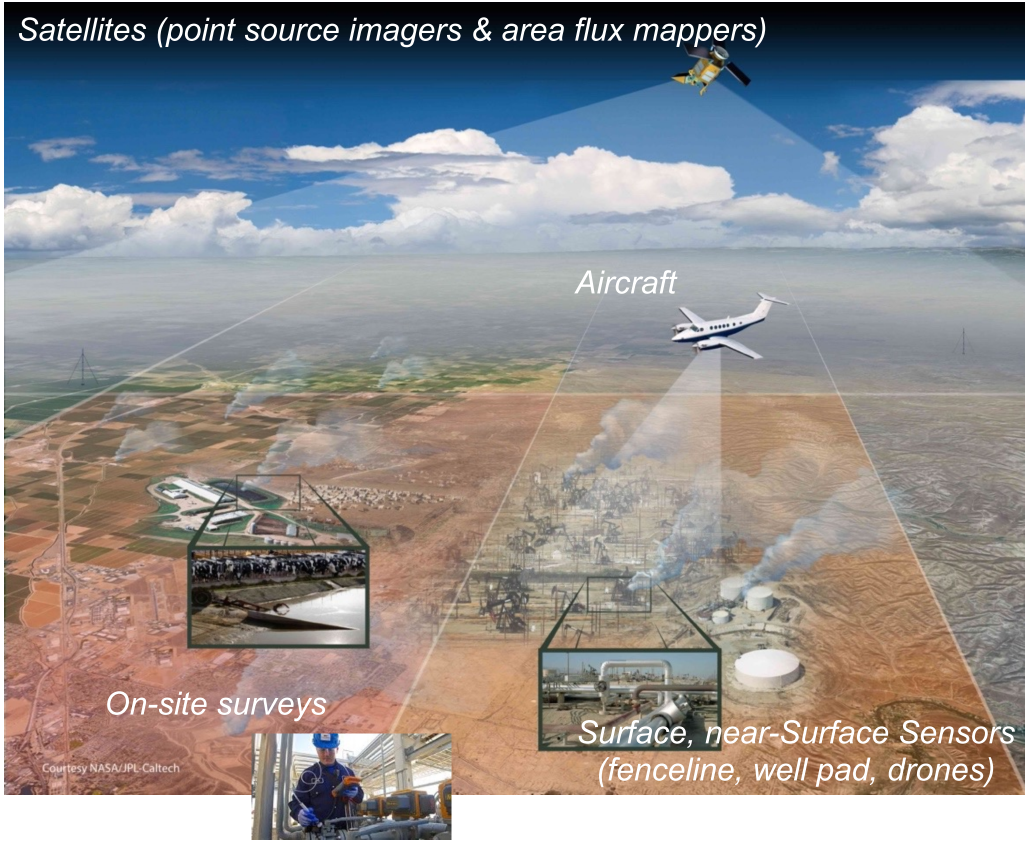


Emerging global system of systems for methane monitoring

- Two primary types of monitoring
  - Type 1: aggregate accounting, inventories
  - Type 2: direct mitigation guidance
- Rapid technological progress
  - Many diverse actors
  - Some major pilot projects
- Barriers to operationalization
  - Timeliness (latency)
  - Completeness (space, time)
  - Data accessibility, transparency
  - Stakeholder awareness, capacity
  - Finance (scale-up and sustain)

No single system can address all methane use-cases; need a portfolio of methods

Multi-tiered Observing System & Analytic Frameworks*

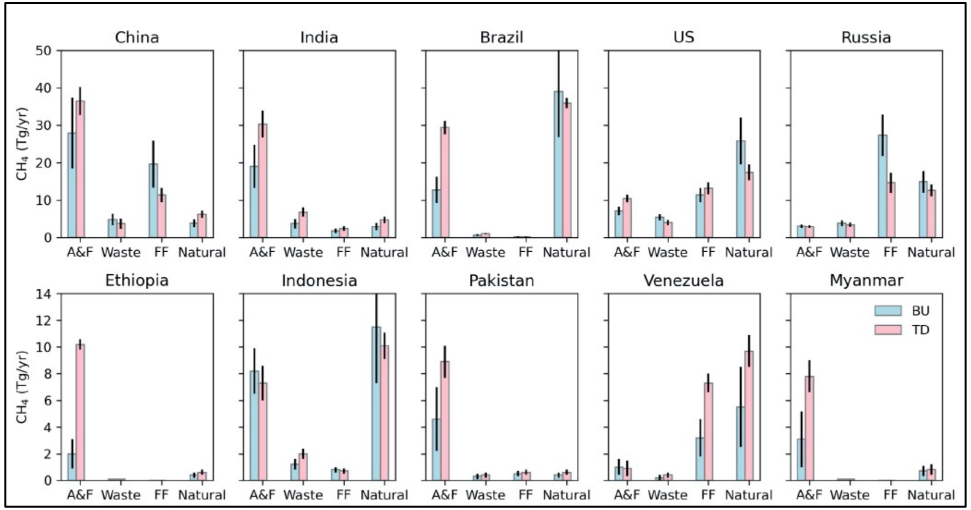


*10+ years of research funded by NASA, CARB, NIST et al

Use-cases for type 1 monitoring (inform GHG inventories and "stock-takes")

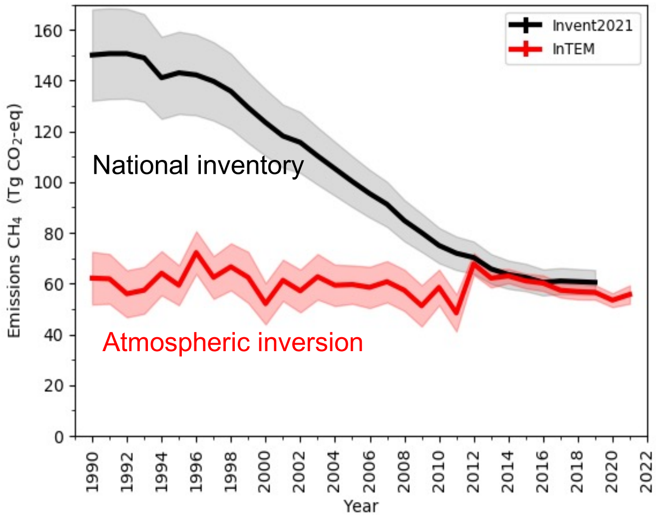
Worden *et al.*, 2022

Independent Country-level Quantification (Annual)



AF: agricultural and fires. FF: fossil fuels or coal, oil, and gas. Natural: wetlands, aquatic sources, and geological seeps. Blue bars: Bottom up (BU) inventory estimates. Red bars: Top down (TD) atmospheric estimates using GOSAT observations. Uncertainties in both quantities are shown as black lines.

Independent emissions trending (UK example)



Source: A. Manning, UK Met Office

Agreement between "top-down" and "bottom-up" varies by region and sector

Critical to establish accurate baselines for effective trending

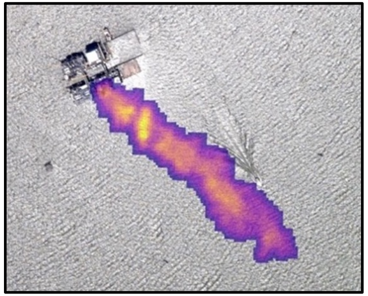
Use-cases for type 2 monitoring (mitigation guidance)

Oil & Gas: Leak Detection & Repair

Efficient screening for operators, regulators

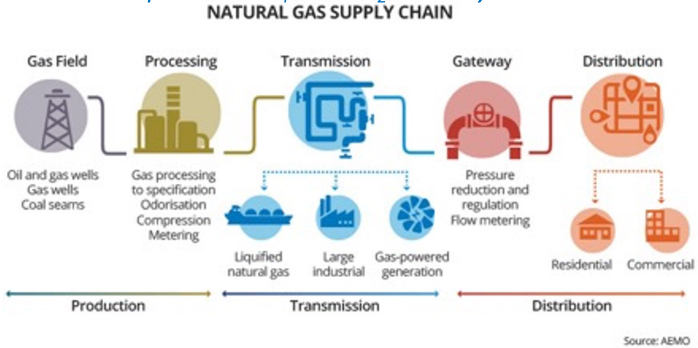
Coal, O&G CH_4: reduce legal but wasteful venting

Guide engineering, policy improvements



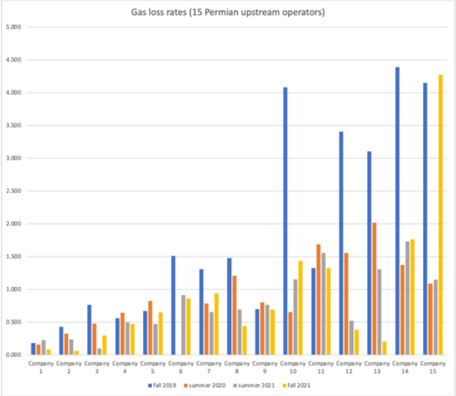
Differentiated gas supply-chains

Independent CH_4 and CO_2 intensity estimates



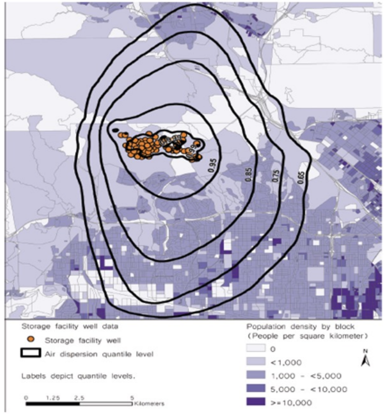
Methane trends & distributions

Improve accountability, assess progress



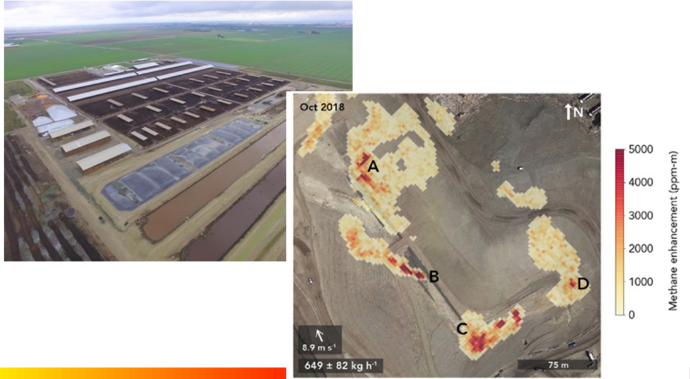
Public health, EJ: flag air-quality, gas hazards

Alert first responders and front-line communities



Landfills & Livestock: diagnose root cause

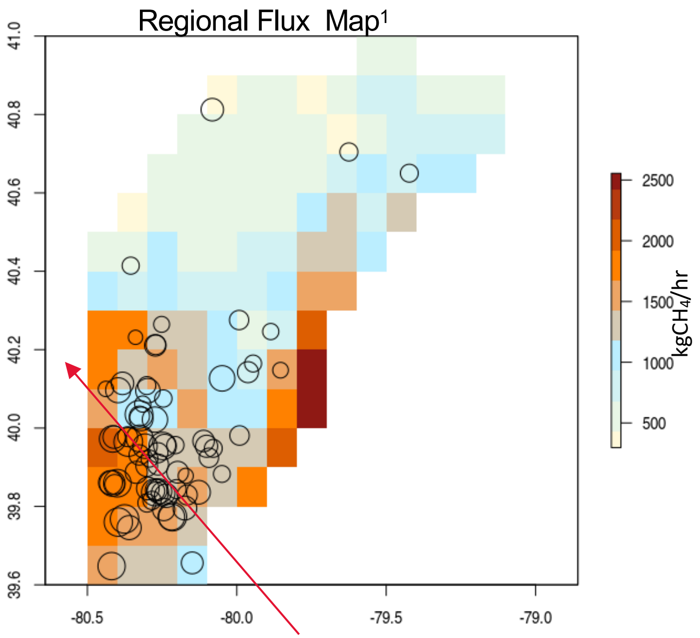
inform best practices & investment priorities



Methods: multi-scale/multi-sensor remote sensing

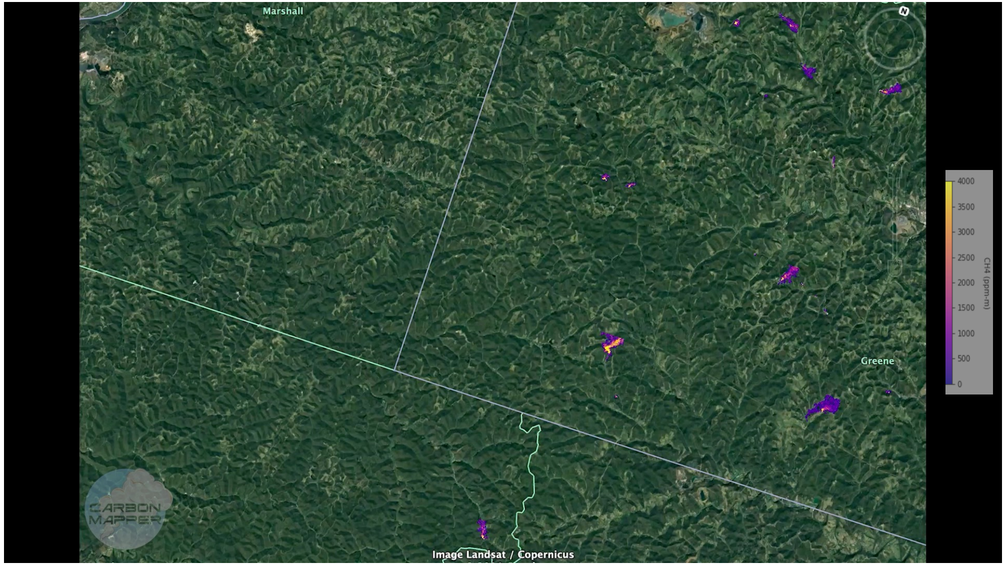
(CH_4 example for Southwest Pennsylvania)

Regional Flux Map[1]



Cusworth *et al., PNAS*, 2022

High-emission point sources[2]



Net regional emissions: 113,000 +/- 32,000 kg CH_4/hr

Point source emissions: 65,000 +/- 26,000 kg CH_4/hr

Net Regional Emissions

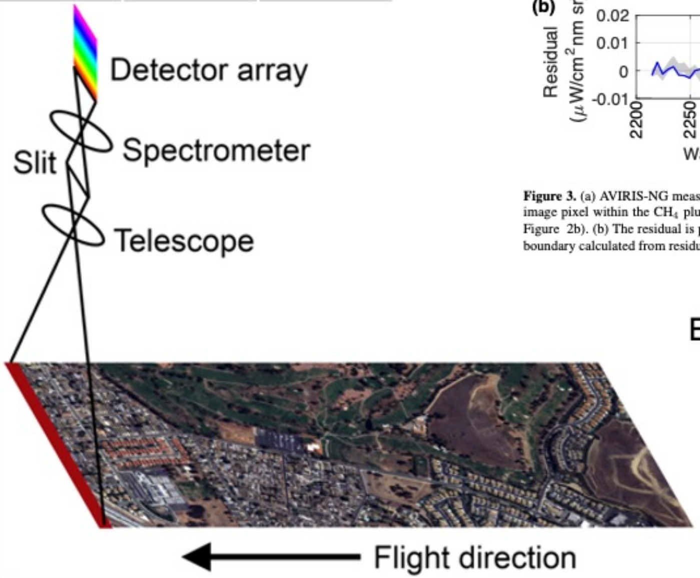
High-emission point sources + Area Emission Sources

[1]Regional flux inversion using Sentinel 5P/TROPOMI satellite observations [2]Point source imaging spectroscopy (e.g., ASU Global Airborne Observatory, NASA AVIRIS-NG)

Point source focus: infrared imaging spectroscopy detects and quantifies strong CH_4 and CO_2 point source emissions & flares

AVIRIS-NG (next generation Airborne Visible/Infrared Imaging Spectrometer) and GAO (Global Airborne Observatory): 5 nm spectral resolution, 380-2510 nm spectral range, SNR 400, ground sample distance (GSD) and swath width vary with altitude

Alt (km)	Swath (km)	GSD (m)
3	1.7	3
5.5	3	5.5
8	4.4	8



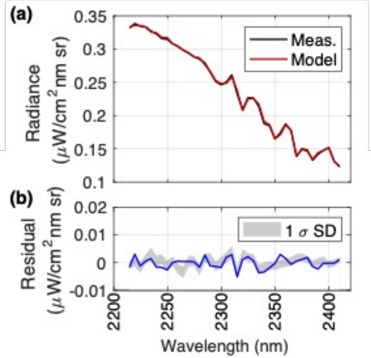


Figure 3. (a) AVIRIS-NG measured and modeled radiance for one image pixel within the CH_4 plume used for the CH_4 retrieval (see Figure 2b). (b) The residual is plotted with 1 σ standard deviation boundary calculated from residuals for the entire scene.

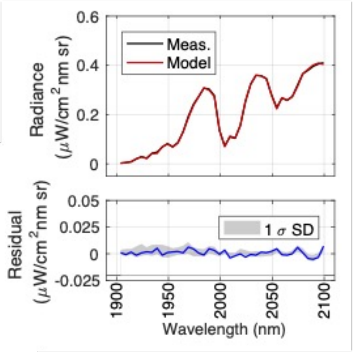
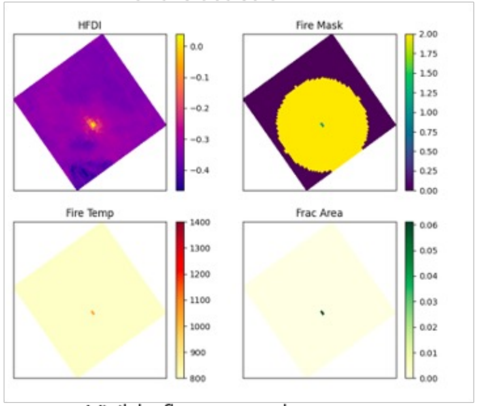


Figure 7. (a) AVIRIS-NG measured and modeled radiance for one image pixel within the CO_2 plume for the CO_2 retrieval (see Figure 6b). (b) The residual is plotted with 1 σ standard deviation boundary calculated from residuals for the entire scene.

Flare detection



Visible flare extends across multiple pixels

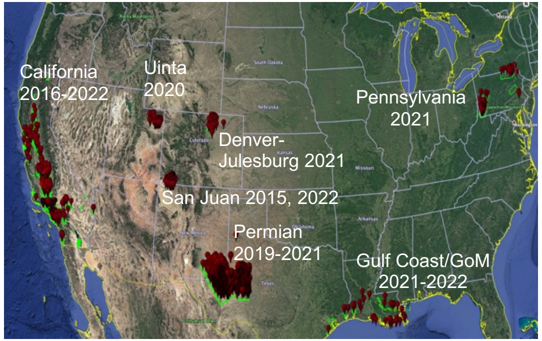
Enhancement + wind speed → Emission rate

$$IME_{r_c} = k \sum_{i=0}^{n} \alpha(i) S(i) \qquad Q = \left(\overline{IME}/_{r}\right) U_{10}$$

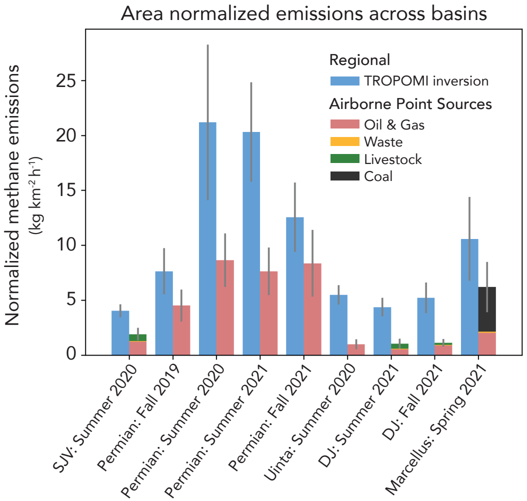
Thorpe *et al.*, *AMT*, 2017; Thompson *et al.*, *GRL*, 2016; Frankenberg *et al.*, *PNAS*, 2016; Duren *et al.*, *Nature*, 2019

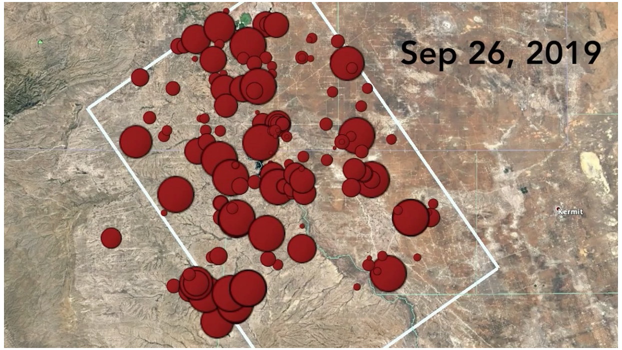
Lessons from multi-scale CH_4 studies in 7 US regions

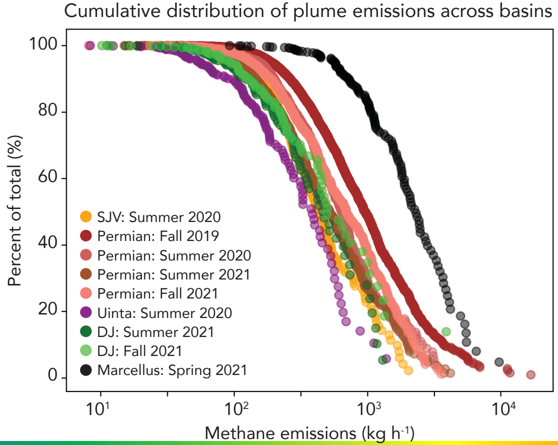
- Small number of CH_4 high emission sources >10 kg/h contribute 20-60% of net regional emissions
- Highly skewed distributions seen both for onshore & offshore oil & gas production
- Mix of persistent **<u>& intermittent</u>** emissions (bi-modal distribution)



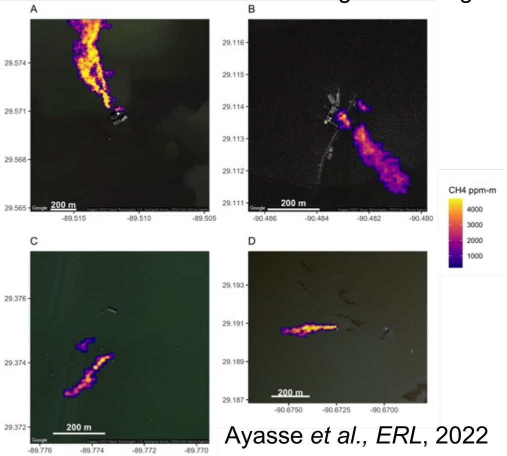
Cusworth *et al.*, *PNAS*, 2022; Duren *et al*, Nature, 2019







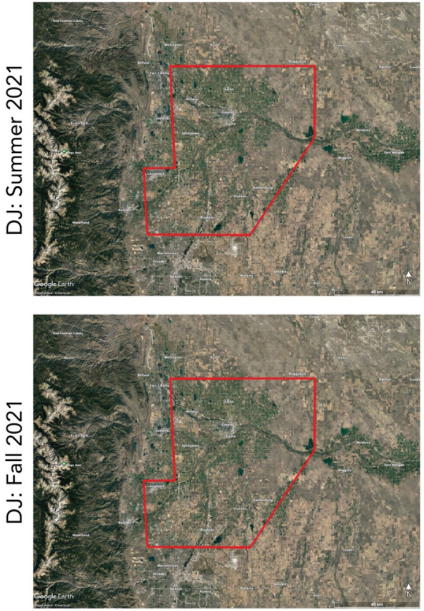
Offshore emissions with ocean glint tracking

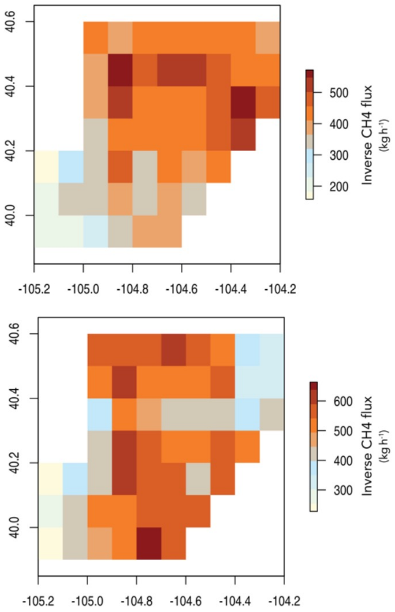


Ayasse *et al.*, *ERL*, 2022

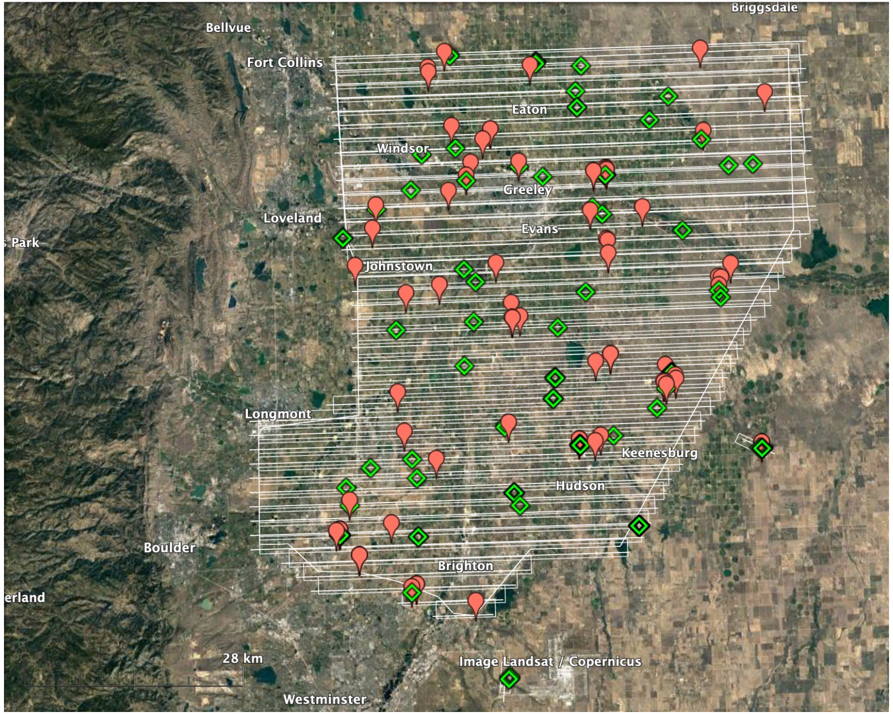
2021 Denver-Julesburg study: multi-scale analysis

Regional flux inversion
TROPOMI satellite observations;
2 months around each campaign





Point source quantification from GAO airborne observations (July and Sept)



Cusworth *et al.*, *PNAS*, 2022

DJ basin summary: seasonable variability

Dates surveyed	Area surveyed (km^2)	Number of detected point source plumes	Sumof point CH4 emissions ($t\ h^{-1}$)[a]	Sector contribution to point source total ($t\ h^{-1}$)[a]		Average number of overpasses per source	Average source persistence (unitless)	Total regional CH4 flux ($t\ h^{-1}$)[c]
Jul 12-22, 2021	4,800	92	4.98 ± 2.1	O&G	2.5	4.5	0.34	21.1 ± 4.1
				Waste	0.3			
				CAFO	2.2			
Sep 19-29, 2021	4,800	94	5.37 ± 1.7	O&G	4.2	4.8	0.28	25.2 ± 6.8
				Waste	0.3			
				CAFO	0.9			

Sept vs July 2021:

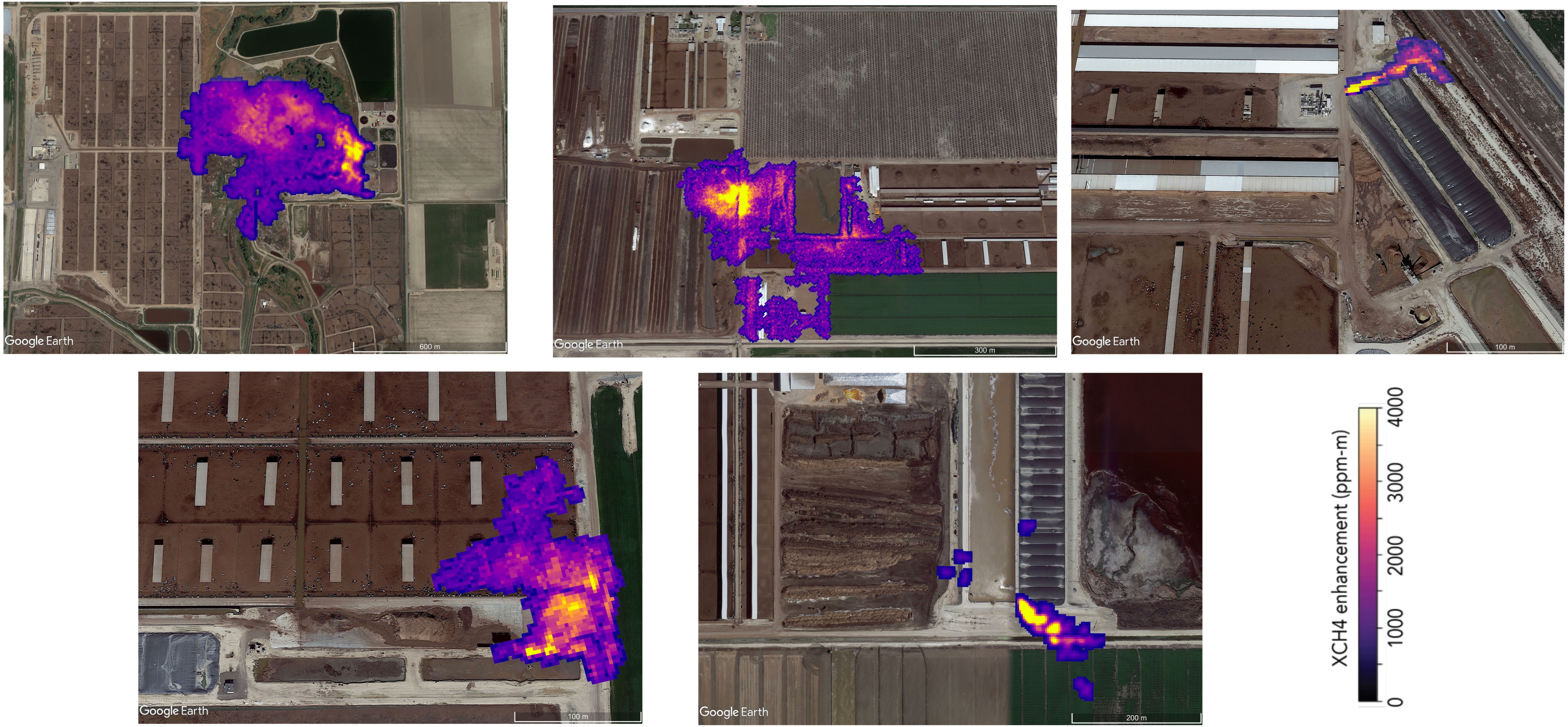
We observed a 19% increase in regional emissions
&
8% increase in point source emissions (+70% for O&G, offset by reduction at CAFOs)

Per EIA for CO July-Sept 2021: gas production flat , oil production increased 6%

Dates surveyed	O&G point-source total ($t\ h^{-1}$)	Production (%)	Compression (%)	Gathering pipelines (%)	Processing (%)
Jul 12-22, 2021	2.54 ± 1.1	71	12	7	9
Sep 19-29, 2021	4.25 ± 1.4	51	13	28	9

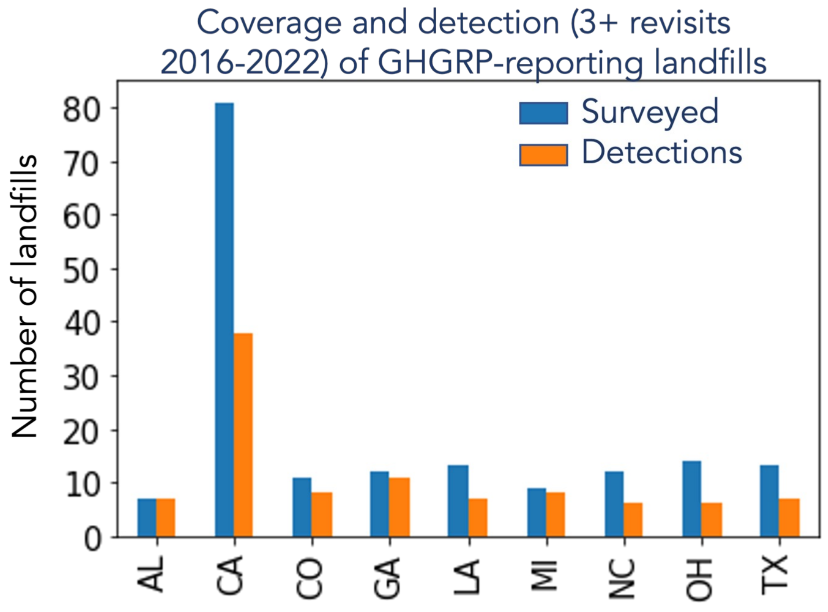
Cusworth *et al.*, *PNAS*, 2022

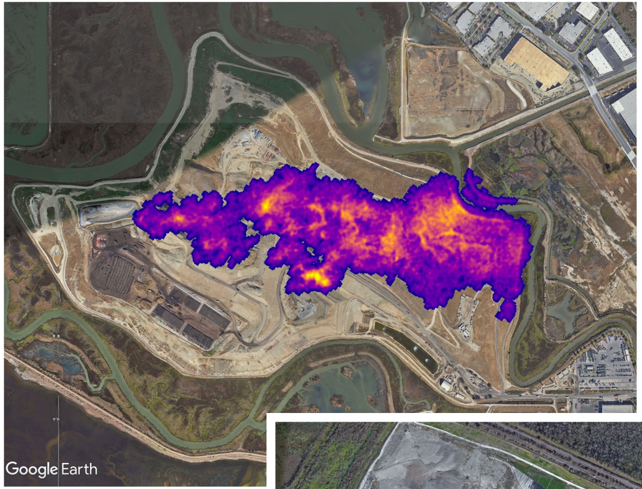
Methane emissions from manure management
(examples from California and Colorado)

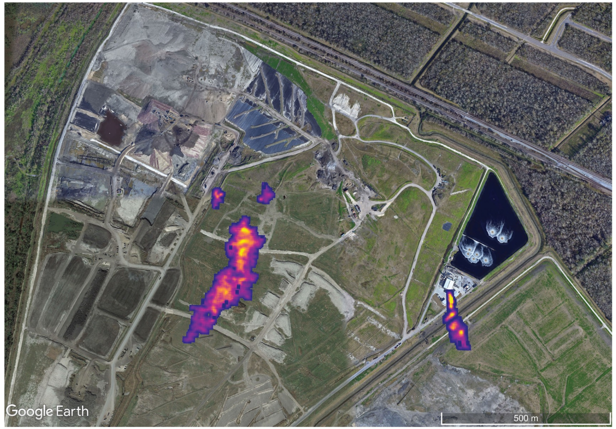


Methane emissions from landfills

Our aircraft surveyed 239 landfills in 17 US states that report to EPA's Greenhouse Gas Reporting Program; over half exhibit high emission point sources

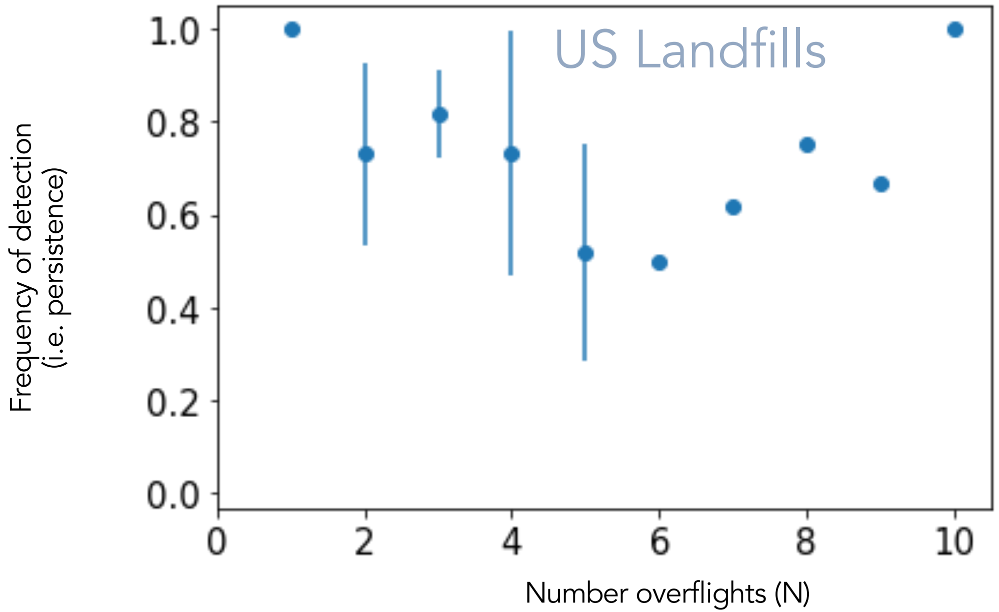


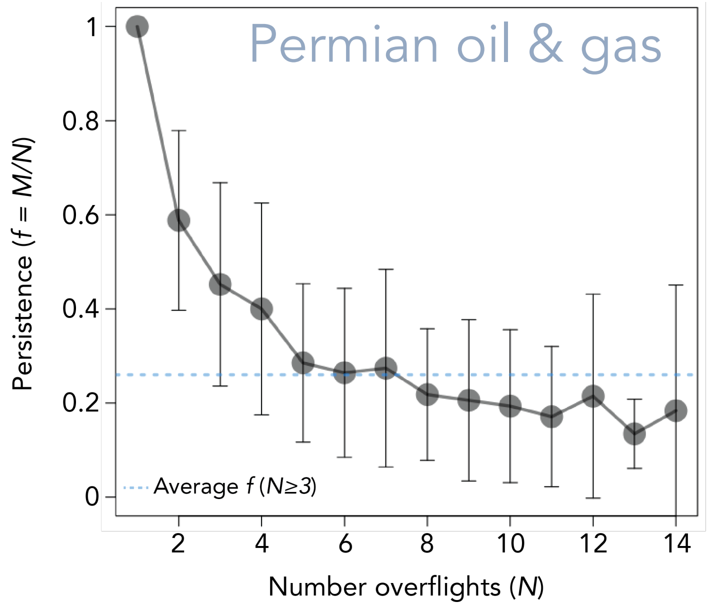




Sample frequency and source persistence

Need persistent, repeated observations to quantify emission persistence, reduce uncertainty, and compare with reported emissions.





Landfill point source emissions are generally more persistent than oil & gas

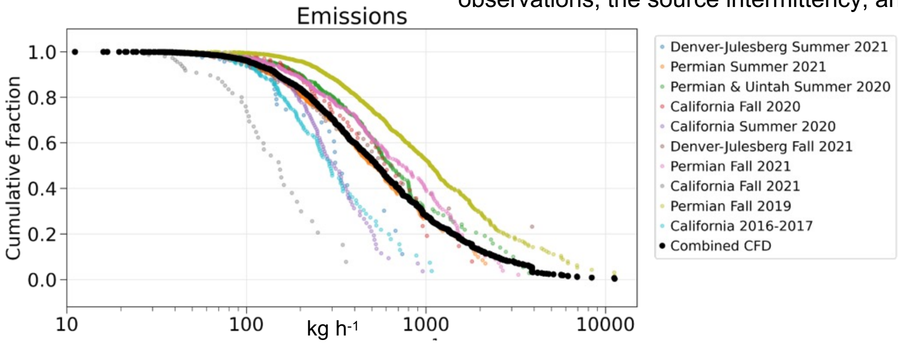
Observing system completeness

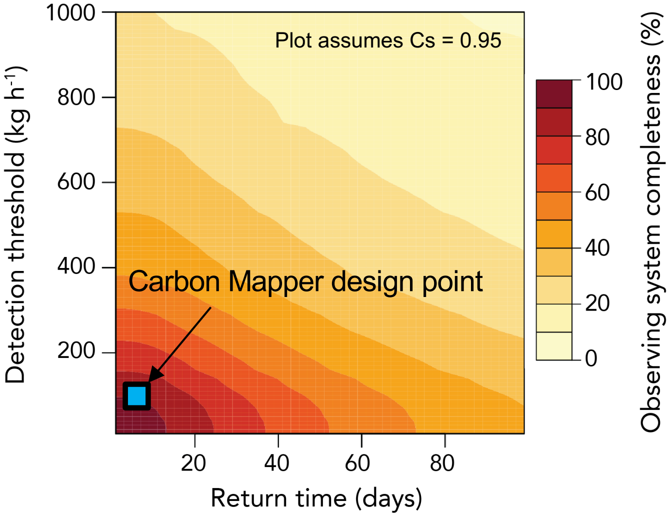
$$C = C_D \times C_S \times C_T$$

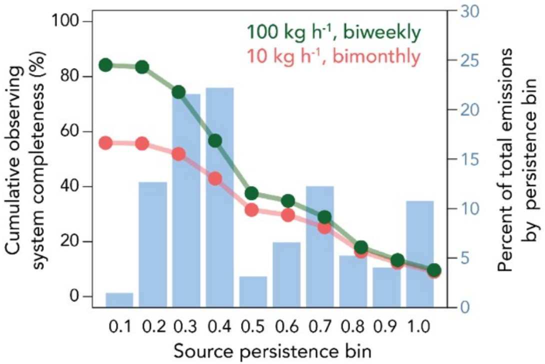
C_D (sensitivity): fraction of point sources that can be detected based on the detection threshold – varies by region

C_S (spatial coverage): fraction of those point source emitters that is observed within a given time interval

C_T (temporal completeness) = probability for an observed source to be actually detected within a time interval; function of N observations, the source intermittency, and the fraction *f* of clear-sky observations



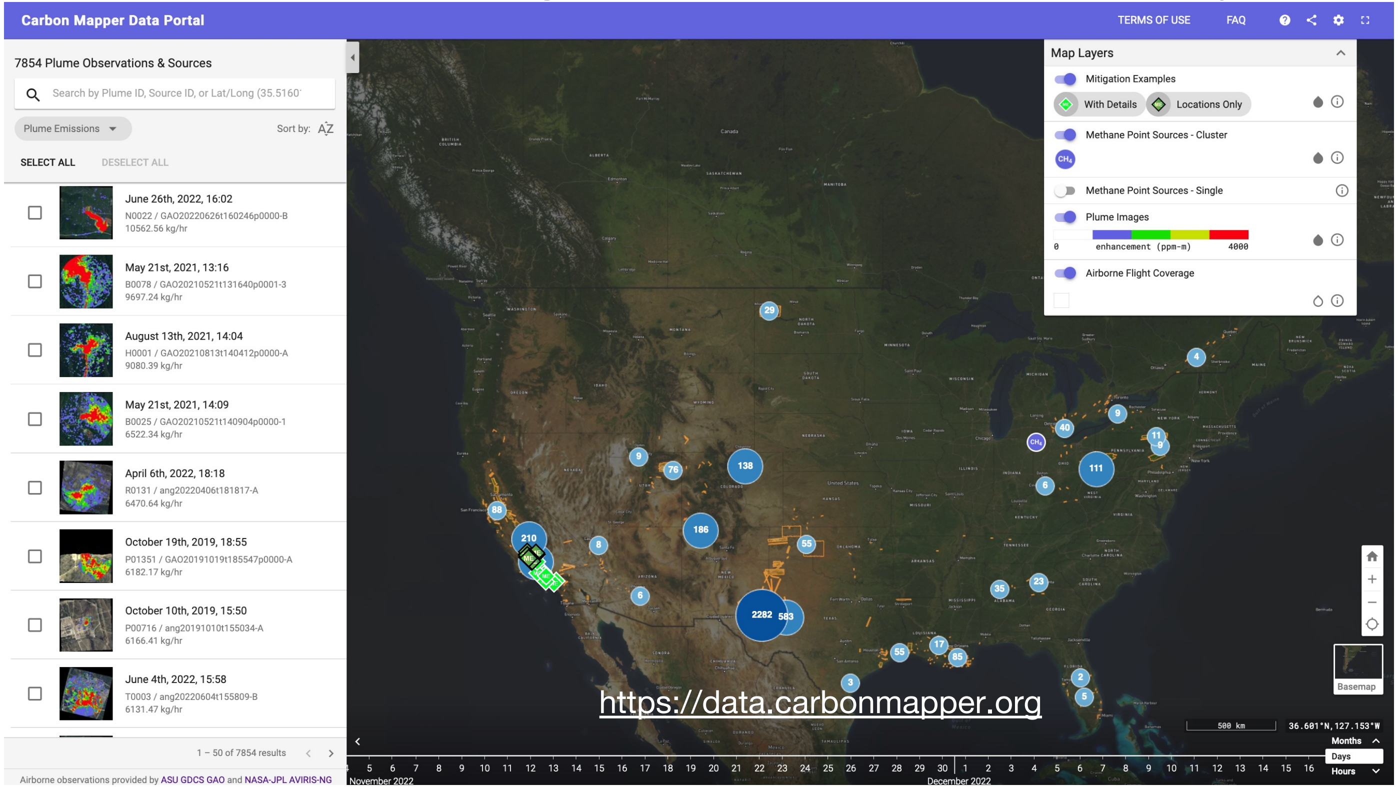




Jacob *et al.*, 2022, *ACP*

Completeness ultimately constrains mitigation potential (can't manage what you don't measure)

Data sharing and transparency



Carbon Mapper data policies

- All airborne CH_4 data since 2016 available on public portal (nearly 8000 CH_4 plumes to date)
- Expedited data release regarding potentially hazardous methane events
- Ongoing release of quantitative, QC reviewed CH_4 and CO_2 data from satellites and aircraft within 90 days

Summary

- Two basic types of CH_4 monitoring with some overlap but generally distinct use-cases, stakeholders, requirements and communities-of-practice
  - Type 1 (aggregate accounting): operational readiness for some large jurisdictions
  - Type 2 (mitigation guidance): approaching prime-time readiness for O&G sector, with varying degrees of completeness, scalability and transparency
- Emerging findings about key sectors – still limited by spatio-temporal completeness
  - Highly skewed point source emissions
  - Bi-modal temporal behavior (persistent and intermittent)
  - Significant variability by region and sector
- Strategies for operational monitoring
  - Scale-up proven technologies ASAP
  - Sustained frequent sampling over large areas for maximum completeness
  - Tiered observational strategies for multi-scale awareness
  - Use highly space-time resolved observations to improve models
  - Data validation and transparency for credibility

Thank you

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carbonmapper.org

www.planet.com/carbon-mapper

ww2.arb.ca.gov/our-work/programs/california-satellite-partnership