Operational Methane Plume Delineation for Airborne and Satellite Imaging Spectrometers

Kelly O'Neill[1]; Daniel Cusworth[1]; Alana Ayasse[1]; Justin Fisk[1]; Riley Duren[1]
[1] Carbon Mapper

Background

Methane

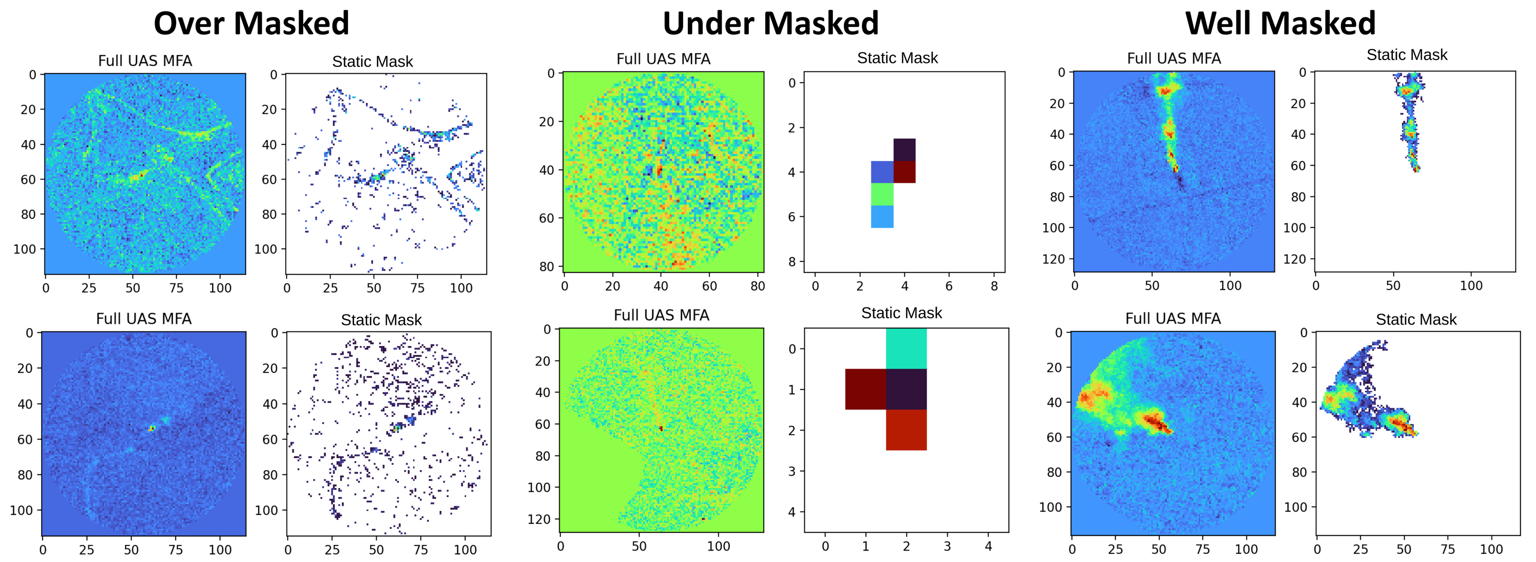
- Atmospheric methane (CH_4) is a potent greenhouse gas responsible for 20% of anthropogenic radiative forcing since 1750, with a global warming potential 80 times higher than that of CO_2 over a 20-year period [1,2]
- Anthropogenic sources constitute 50-65% of CH_4 emissions and in many cases are underestimated in bottom-up emission budgets [3]
- 20-50% of regional budgets may be produced by point-source super-emitters [4]

Quantification

- Airborne and satellite imaging spectrometers such as AVIRIS-NG, GAO, and EMIT are common platforms for the remote sensing of high emission methane events [4,5,6]
- These sensors utilize column-wise matched filters to detect and quantify emissions using the Integrated Mass Enhancement (IME) algorithm, which uses explicit spatial delineation of a plume's enhancement and length to derive flux rates [7]
- In complex observing environments these parameters can be hard to estimate or highly sensitive to noise or retrieval artifacts

Masking Approaches

- In the research literature upwind sampling followed by gaussian and mean filtering has produced well constrained plume specific masks [7,8]
- This method requires manual selection of samples which do not contain retrieval artifacts or unique noise patterns making it ill fitted to the processing timelines presented by large airborne datasets or continuous incoming satellite observations
- In production environments static ppm-m thresholding followed by connected component analysis is used to automate the masking procedure [4]
- Static thresholds lead to under/over masking when presented with dynamic background noise found in satellite observing systems, leading to potential emission rate biases over specific land covers and solar geometries



Objectives

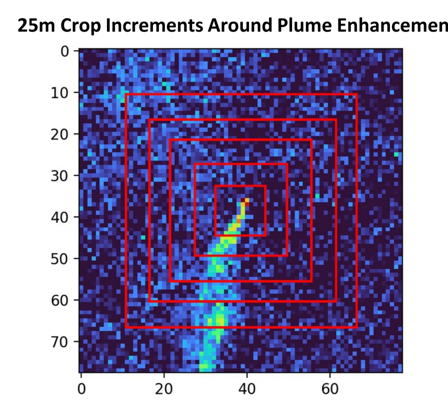
- Create an automated masking approach suitable for production settings which utilizes plume specific dynamic thresholding
- Assess its performance across a range of land covers and plume morphologies

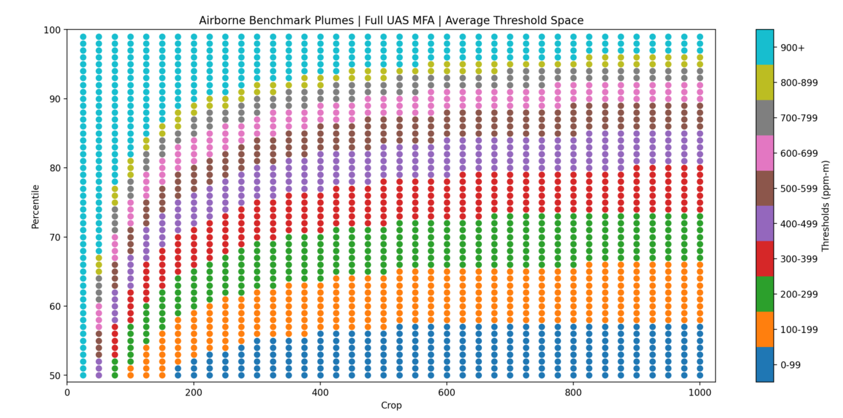
Data

- Airborne Optimization data consisted of 109 GAO scenes from an October 2022 controlled release experiment, in which Stanford provided metered emission values[9]
- Airborne assessment data consisted of 1,266 GAO and AVIRIS-NG plumes collected across campaigns between 2019 and 2023 throughout North and South America [10]
- AVIRIS-NG and GAO are hyperspectral imaging spectrometers with a shared architecture [11]
  - 380 – 2510nm wavelength range
  - 600 cross track elements
  - 5.6 - 6.0nm spectral resolution
- EMIT data consisted of 1,094 plumes detected between 2022 and 2023 [10]
- EMIT is a satellite successor to AVIRIS-NG with the given architecture [12]
  - 381 – 2493nm wavelength range
  - 1,200 cross track elements
  - ~7.5nm spectral resolution

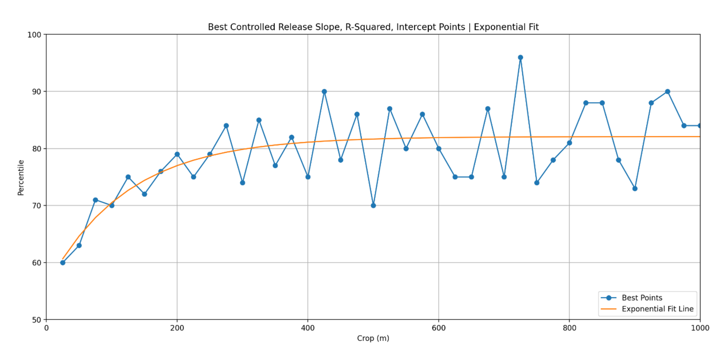
Methods

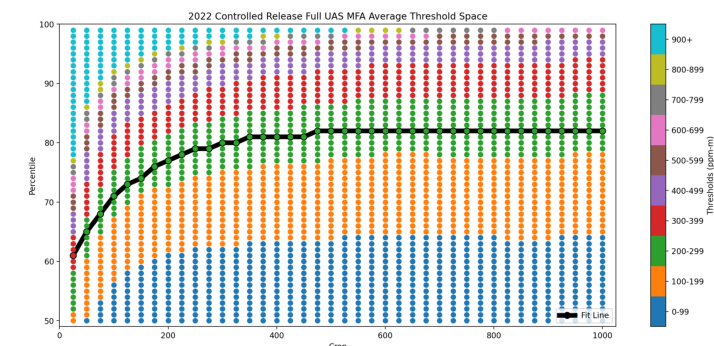
- Thresholds can be understood as a percentile of a crop around a plume source, with higher percentiles defining enhancements in larger spatial areas, these combinations define a threshold solution space



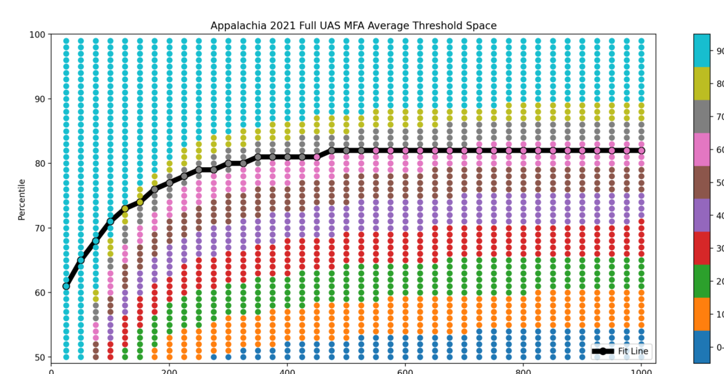


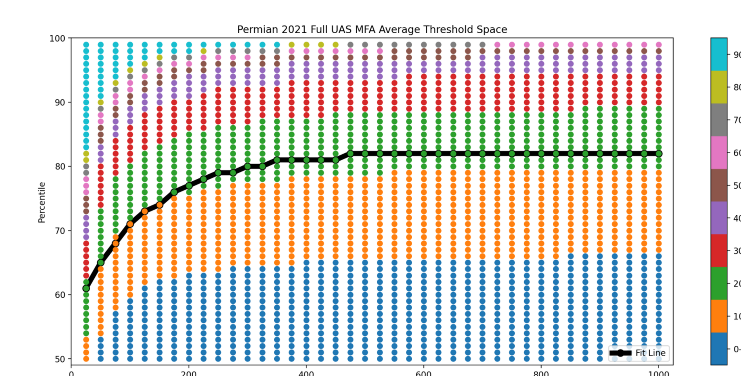
- To explore this space, at each point the given crop/percentile is applied to all plumes with the average threshold among them plotted above
- Thresholds were used to compute masks and emissions for each controlled release plume, which were assessed in crop/percentile aggregates against truth values
- At each crop, the percentile producing the best result (equally weighting Slope, R-Squared, and Intercept) was plotted and then fit with an exponential function



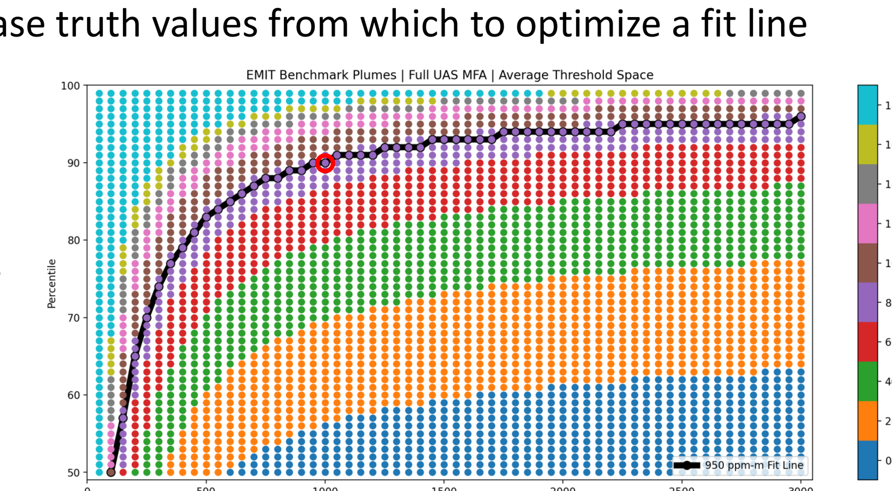


- The fit line denotes an expected extent of enhancements within a spatial domain
- In the Controlled Release this can be approximated by using a static 250ppm-m threshold, however in scenes with diverse background noise characteristics other thresholds are selected





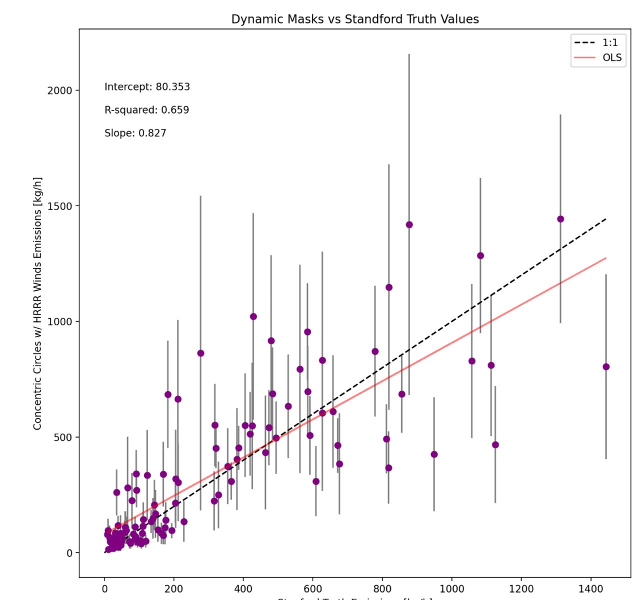
- EMIT has no CH_4 controlled release truth values from which to optimize a fit line
- We have seen that optimized crop/percentile curves follow averaged thresholds, independent of sensor, gas type, or retrieval
- Plotted average thresholds of all 2023 EMIT CH_4 plumes in the Carbon Mapper Catalog



- Selected a 950ppm-m threshold line which passes through the 90th percentile at 1000m, a known combination that previously produced reasonable results

Results

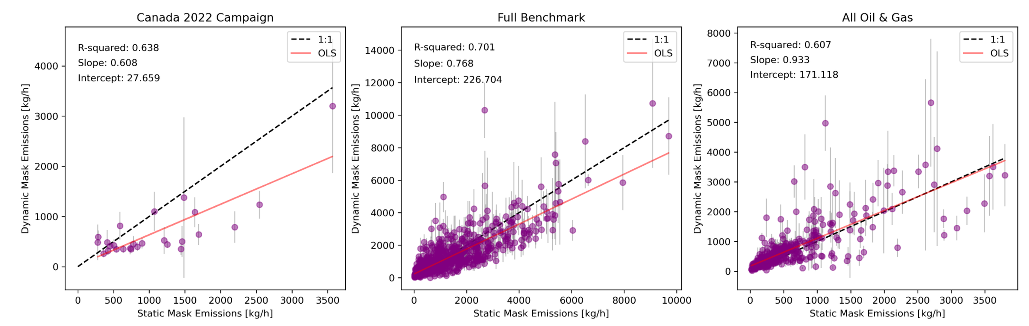
- For each plume, crop/percentile combinations are applied to derive several candidate masks
- The candidate mask producing an IME closest to the average is selected for quantification
- Airborne quantification utilizes a Concentric Circles method while EMIT uses standard IME
- HRRR and ECMWF wind products are used depending on availability
- Masking uncertainties, in the form of mask standard deviations, are propagated into error assessment along with wind and quantification uncertainties

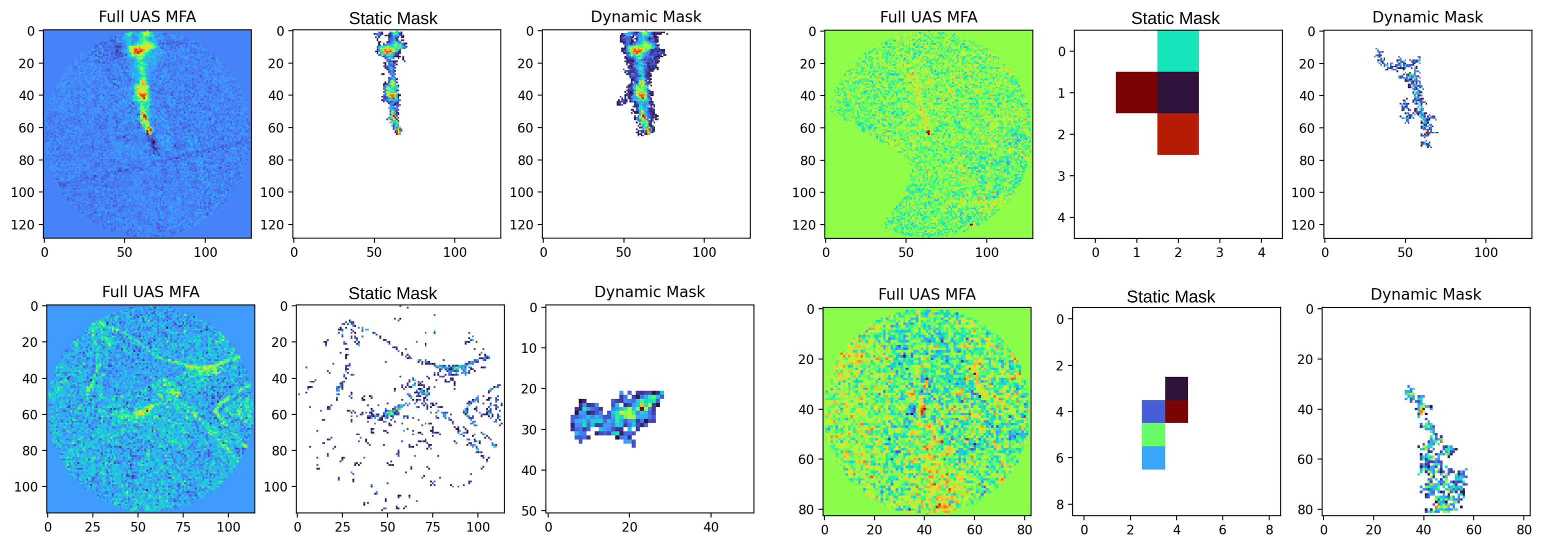


Results cont.

GAO & AVIRIS-NG

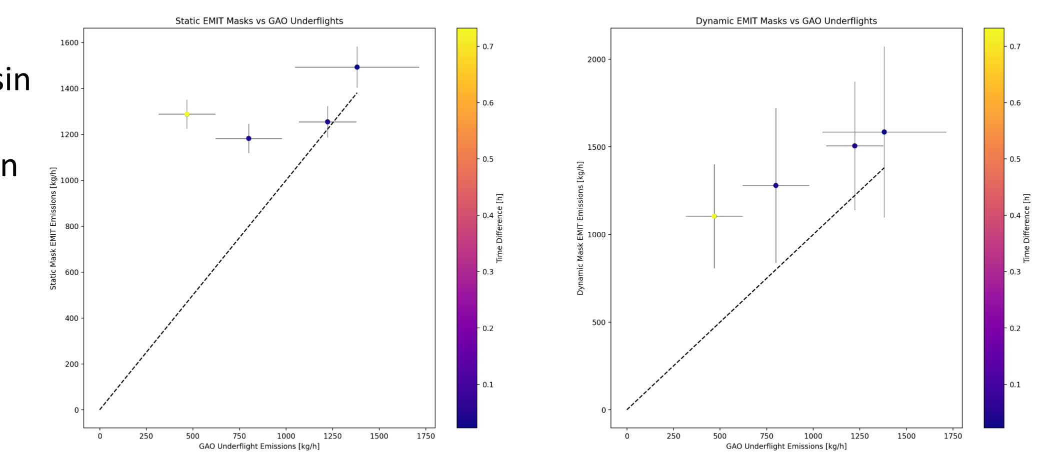
- Canada 2022 emissions are significantly lower due to background noise suppression
- Full benchmark is around the 1:1 with a slight negative trend
- Oil & Gas is tightly correlated with the 1:1, previous masks designed for this type of plume

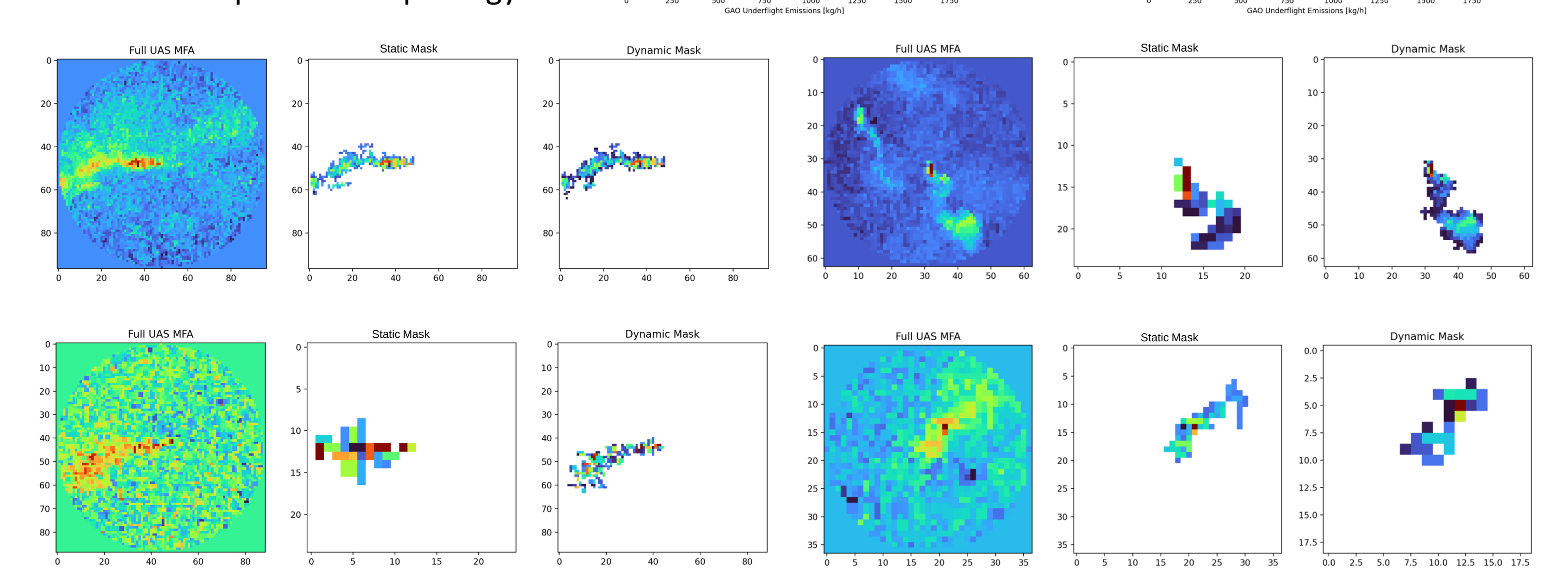




EMIT

- Assessed against GAO under flights flown in the Permian Basin during August 2023
- Same sources detected between 5 - 45min after overpass
- Dynamic masks improve correlation with 1:1 line while maintaining a slight high bias
- Visual inspection of masks showed improved morphology





Conclusions

- Dynamic thresholding produces improved masking over diverse backgrounds
- Framework provides additional uncertainty metrics to better refine emission errors
- Technique is adjustable to various sensors, but limited by availability of truth values
- Highly refinable overtime as more truth data becomes available

Future Work

- Fits are constrained by size and morphology of validation plumes, additional metered releases and under flights would help refine this technique for large or diffuse plumes
- Particularly vital for EMIT which currently relies on a generalized non-optimized curve

References

1. Saunois, M., et al. (2016). The global methane budget 2000 – 2012. Earth System Science Data, 8(2). https://doi.org/10.5194/essd-8-697-2016
2. EPA (2022). Understanding global warming potentials. [Online], Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials. Accessed: November 27, 2023.
3. Varon, D. J., et al. (2019). Satellite discovery of anomalously large methane point sources from oil/gas production. Geophysical Research Letters, 46 (22). https://doi.org/10.1029/2019gl083798
4. Duren, R. M., et al. (2019). California's methane super-emitters. Nature, 575 (7781). https://doi.org/10.1038/s41586-019-1720-3
5. Frankenberg, C., et al. (2016). Airborne methane remote measurements reveal heavy-tail flux distribution in four corners region. Proceedings of the National Academy of Sciences, 113 (35). https://doi.org/10.1073/pnas.1605617113
6. Thorpe, A.K., et al. (2023). Attribution of individual methane and carbon dioxide emission sources using EMIT observations from space. Science Advances, 9(46). https://doi.org/10.1126/sciadv.adh2391
7. Varon, D. J., et al. (2018). Quantifying methane point sources from fine-scale satellite observations of atmospheric methane plumes. Atmospheric Measurement Techniques, 11 (10). https://doi.org/10.5194/amt-11-5673-2018
8. Zhipeng Pei, et al. (2023). Improving quantification of methane point source emissions from imaging spectroscopy. Remote Sensing of Environment, 295. https://doi.org/10.1016/j.rse.2023.113652
9. Abbadi, S.H., et al. (2023). Comprehensive evaluation of aircraft-based methane sensing for greenhouse gas mitigation. EarthArXiv Pre-Print. https://doi.org/10.31223/X51D4C
10. https://data.carbonmapper.org/
11. JPL (2021). Specifications. AVIRIS Next Generation. [Online], Available: https://avirisng.jpl.nasa.gov/specifications.html . Accessed: November 27, 2023.
12. Smith, J. M. (2023). Meet EMIT, the Newest Imaging Spectrometer. [Online], Available: https://www.earthdata.nasa.gov/learn/articles/meet-emit . Accessed: May 20, 2024.

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