Understanding the Opportunity and Limitation of Source-Based Aerial Methane Measurements:

CH4 Connections Conference, Fort Collins, CO, Oct. 20–21, 2022

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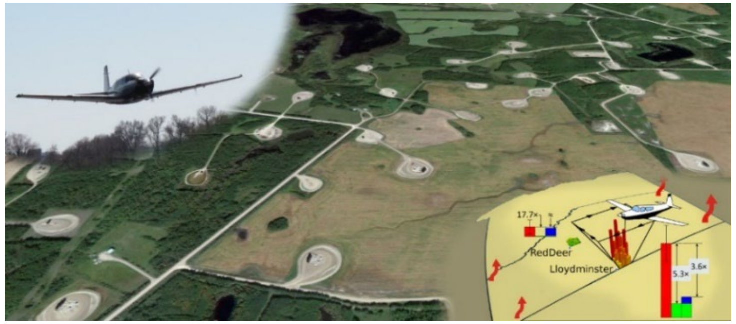
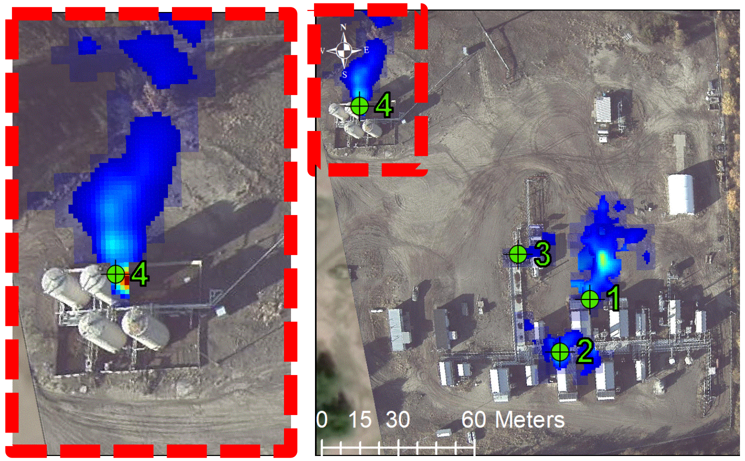
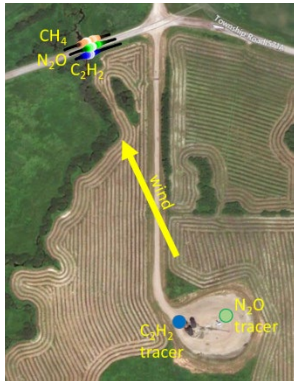
The Multi-scale Methane Challenge

- Basin-level to global scale
  - Total inventories & tracking aggregate reductions
- Site/facility-level quantification
  - Total inventories & tracking aggregate reductions
  - Screening for mitigation opportunities
  - Compliance with regulations
- Source-level measurement & mitigation
  - Source-specific regulations (e.g. tanks, unlit flares, compressors)
  - Actual mitigation occurs at sources







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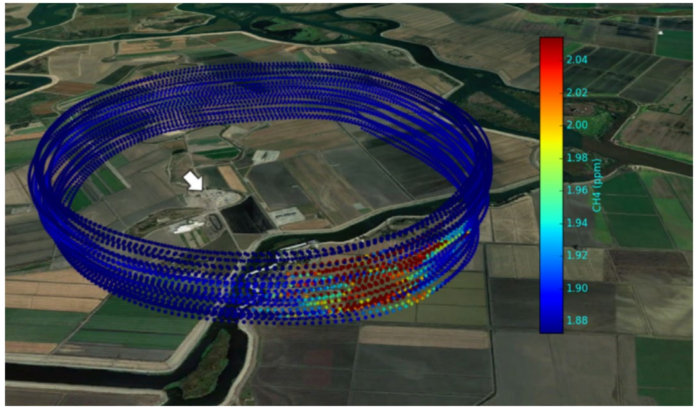
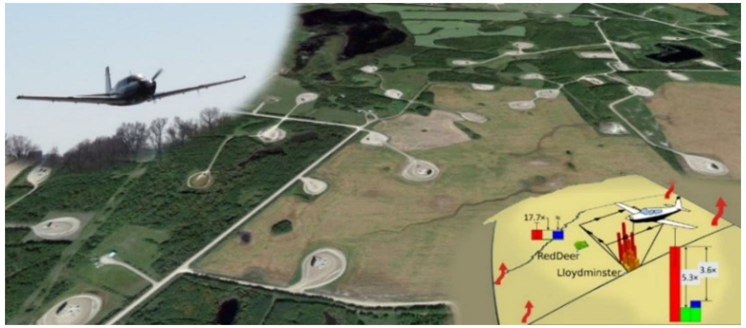
The First Revolution of Airborne Measurement Technologies

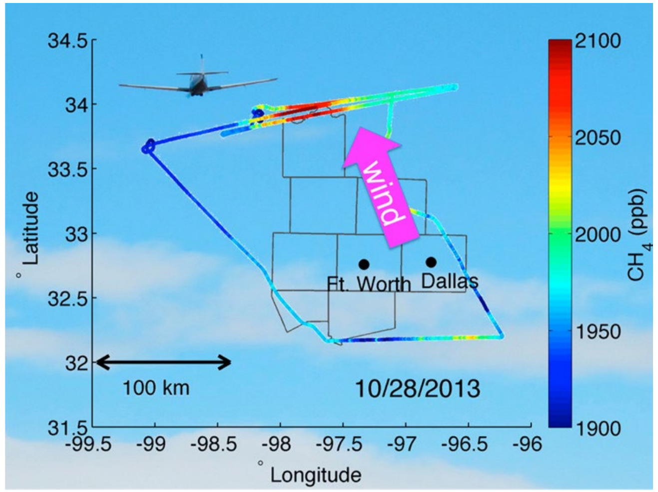
- Mass-Balance Approaches



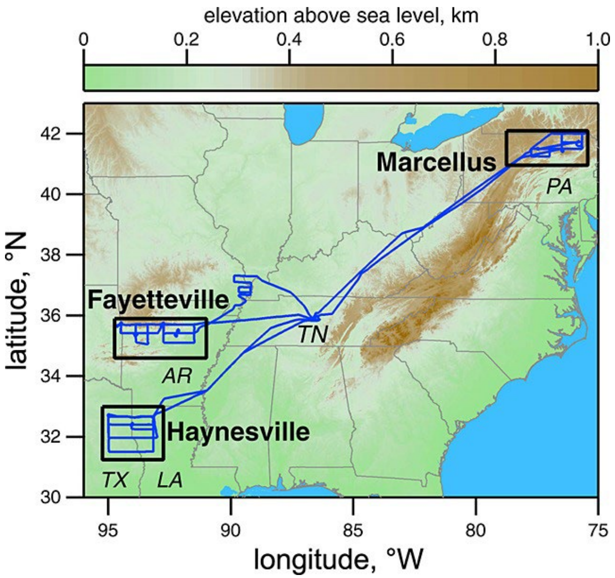
(Conley et al., AMT 2017)



(Johnson et al., EST 2017)



(Karion et al., EST 2015)



(Peischl et al., JGR 2015)

RESEARCH

GREENHOUSE GASES

Assessment of methane emissions from the U.S. oil and gas supply chain

Ramón A. Alvarez[1]*, Daniel Zavala-Araiza[1], David R. Lyon[1], David T. Allen[2], Zachary R. Barkley[3], Adam R. Brandt[4], Kenneth J. Davis[3], Scott C. Herndon[5], Daniel J. Jacob[6], Anna Karion[7], Eric A. Kort[8], Brian K. Lamb[9], Thomas Lauvaux[3], Joannes D. Maasakkers[6], Anthony J. Marchese[10], Mark Omara[1], Stephen W. Pacala[11], Jeff Peischl[12,13], Allen L. Robinson[14], Paul B. Shepson[15], Colm Sweeney[13], Amy Townsend-Small[16], Steven C. Wofsy[6], Steven P. Hamburg[1]

Methane emissions from the U.S. oil and natural gas supply chain were estimated by using ground-based, facility-scale measurements and validated with aircraft observations in areas accounting for ~30% of U.S. gas production. When scaled up nationally, our facility-based estimate of 2015 supply chain emissions is 13 ± 2 teragrams per year, equivalent to 2.3% of gross U.S. gas production. This value is ~60% higher than the U.S. Environmental Protection Agency inventory estimate, likely because existing inventory methods miss emissions released during abnormal operating conditions. Methane emissions of this magnitude, per unit of natural gas consumed, produce radiative forcing over a 20-year time horizon comparable to the CO_2 from natural gas combustion. Substantial emission reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems.

Downloaded from http://science.sciencemag.org/ on October 11, 2020

Alvarez et al., Science 361, 186–188 (2018) 13 July 2018 1 of 3

(Alvarez et al., Science 2018)

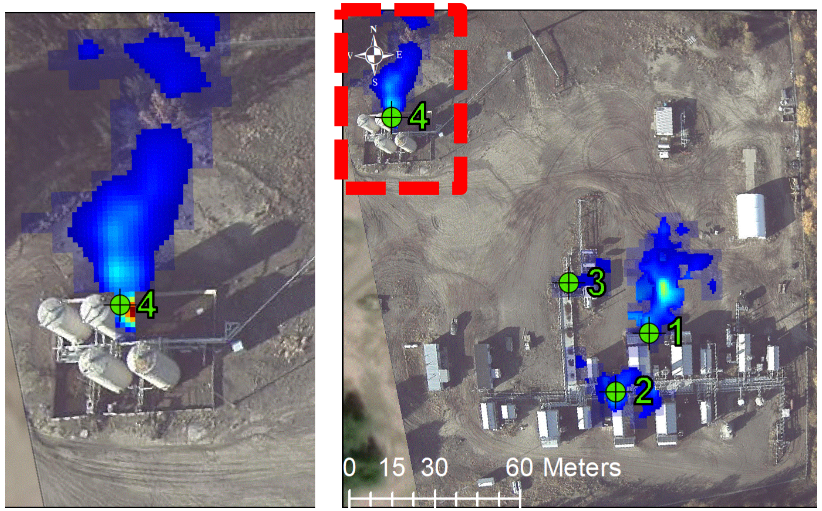
Recent Emergence of Source-Level Airborne Measurement Approaches

- A second revolution in possibilities?

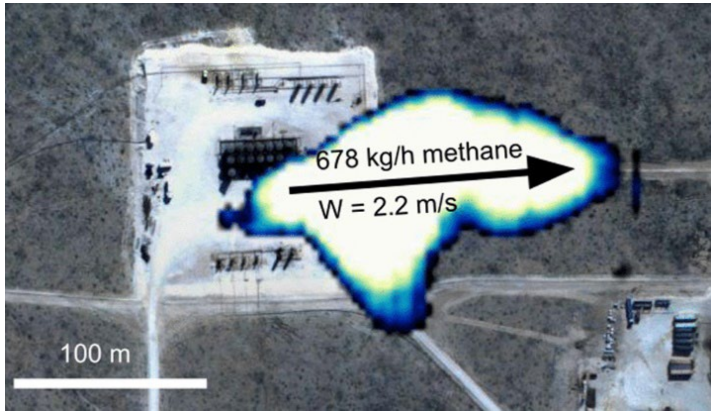
Bridger Photonics
Gas Mapping LiDAR (GML)™
- Active laser-based sensor
  - ~1m resolution
  - ~100m swath width

Kairos Aerospace
LeakSurveyor™
- Passive imaging spectrometer
  - ~3m resolution
  - ~800m swath width

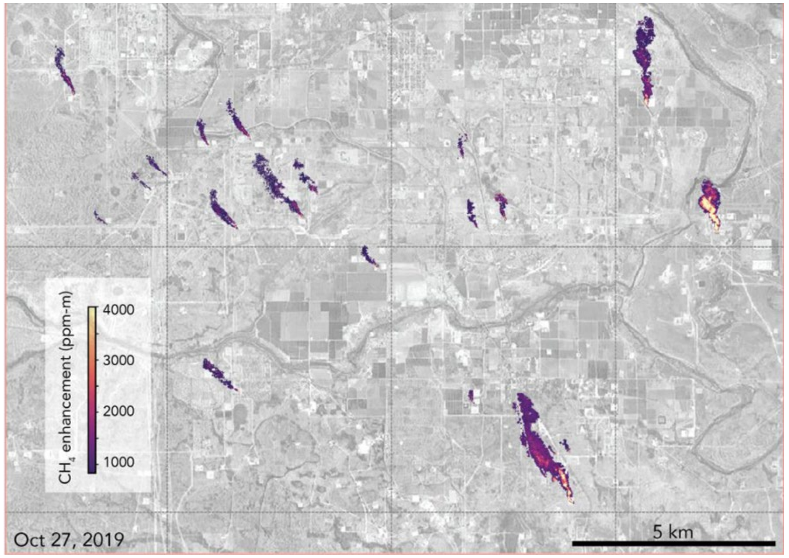
NASA/JPL
AVIRIS-NG
- Passive imaging spectrometer
  - ~3m resolution @3000m AGL
  - ~1800m swath width @3000m AGL



(Tyner & Johnson, EST 2021)

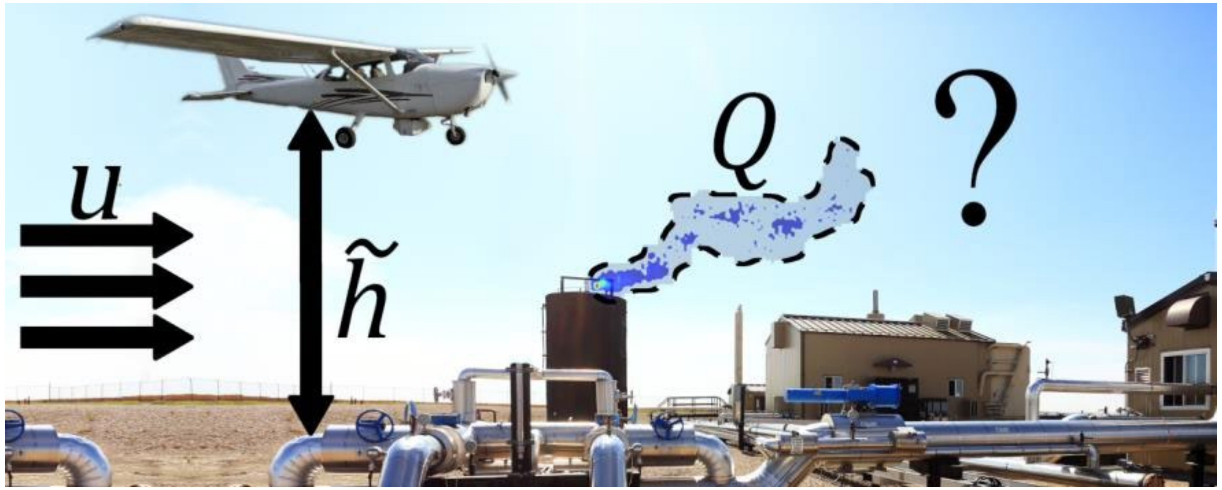


(Chen et al., EST 2022)



(Cusworth et al., Energy & Climate 2021)

Robust, Critical Evaluation of Measurement Technologies



- Fully- and semi-blinded controlled release testing

- B.M. Conrad, D.R. Tyner, M.R. Johnson (2022) **Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies**, *Remote Sensing of Environment* (under review: preprint)
- M.R. Johnson, D.R. Tyner, A.J. Szekeres (2021) **Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR**, *Remote Sensing of Environment*, 259:112418. (doi: 10.1016/j.rse.2021.112418)

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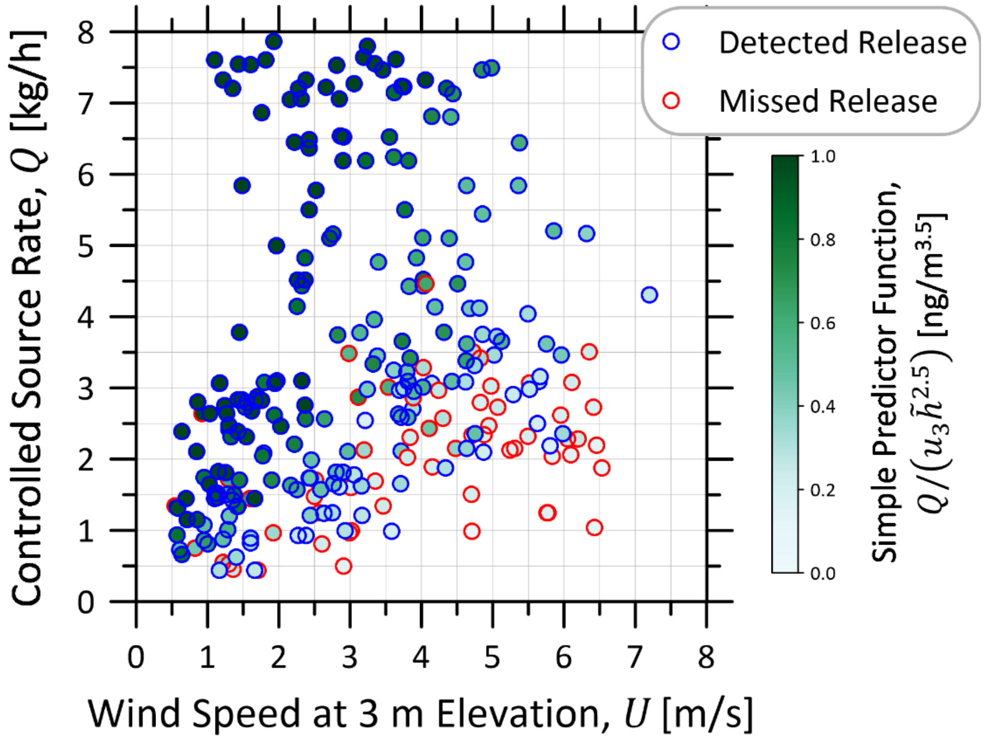
1. Fully-Blinded Controlled Release Testing of *Sensitivity Limits*

- Conducted under cover of parallel survey of oil and gas facilities
  - Airplane has no knowledge they are even being tested



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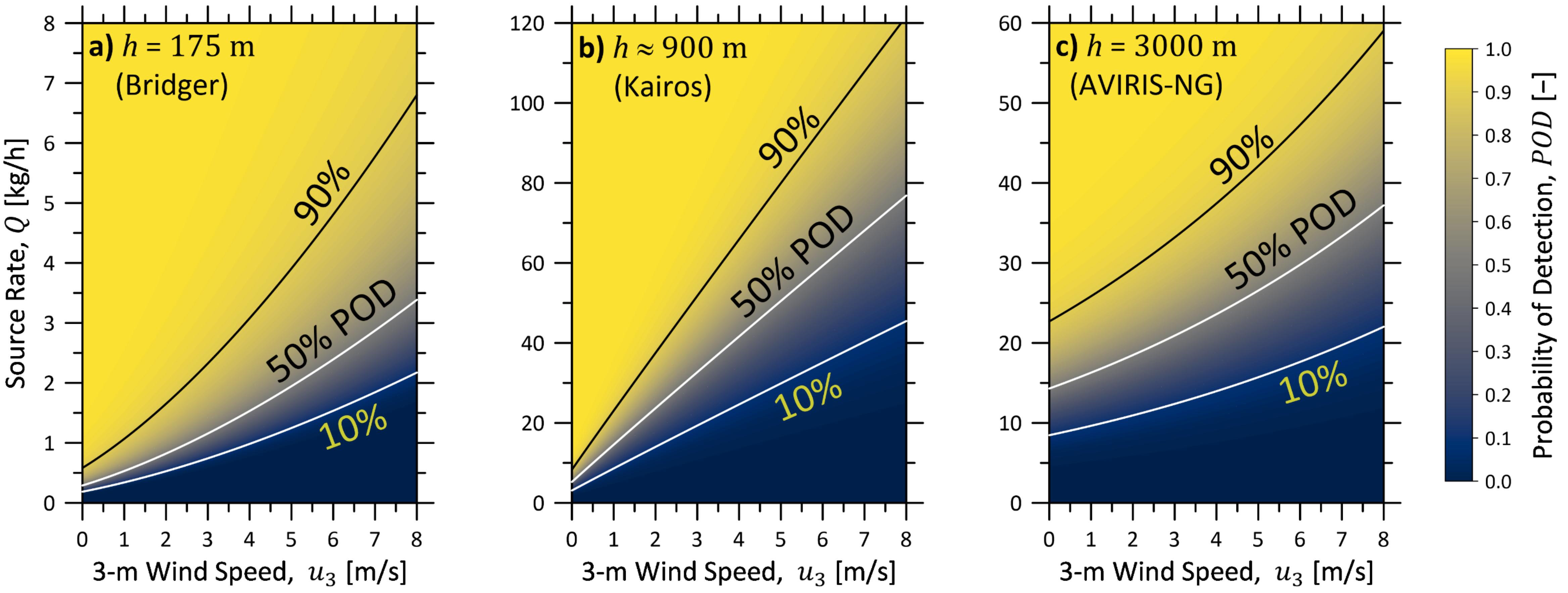
Continuous Probability of Detection (POD) Functions



- Probability of detection any source Q for a given wind speed u and altitude h

B.M. Conrad, D.R. Tyner, M.R. Johnson (2022) Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies, *Remote Sensing of Environment* (under review: preprint)

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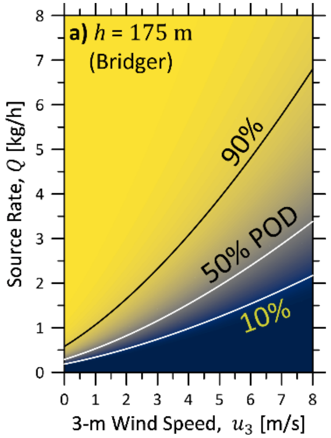
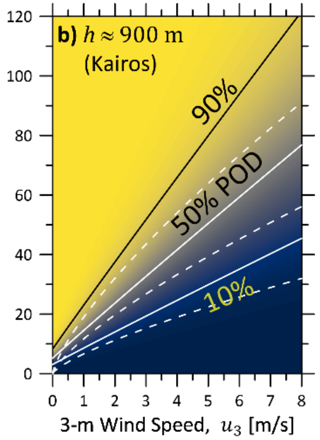
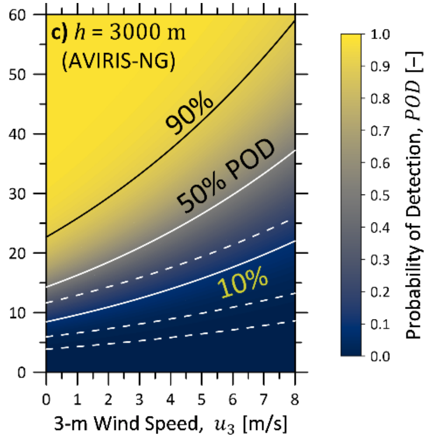
Continuous Probability of Detection (POD) Functions

	Bridger GML™	Kairos LeakSurveyor™	NASA AVIRIS-NG
			
Typical Altitude:	175 m	900 m	3000 m
50% POD @ 3m/s:	1.2 kg/h	32.6 kg/h	20.4 kg/h
Measurement Swath:	97 m	800 m	1830 m

- Probability of detection any source Q for a given wind speed u and altitude h

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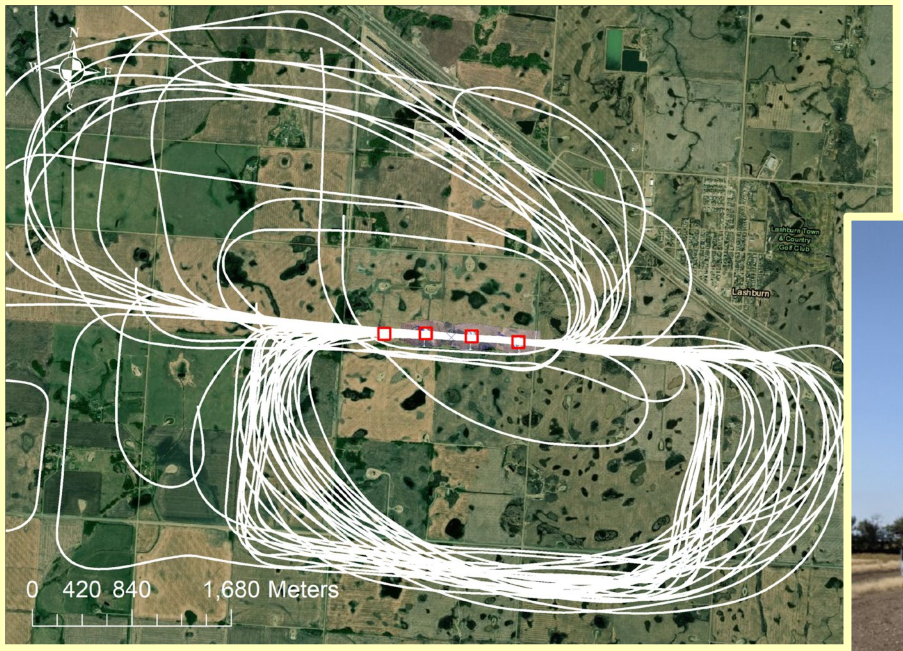
2. Semi-Blinded Controlled Release Testing of ***Quantification Accuracy***

- Semi-blinded (collaborative) controlled release tests
  - Plane flies laps over controlled release points and quantifies
  - Actual release rates are not shared with plane



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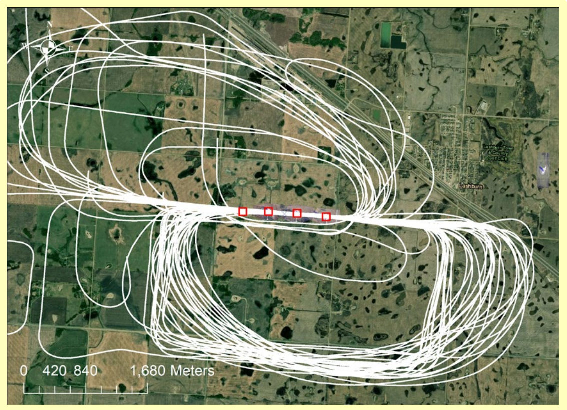

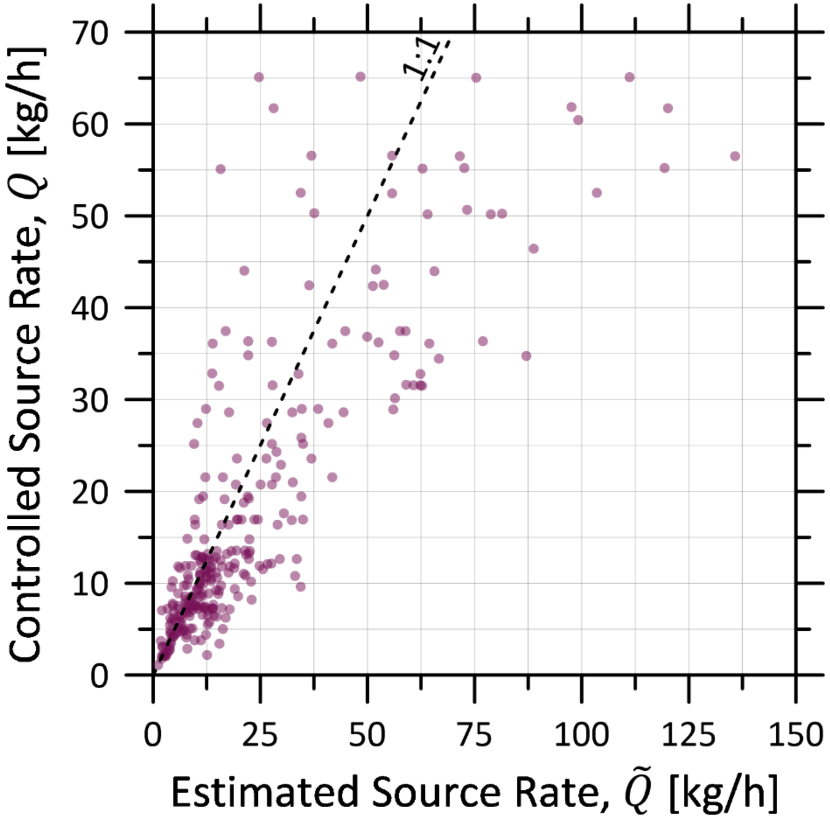

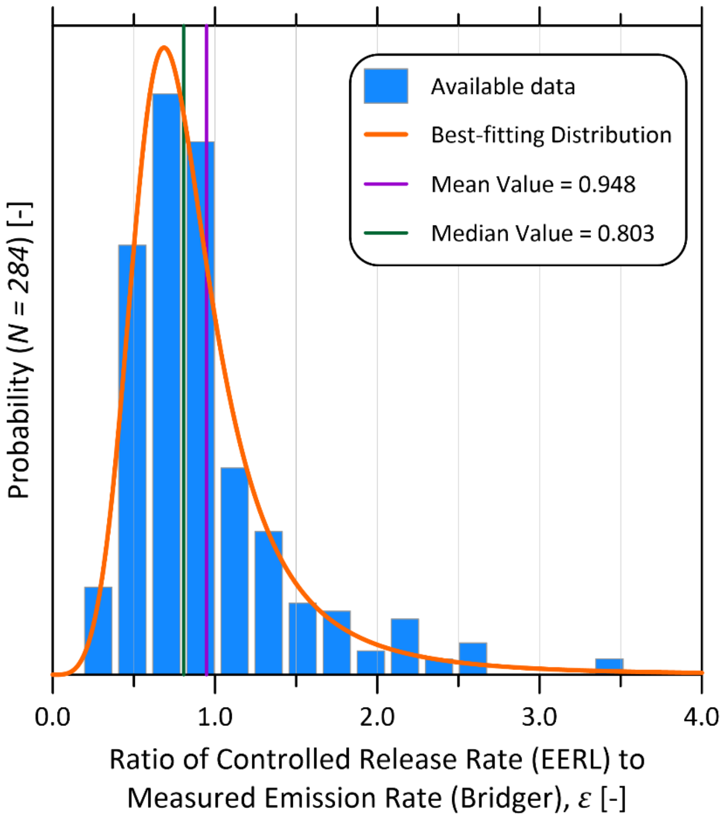

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A Measurement-Based Methane Inventory for British Columbia (BC), Canada

- Demonstrate feasibility of measurement-based methane inventories using aerial measurements
- Key enabling pieces:
  - Technology with sufficient sensitivity to capture majority of sources
  - Detailed probability of detection (POD) functions in varying conditions
  - Detailed uncertainty model for technology
  - Bottom-up data for unmeasured sources

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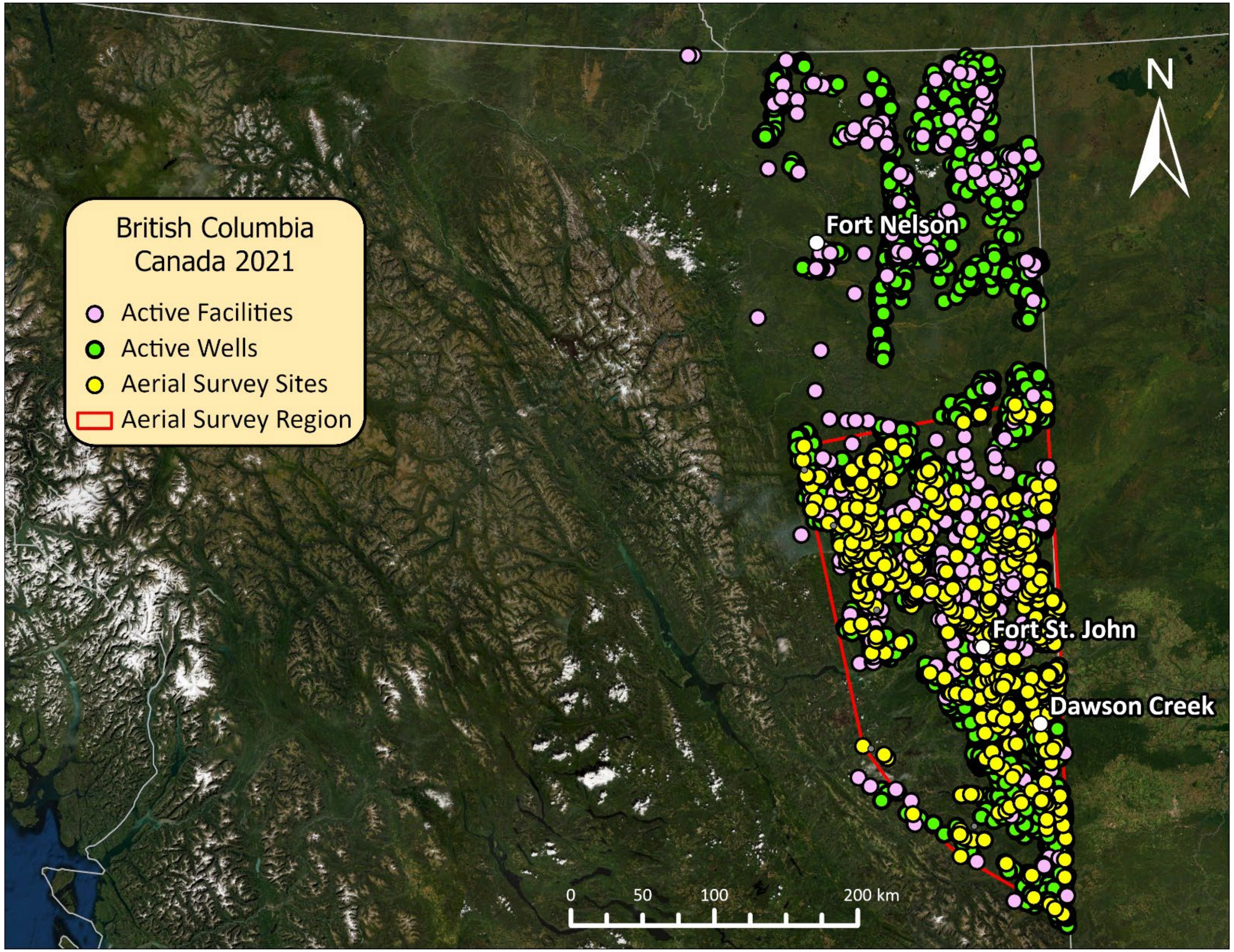
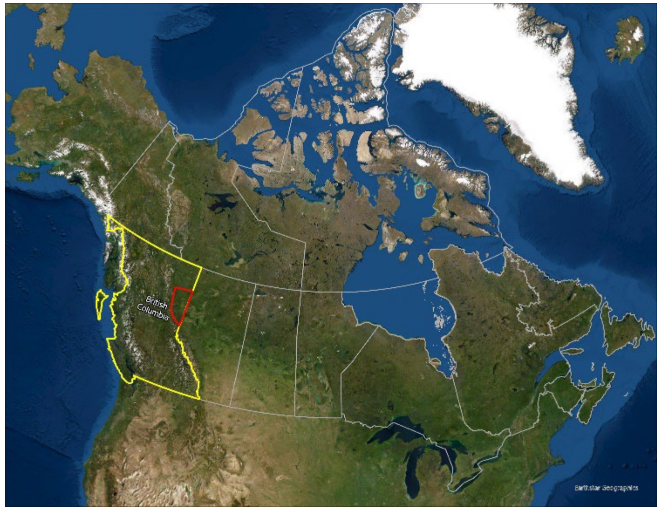
A Measurement-Based Methane Inventory for British Columbia (BC), Canada



- Survey includes:
  - 59% of all active facilities
  - 8% of all active wells



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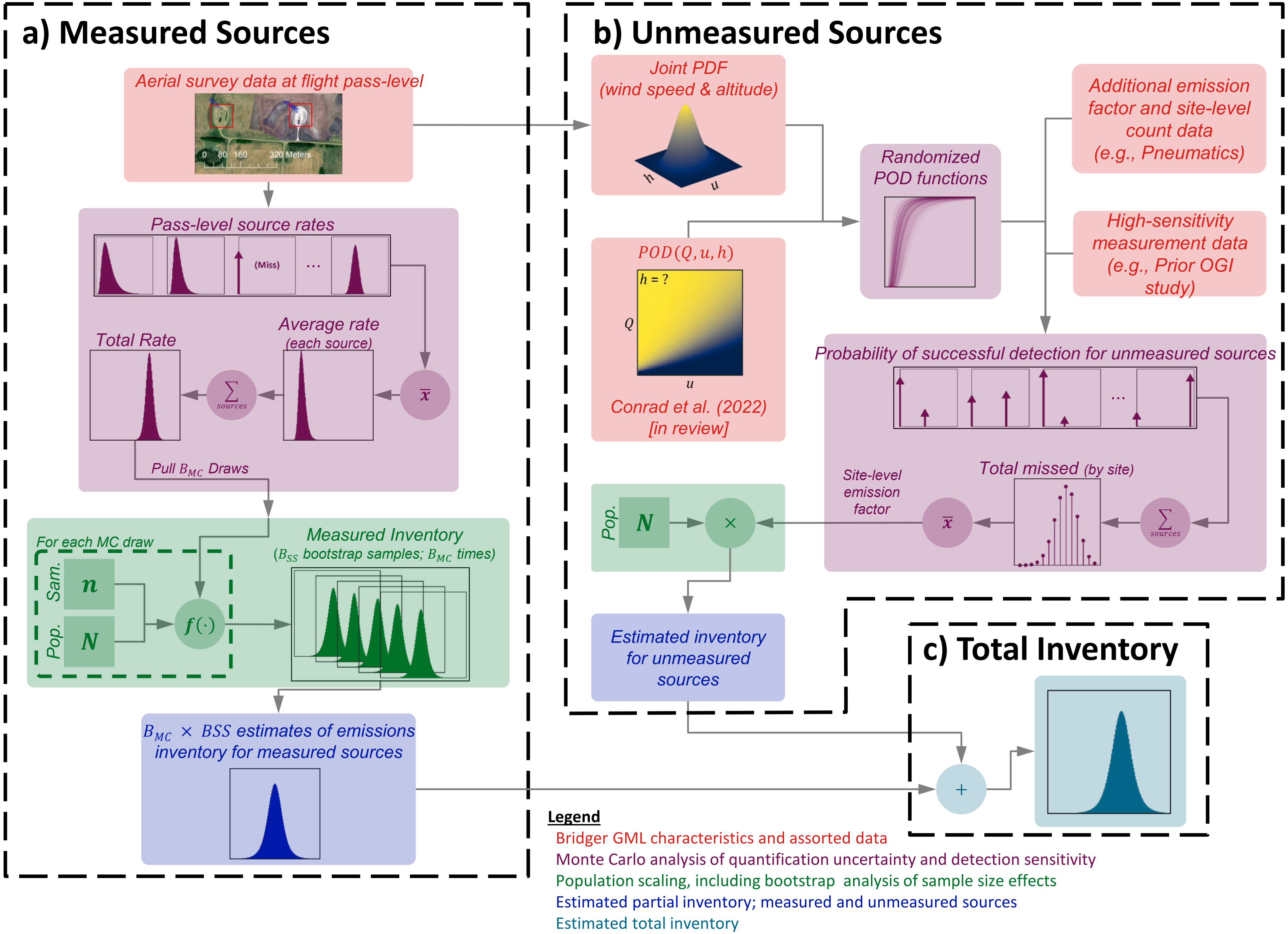
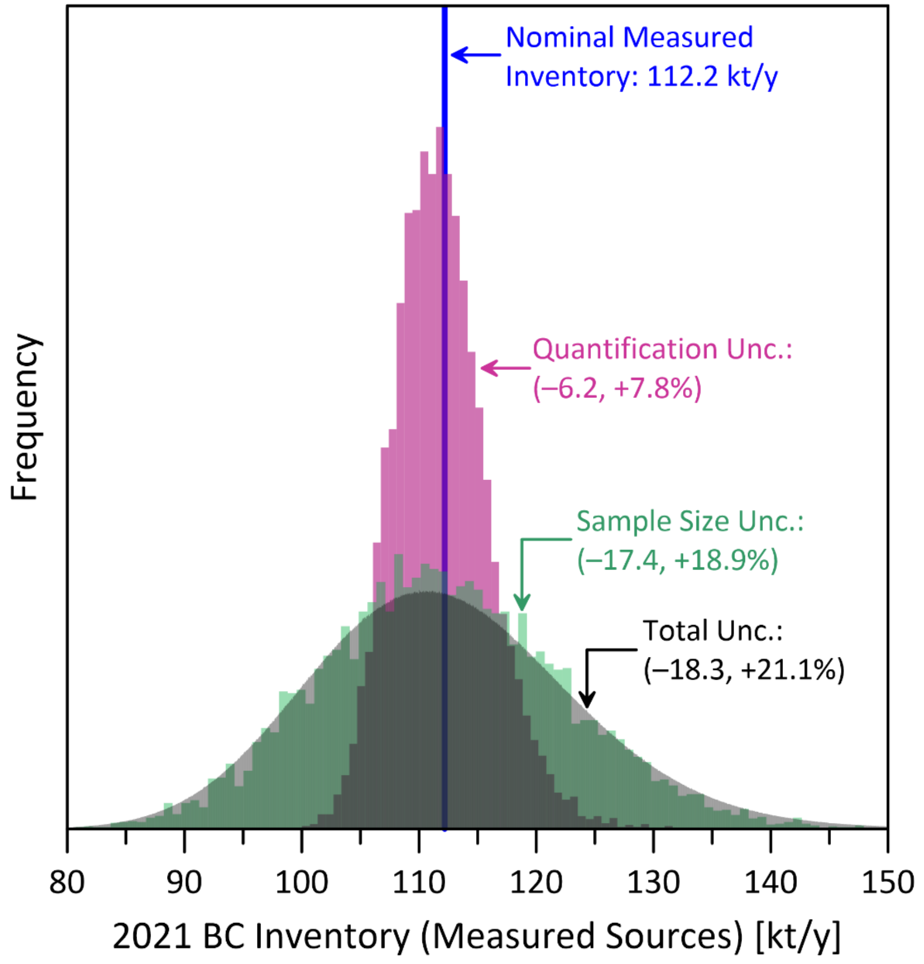
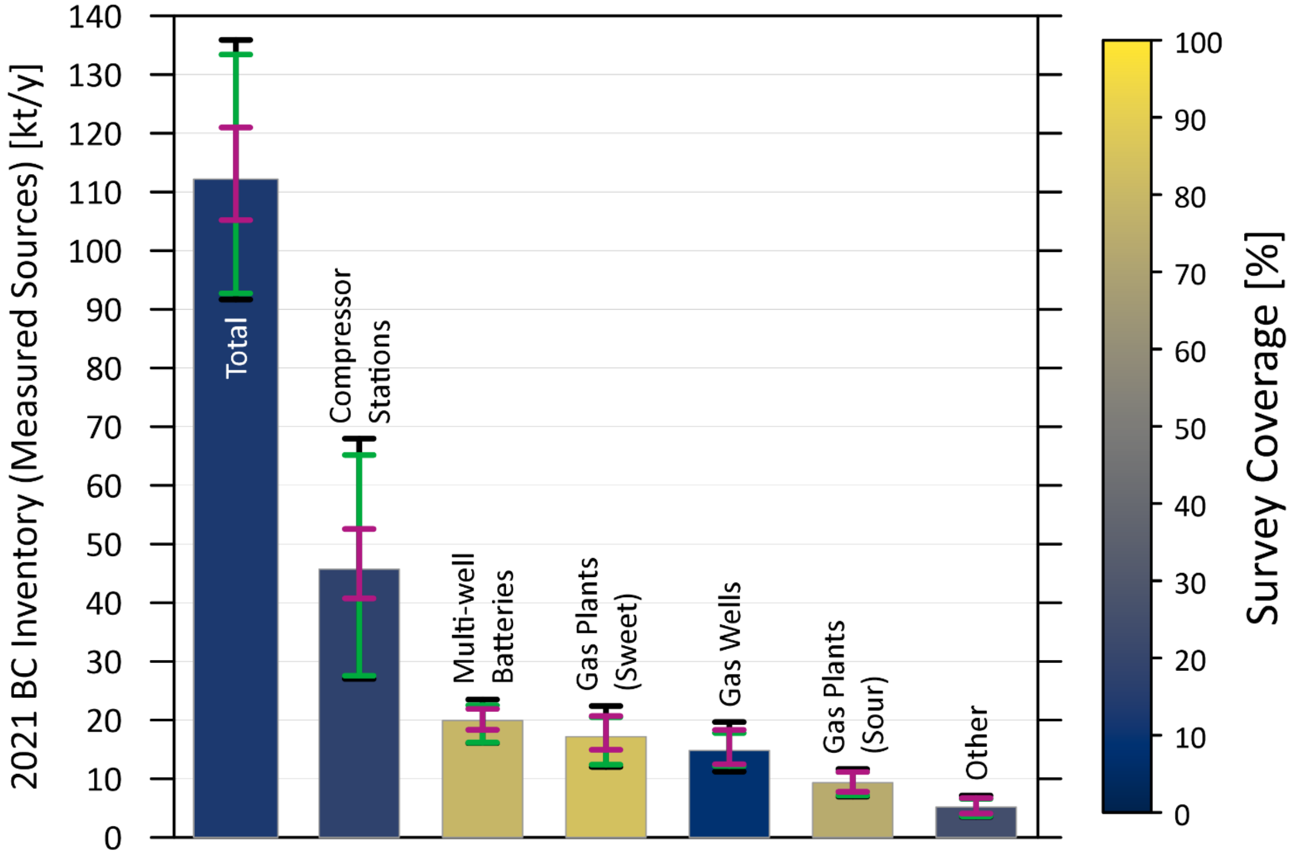
Protocol to Create a "*Hybrid*" Bottom-Up *Measurement-Based* Inventory



Johnson, Conrad, & Tyner (2022) to be submitted

Quantification and Sample Size Uncertainties in ***Measured*** Inventory Sources





- Very powerful approach to quantify, analyze, and *minimize* uncertainty

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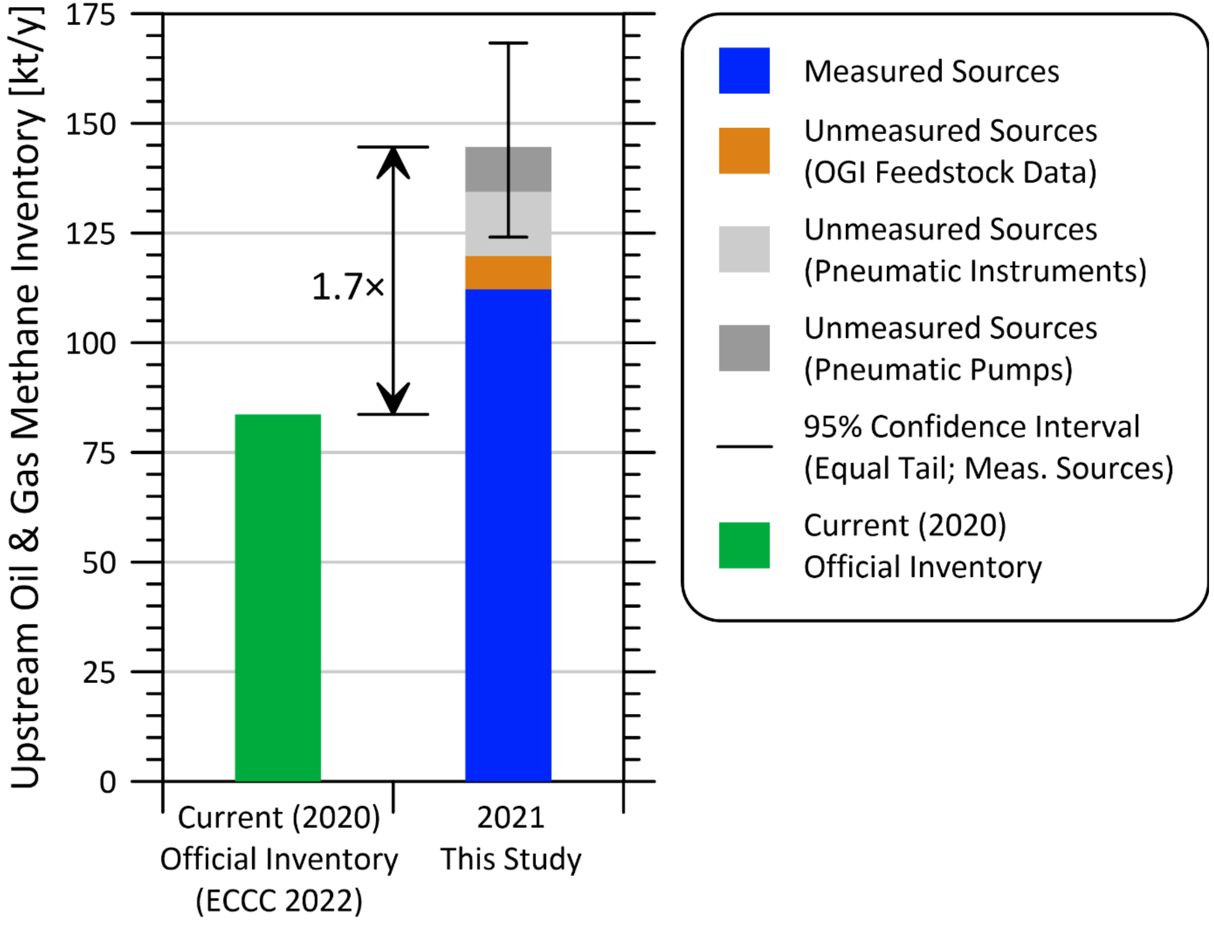
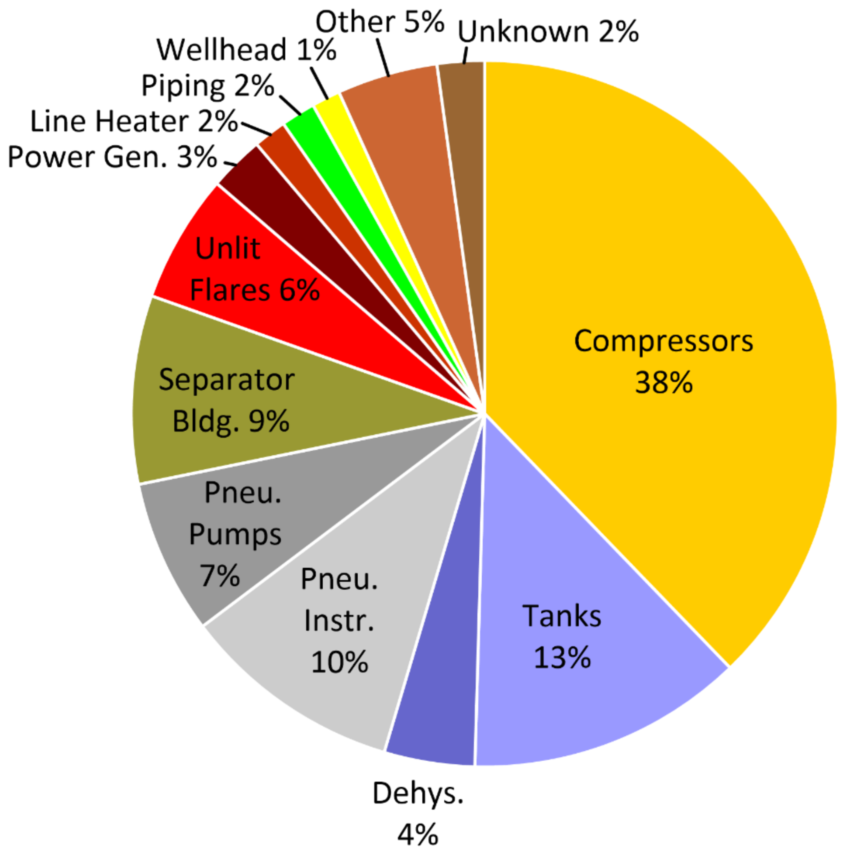
2021 Measurement-Based Methane Inventory for BC





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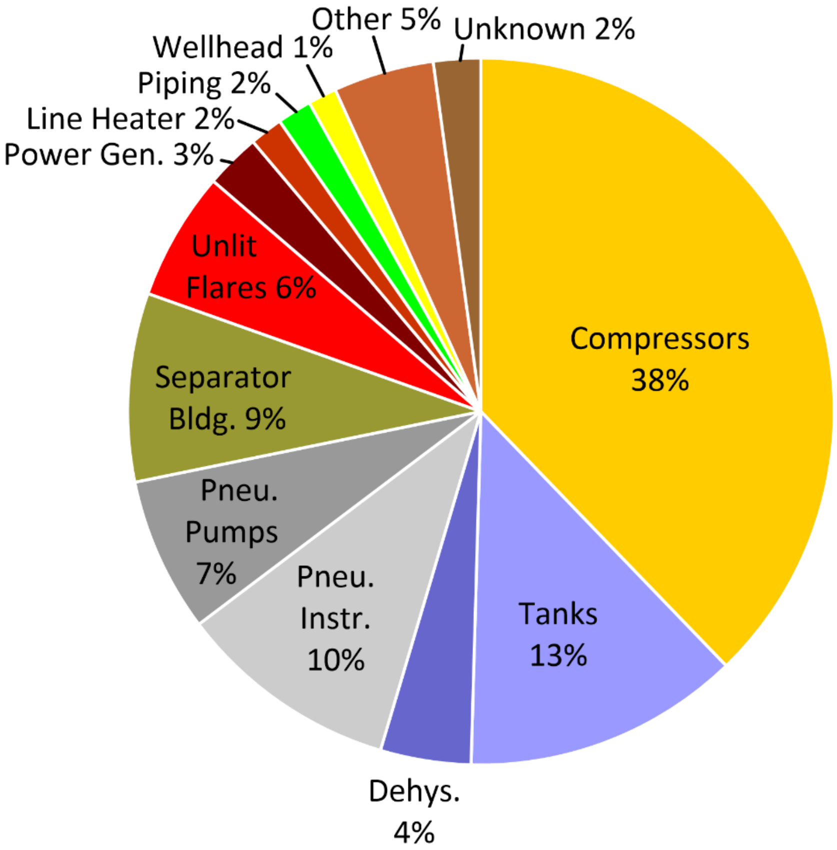
Contrast Sources in Measured(Hybrid) vs. Current Bottom-Up Inventory

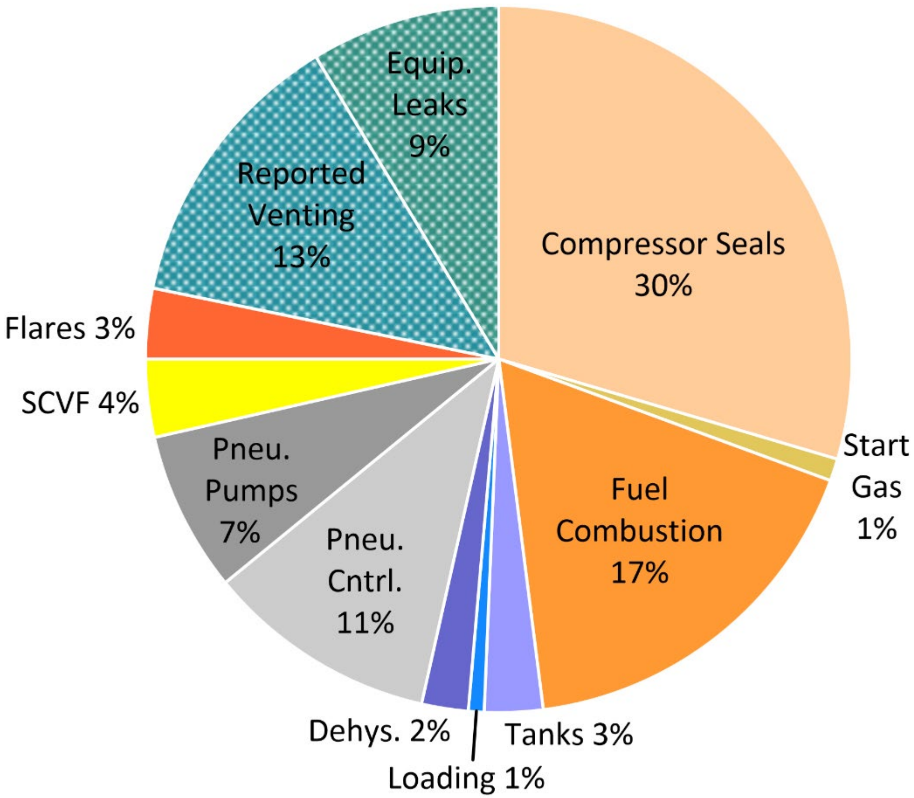
2021 EERL Meas.-Based Inventory

British Columbia Inventory by Source



Current Official (ECCC) 2020 Inventory

British Columbia Inventory by Source



- Regulations won’t work if they tackle the wrong problem

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Conclusions

- New aerial technologies are a revolution in possibilities, but:
  - Robust, independently-proven, probabilistic sensitivity and uncertainty models are critical
  - Protocols for interpreting data, leveraging POD and uncertainty models, equally important
  - Critical to understand where different technologies fit and how they may best be used
- Oil and gas sector emission patterns are/will rapidly evolve
  - We must expect inventories and source distributions to be changing rapidly year-over-year
  - As we seek to push emissions lower toward zero, measurements will only become more critical
- Measurement-based inventories and policy are essential to achieving mitigation targets

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Acknowledgements

Natural Resources Canada / Ressources naturelles Canada

Canada

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BC OGRIS
BC Oil and Gas Research and Innovation Society

BC Oil & Gas COMMISSION

NSERC CRSNG

UN environment programme
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BRIDGER PHOTONICS

GREENPATH ENERGY LTD

Environment and Climate Change Canada / Environnement et Changement climatique Canada

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Selected References

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- S.A. Festa-Bianchet, D.R. Tyner, S.P. Seymour, M.R. Johnson (2022) **Methane Venting at Cold Heavy Oil Production with Sand (CHOPS) Facilities is Significantly Underreported and led by High-Emitting Wells with Low or Negative Value**, *Environmental Science & Technology* (under review)
- S.A. Festa-Bianchet, S.P. Seymour, D.R. Tyner, M.R. Johnson (2022) **A Wavelength Modulation Spectroscopy-Based Methane Flux Sensor for Quantification of Venting Sources at Oil and Gas Sites**, *Sensors*, 22(11), 4175 (doi: 10.3390/s22114175)
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- C.A. Brereton, L.J. Campbell, M.R. Johnson* (2020) **Influence of turbulent Schmidt number on fugitive emissions source quantification**, *Atmospheric Environment X*, 7:100083 (doi: 10.1016/j.aeaoa.2020.100083)
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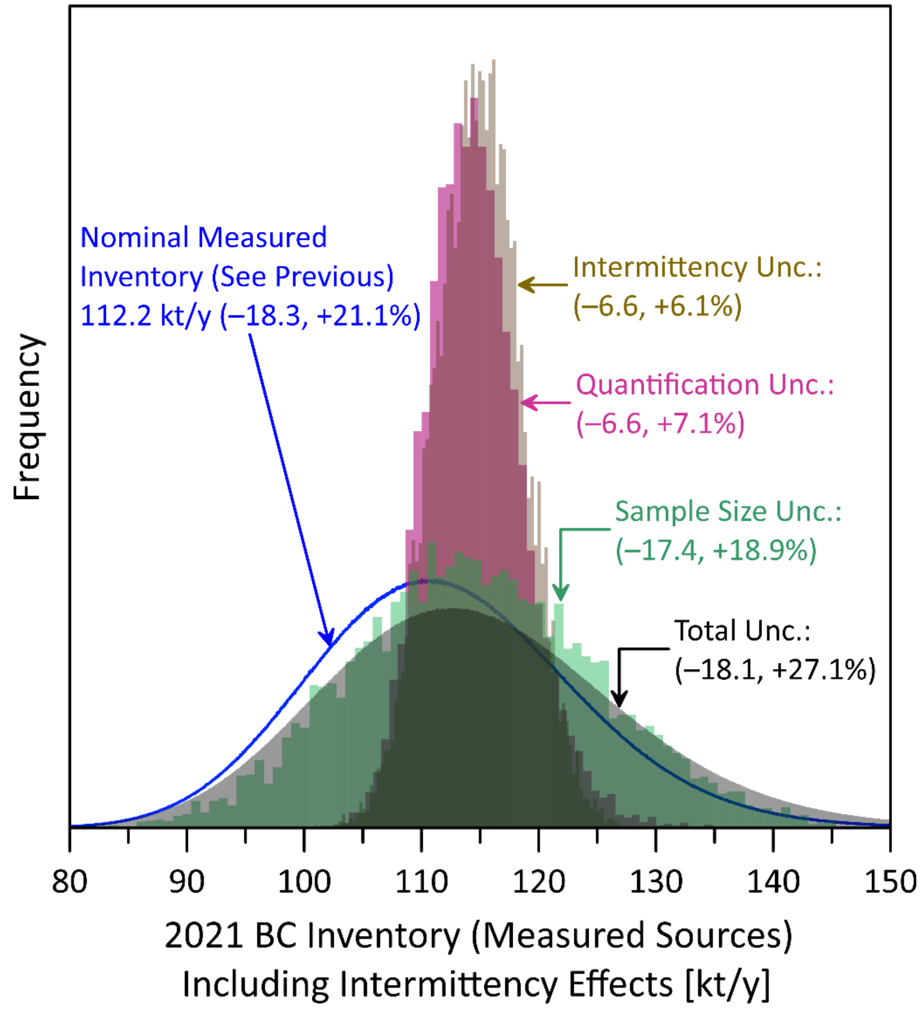
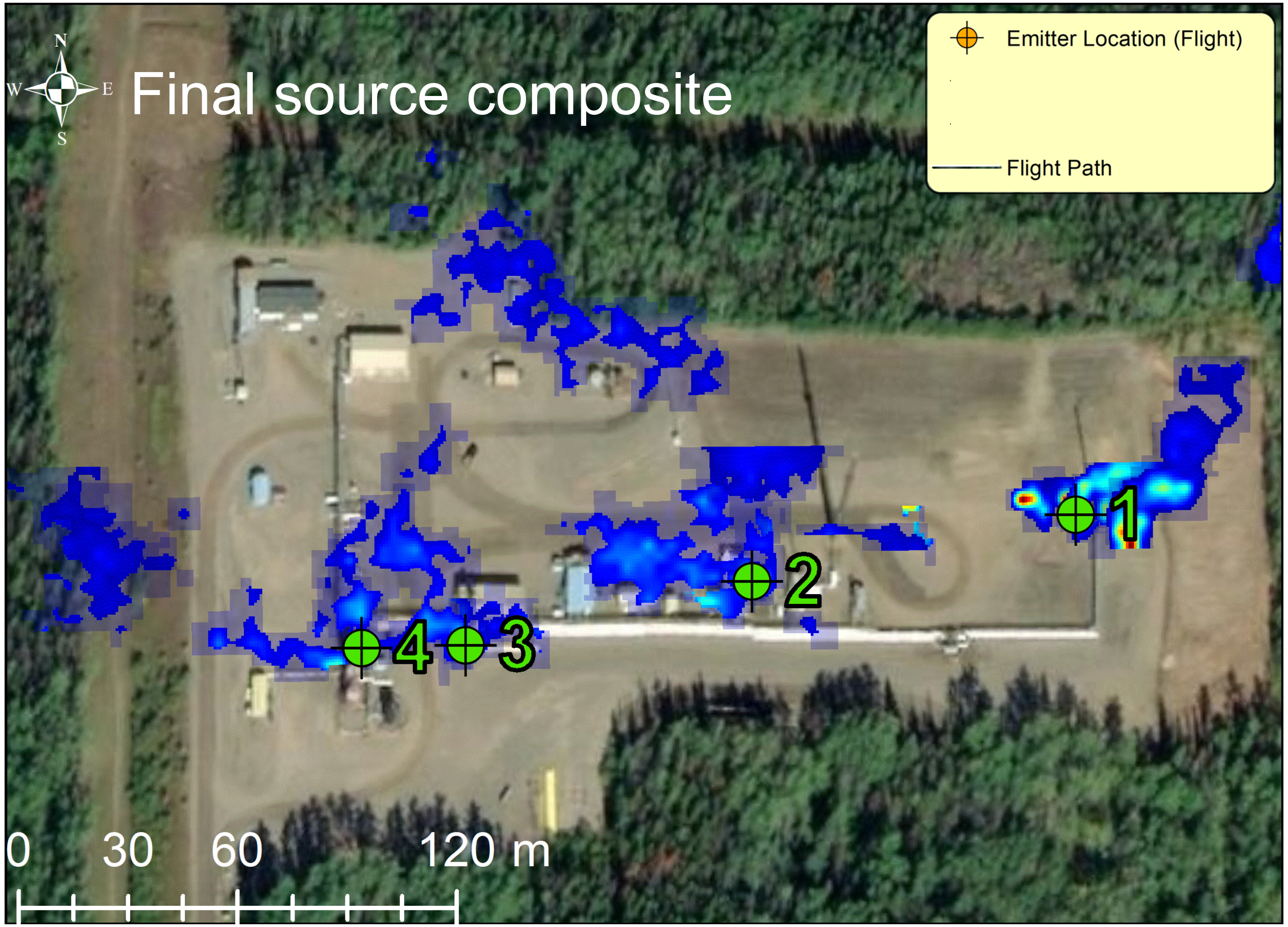
What About Source Variability / Intermittency?

- A novel approach to bounding the potential uncertainties
- Premise:
  - Grossly overestimate variability using empirical raw data assuming pass-by-pass data
  - Bootstrap values assuming they have no uncertainty
  - Then run complete analysis adding back in quantification plus sample size uncertainies



Example Aerial Technology: Bridger Photonics Gas Mapping LiDAR

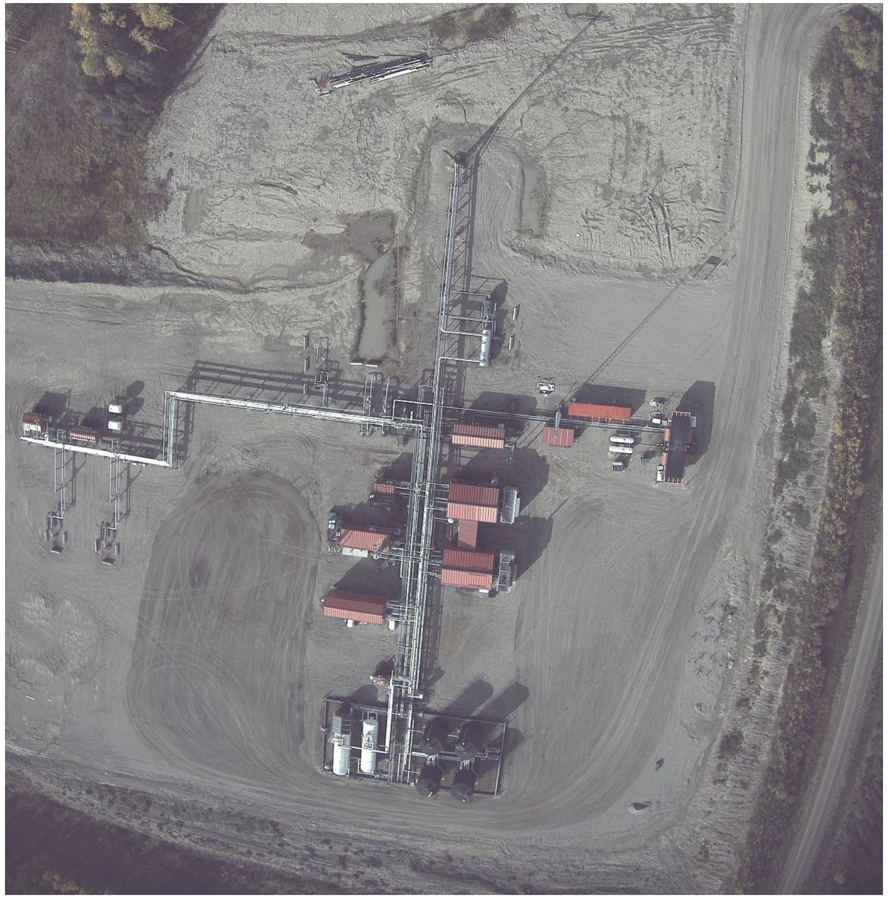
- Sites have one or more passes
- Flights with detected emissions are revisited in a subsequent day
- Source quantification for inventory development purposes requires interpretation of data from each pass



Tyner & Johnson, Environ. Sci. Technol, 2021
(doi: 10.1021/acs.est.1c01572)

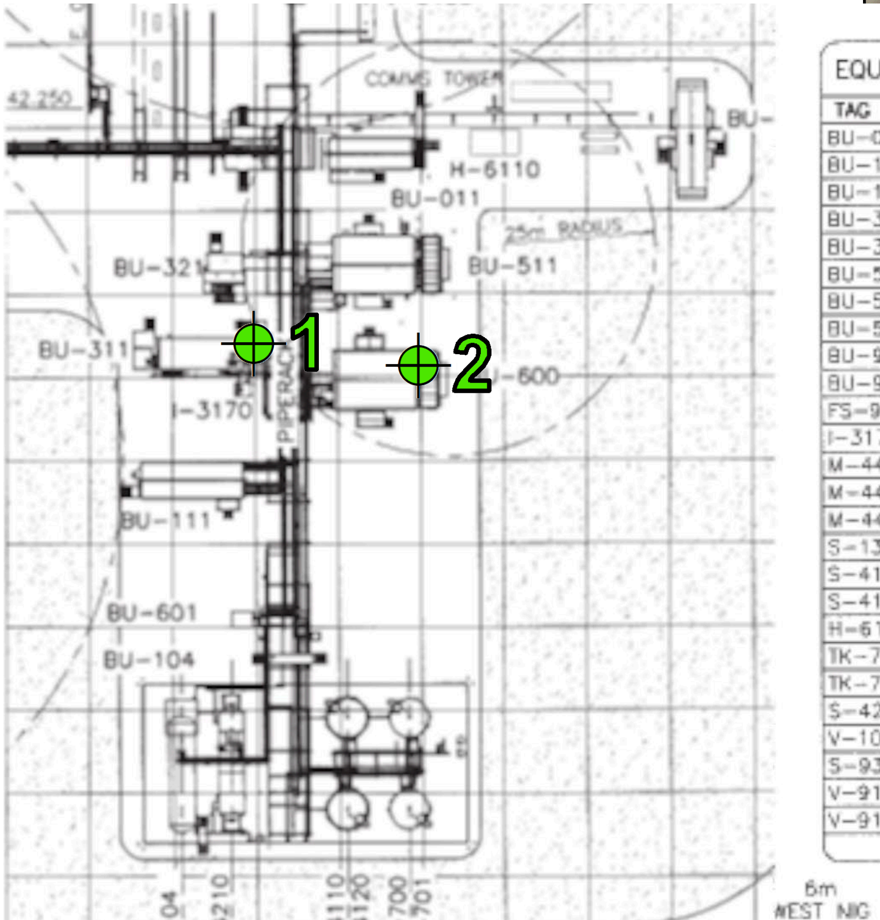
Source Attribution: Geo-locating Aerial Survey Imagery

- Combining satellite imagery, geo-located aerial photos, plot plans, & ground survey data to attribute

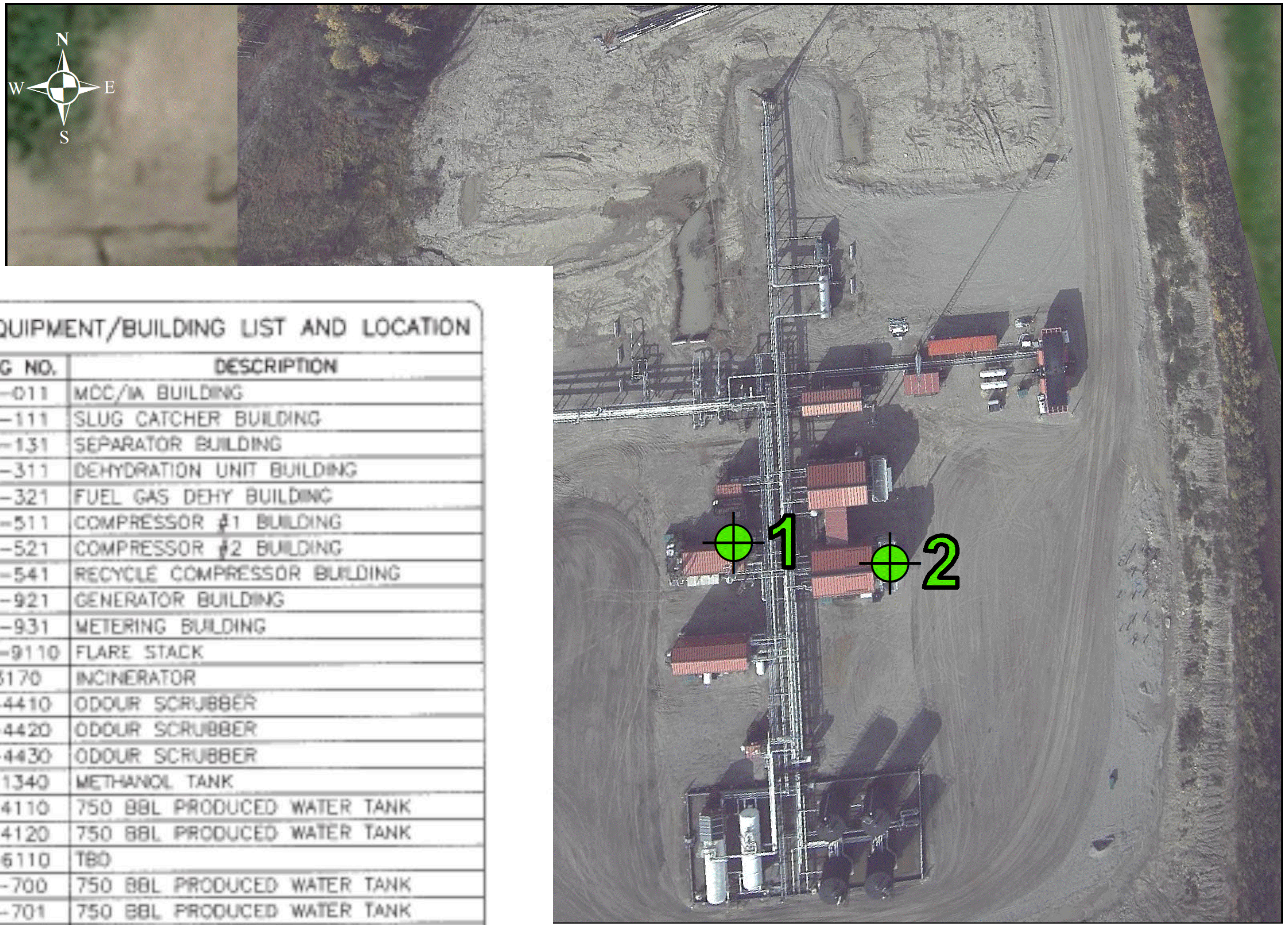


Source Attribution: Match Sources to Plot Plans

- Plot Plans provide a site schematic and equipment list
- Match Sources to Plot Plan



EQUIPMENT/BUILDING LIST AND LOCATION	
TAG NO.	DESCRIPTION
BU-011	MCC/IA BUILDING
BU-111	SLUG CATCHER BUILDING
BU-131	SEPARATOR BUILDING
BU-311	DEHYDRATION UNIT BUILDING
BU-321	FUEL GAS DEHY BUILDING
BU-511	COMPRESSOR #1 BUILDING
BU-521	COMPRESSOR #2 BUILDING
BU-541	RECYCLE COMPRESSOR BUILDING
BU-921	GENERATOR BUILDING
BU-931	METERING BUILDING
FS-9110	FLARE STACK
I-3170	INCINERATOR
M-4410	ODOUR SCRUBBER
M-4420	ODOUR SCRUBBER
M-4430	ODOUR SCRUBBER
S-1340	METHANOL TANK
S-4110	750 BBL PRODUCED WATER TANK
S-4120	750 BBL PRODUCED WATER TANK
H-6110	TBO
TK-700	750 BBL PRODUCED WATER TANK
TK-701	750 BBL PRODUCED WATER TANK
S-4210	CONDENSATE STORAGE TANK
V-104	CONDENSATE STORAGE TANK
S-9330	CORROSION INHIBITOR TANK
V-9120	LP FLARE KNOCK-OUT DRUM
V-9130	HP FLARE KNOCK-OUT DRUM



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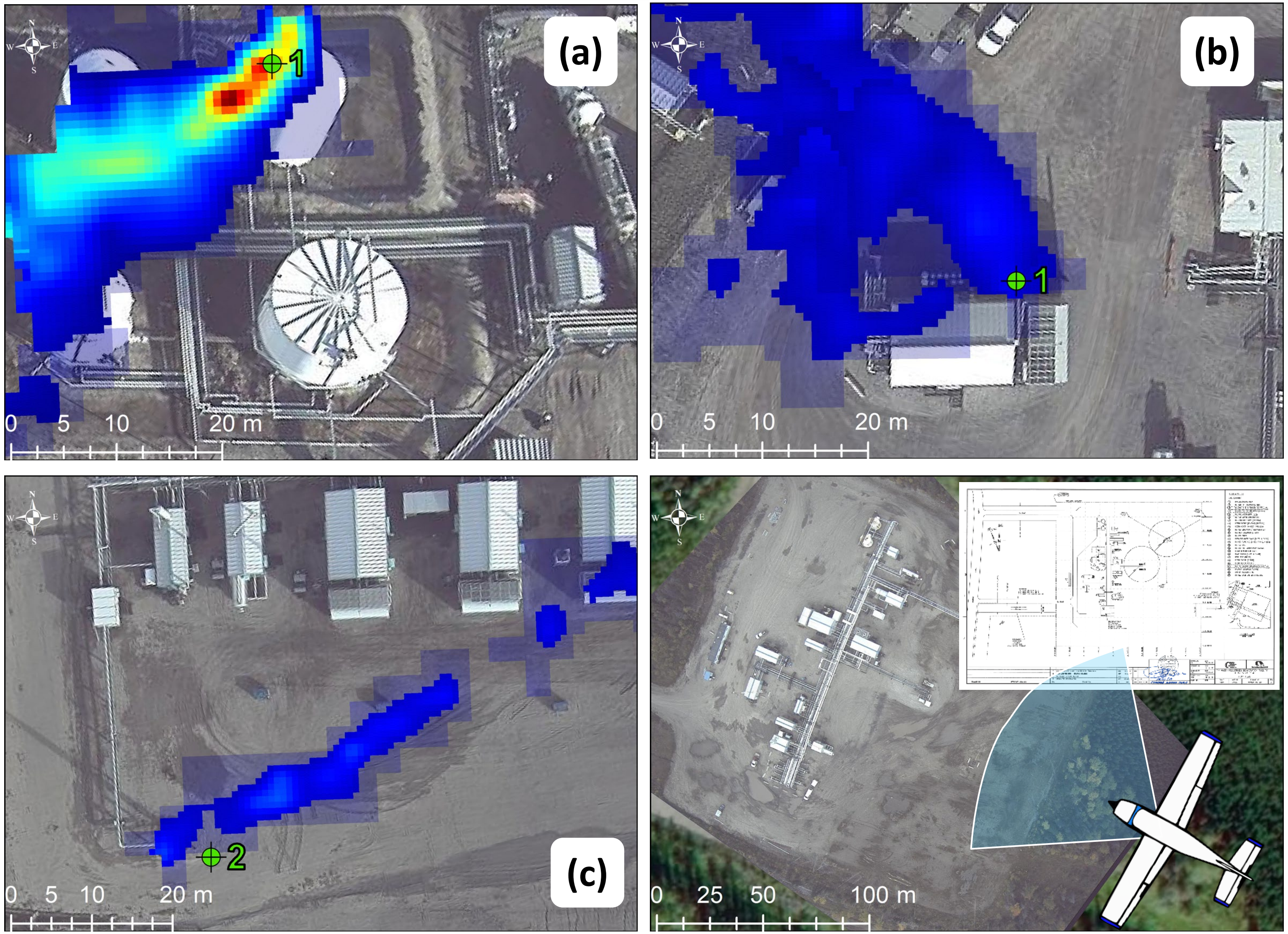
High Resolution (~1m) Data Enables Attribution to Specific Sources

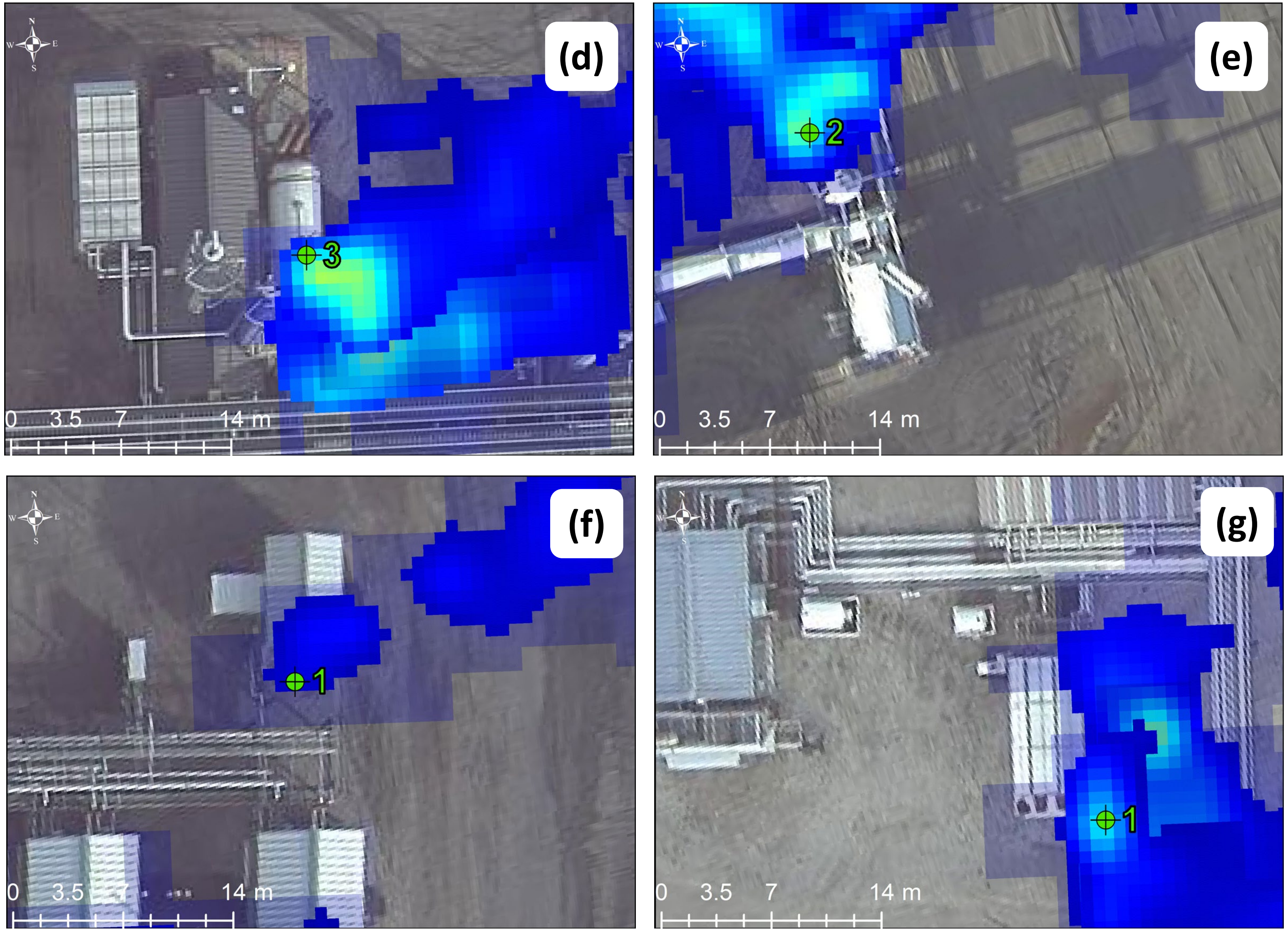
- Key sources:
  a) Tanks
  b) Compressors
  c) Unlit flares



Tyner & Johnson, Environ. Sci. Technol, 2021
(doi: 10.1021/acs.est.1c01572)

High Resolution (~1m) Data Enables Attribution to Specific Sources

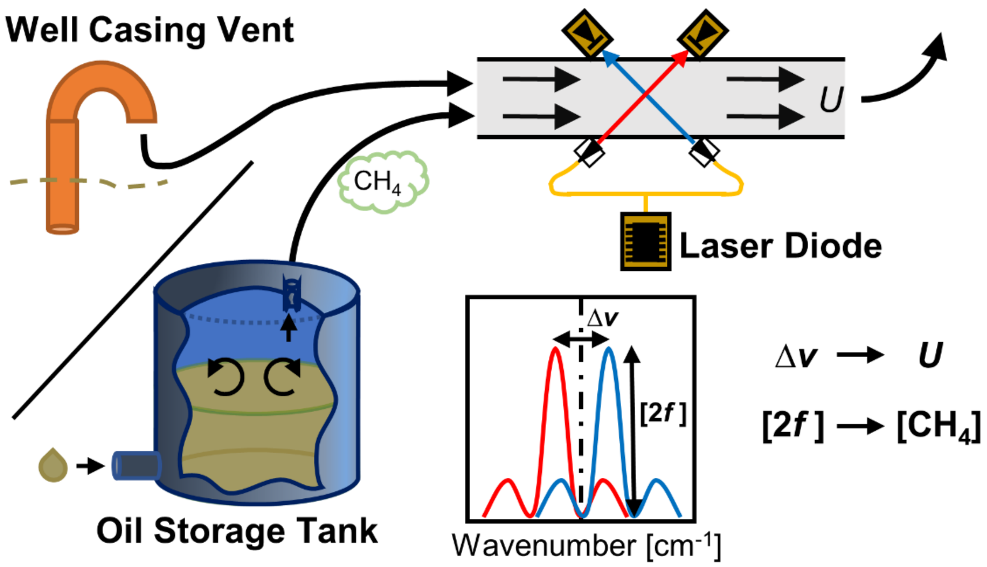
- Other detected sources in BC:
  - d) Amine boiler unit
  - e) Dehydrator
  - f) Generator
  - g) Cooler
  - h) Etc.

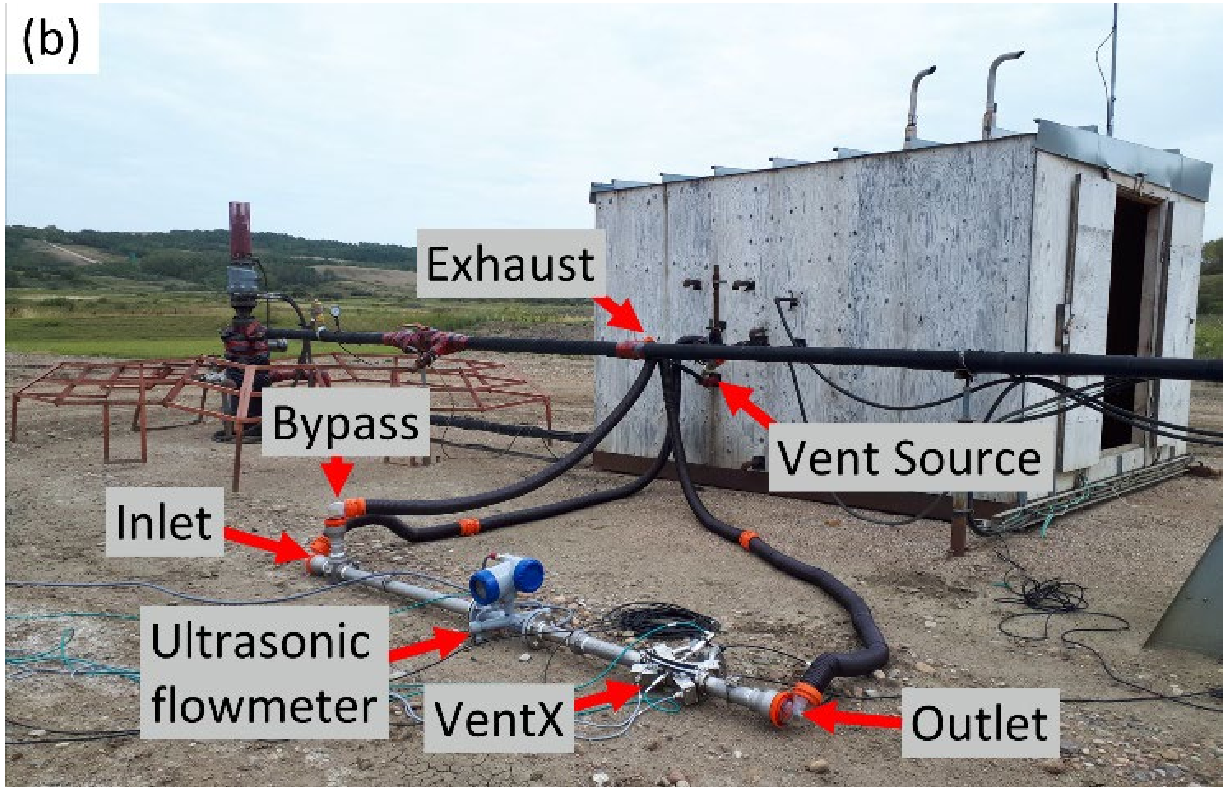


Tyner & Johnson, Environ. Sci. Technol, 2021
(doi: 10.1021/acs.est.1c01572)

Parallel On-Site Measurements of Key Sources

- “VentX” Measurements of Unsteady Methane Vent Sources
  - Engine shed vents (CHOPS) in Saskatchewan





Festa-Bianchet et al. (2022), *Sensors* (doi: 10.3390/s22114175).
Seymour et al. (2022), *Sensors* (doi: 10.3390/s22166139).

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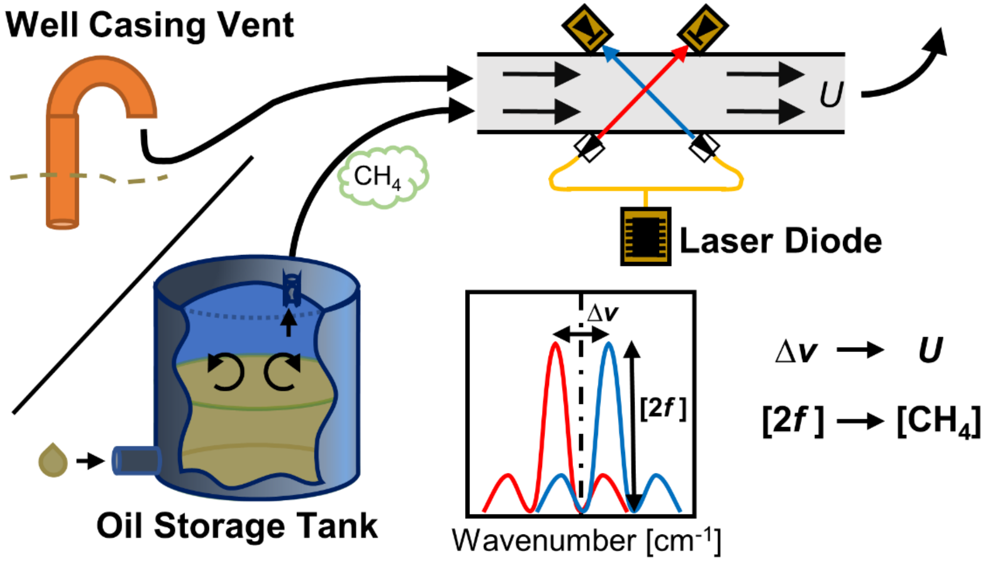
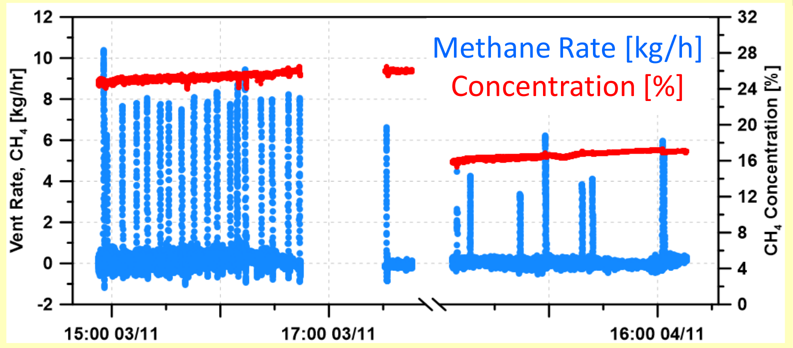
Parallel On-Site Measurements of Key Sources

- "VentX" Measurements of Unsteady Methane Vent Sources
  - Engine shed vents (CHOPS) in Saskatchewan
  - Tank vents in Alberta





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2021 Carleton-EERL National Methane Survey

- National-scale effort
  - ~8200 sites across 4 provinces

Natural Resources Canada / Ressources naturelles Canada

Canada

EDF ENVIRONMENTAL DEFENSE FUND

BC OGRIS BC Oil and Gas Research and Innovation Society

UN environment programme 50 1972-2022

BC Oil & Gas COMMISSION

NSERC CRSNG

Environment and Climate Change Canada / Environnement et Changement climatique Canada

BRIDGER PHOTONICS

GREENPATH ENERGY LTD

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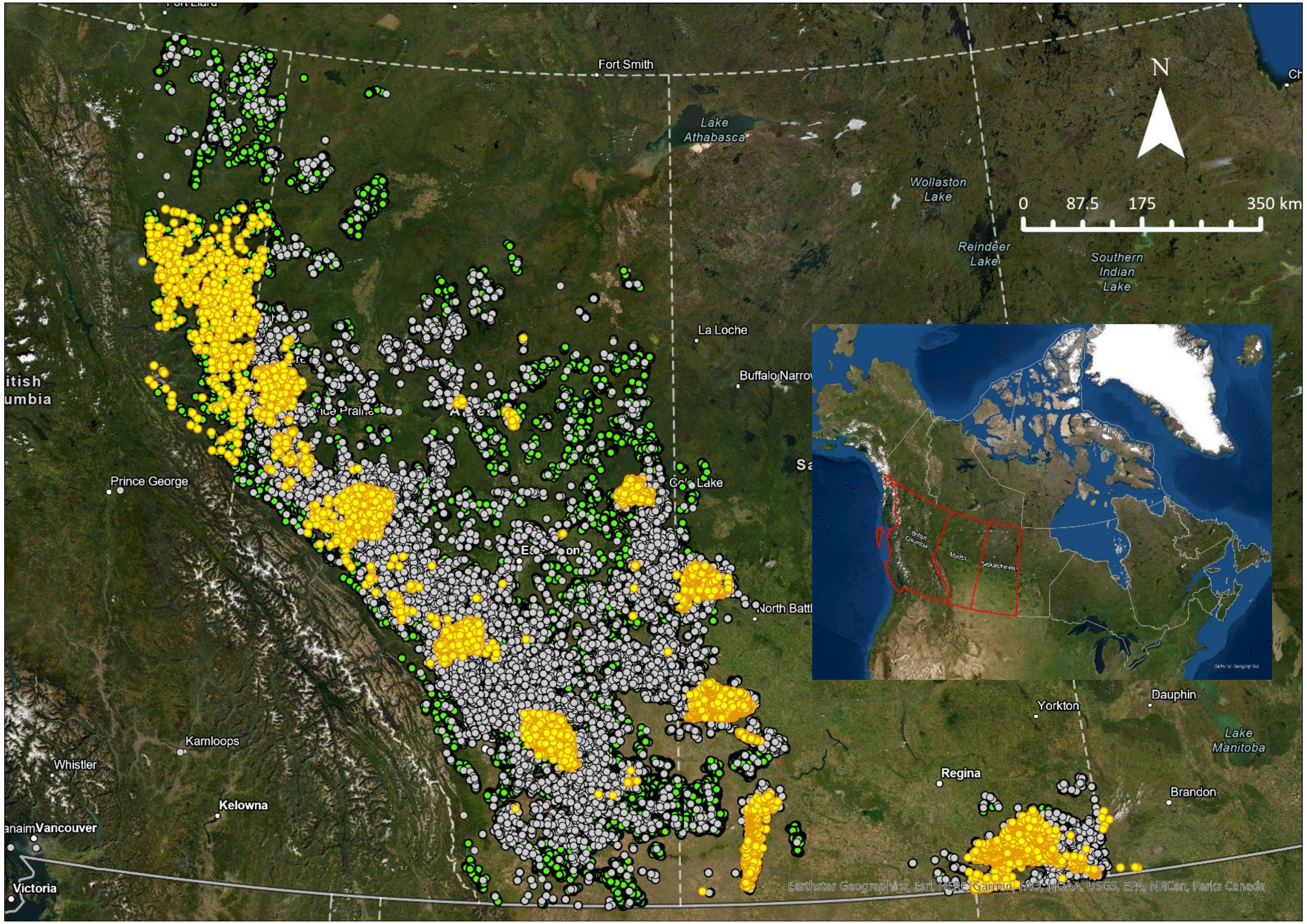
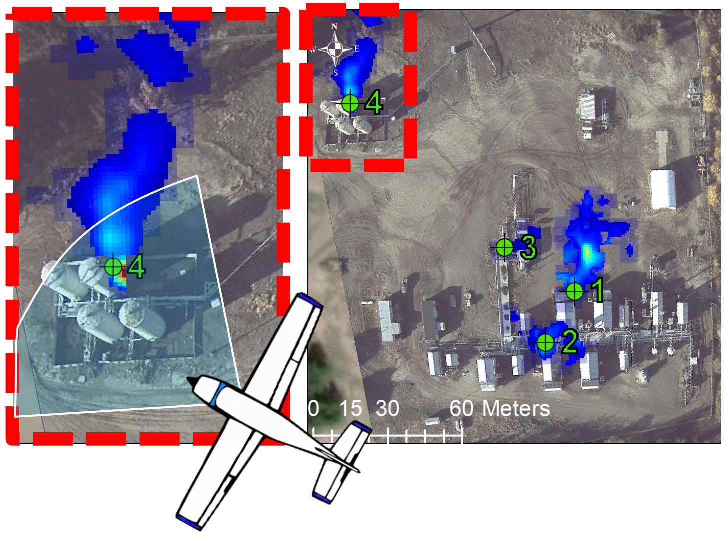
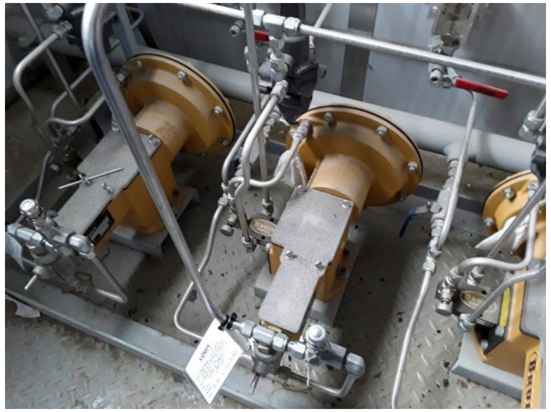


On Site Follow-ups and Root Cause Analysis





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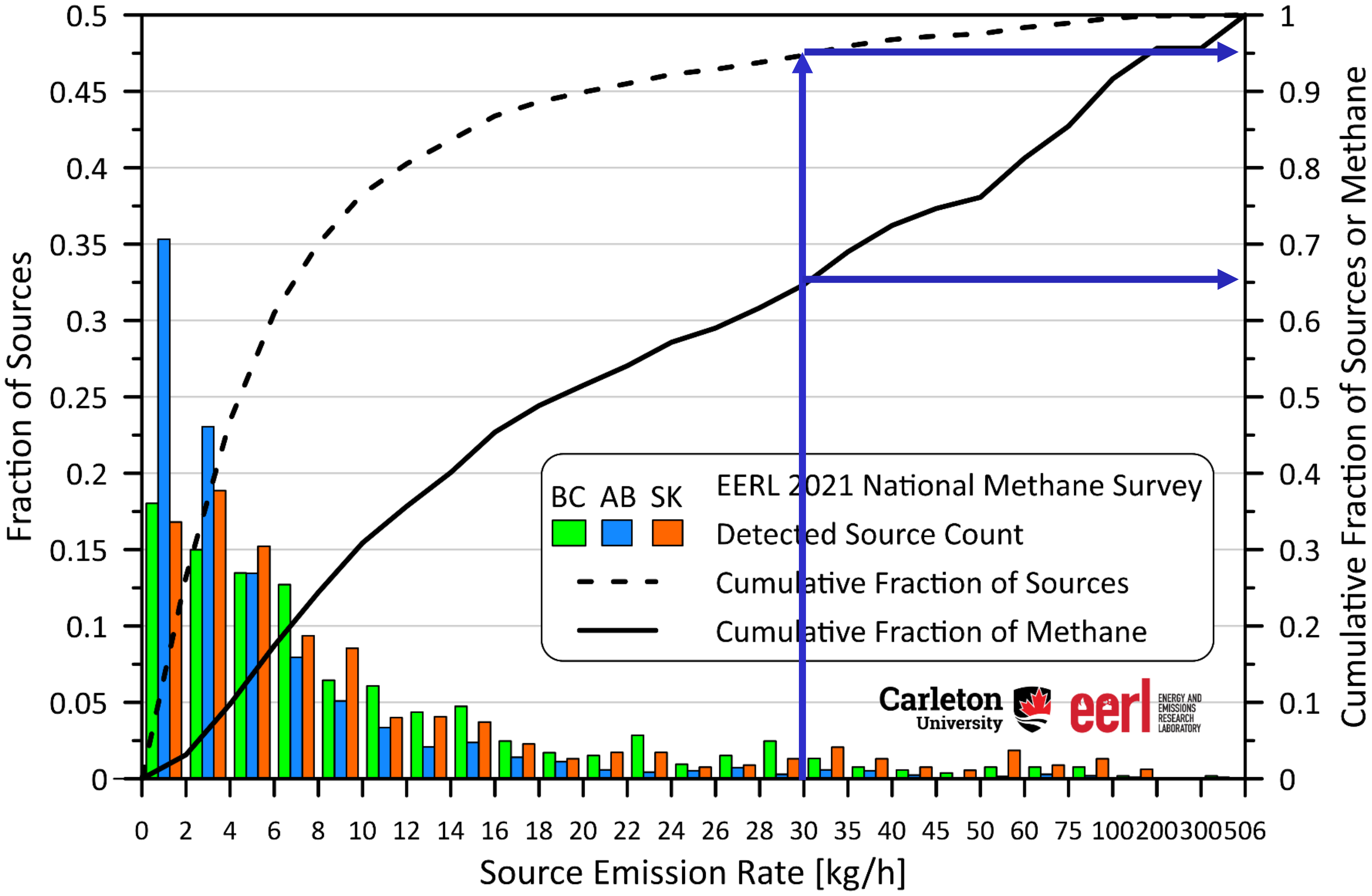
EERL 2021 National Survey: Distributions of Detected Sources

- Similar, highly-skewed distributions across all provinces
  - Note these measured sources are ~80% of total methane (shown later)
- 95% of GML measured sources less than 30 kg/h
  - 2/3 of measured methane / ~81% of all methane
  - Not just about "super-emitters"
  - Mid-sized source key and will become more important as mitigation efforts succeed



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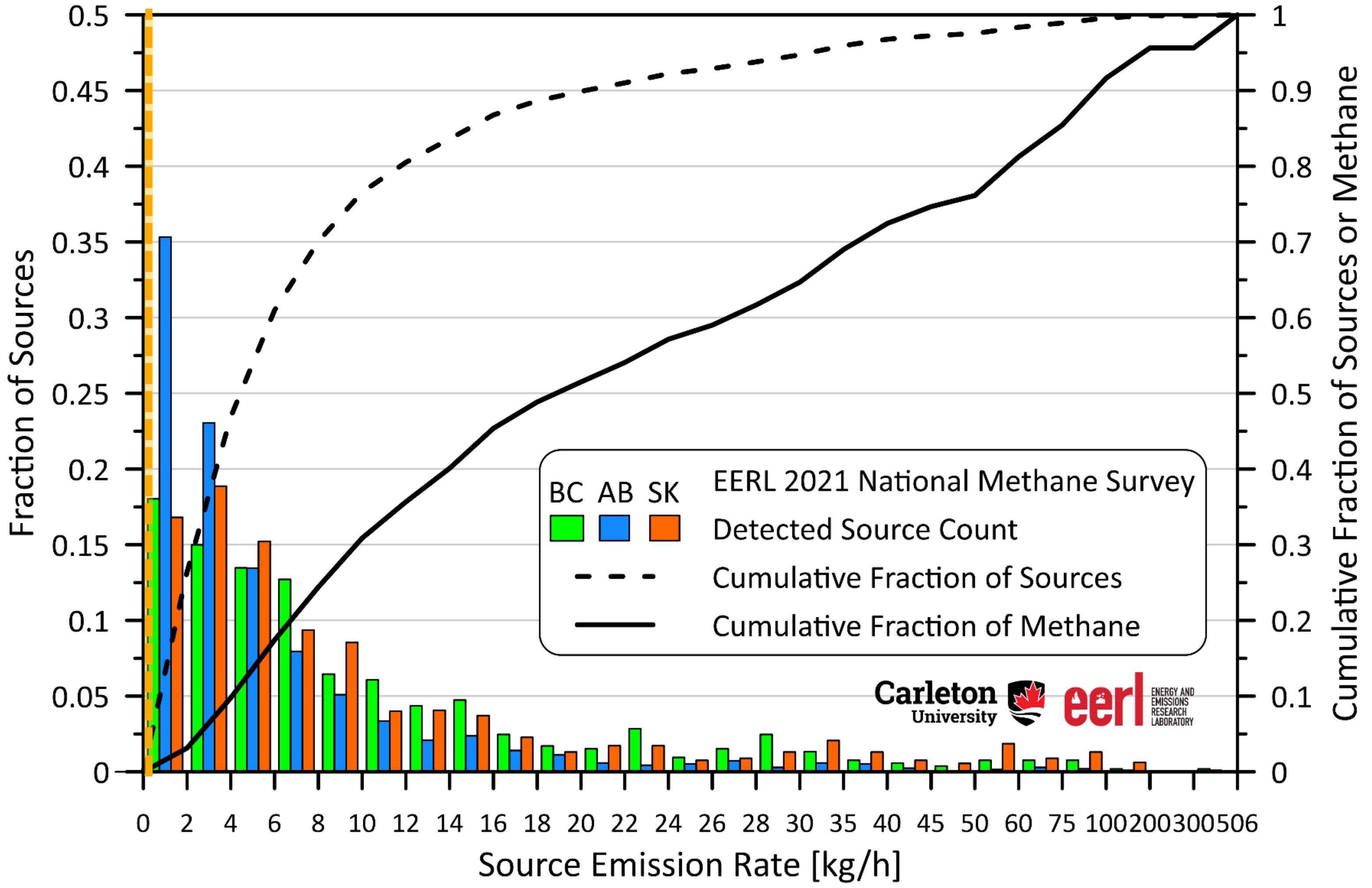
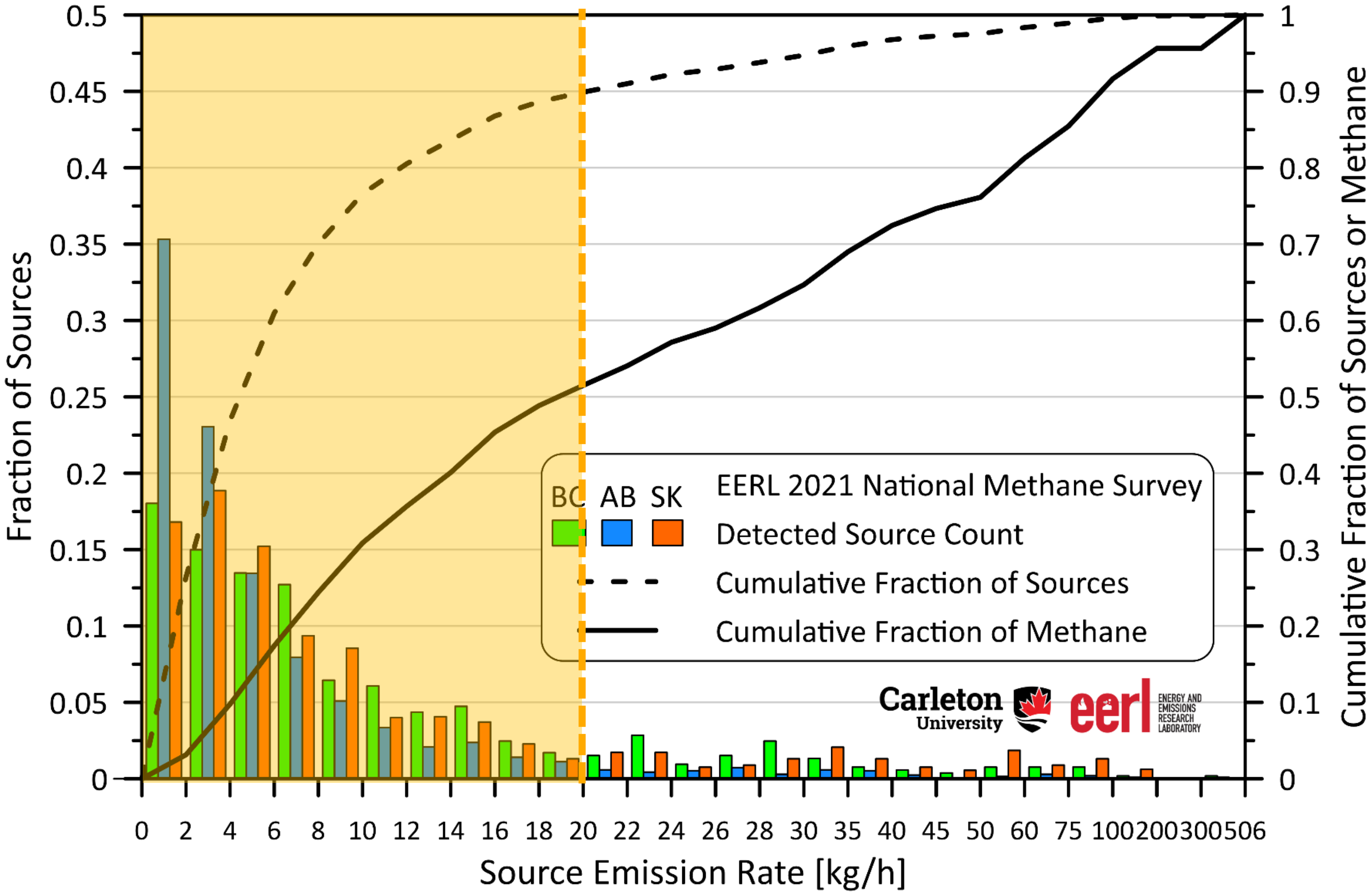
EERL 2021 National Survey: Distributions of Detected Sources

- Measured distributions represent ~80% of total methane *(shown later)*



EERL 2021 National Survey: Distributions of Detected Sources

- Measured distributions represent ~80% of total methane *(shown later)*
- At 20 kg/h sensitivity can see:
  - ~10% of these sources / 48% of this methane
  - ~38% (0.48*0.8) of all methane



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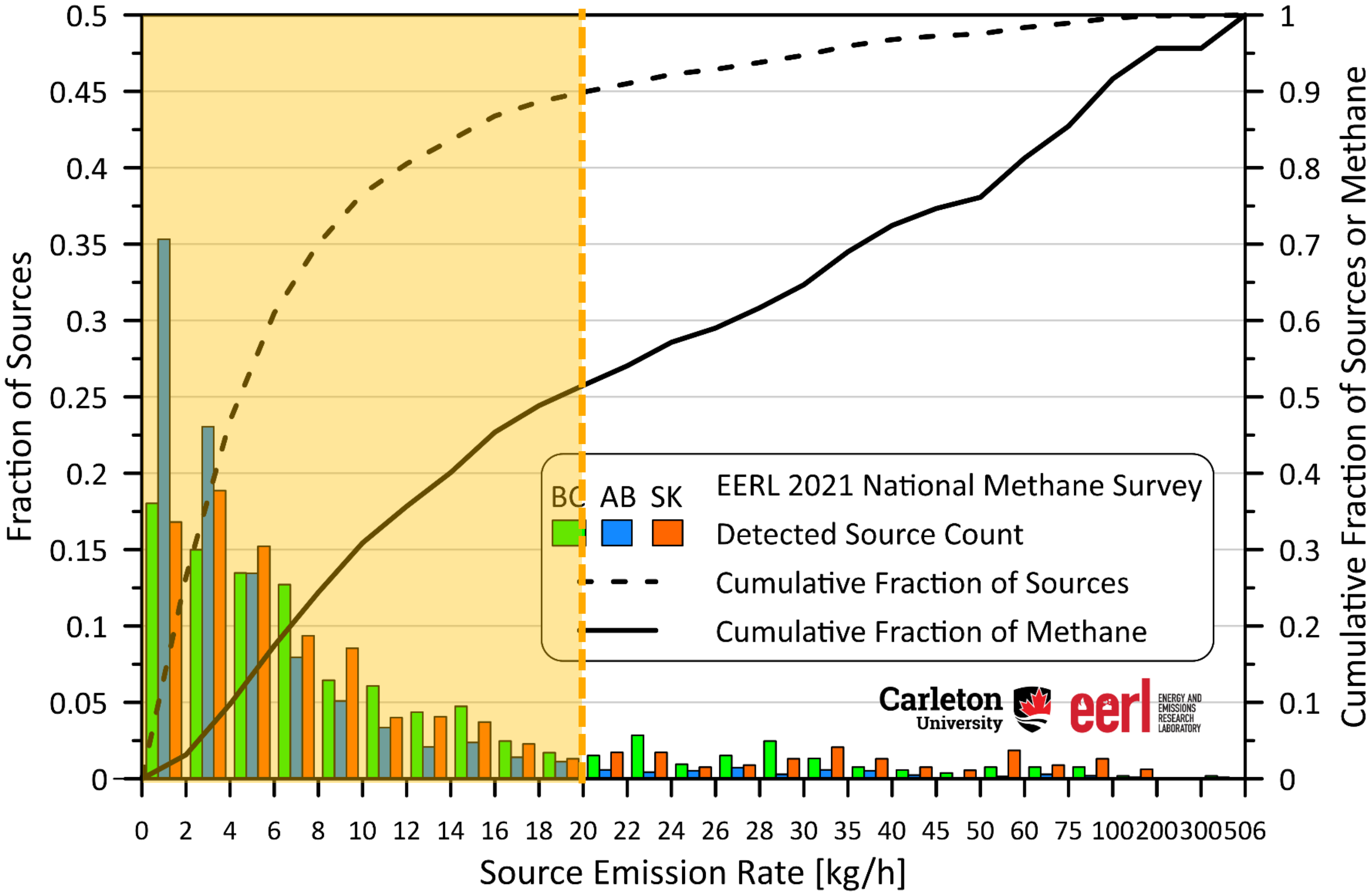
  - ~38% (0.48*0.8) of all methane
- At 32 kg/h sensitivity can see:



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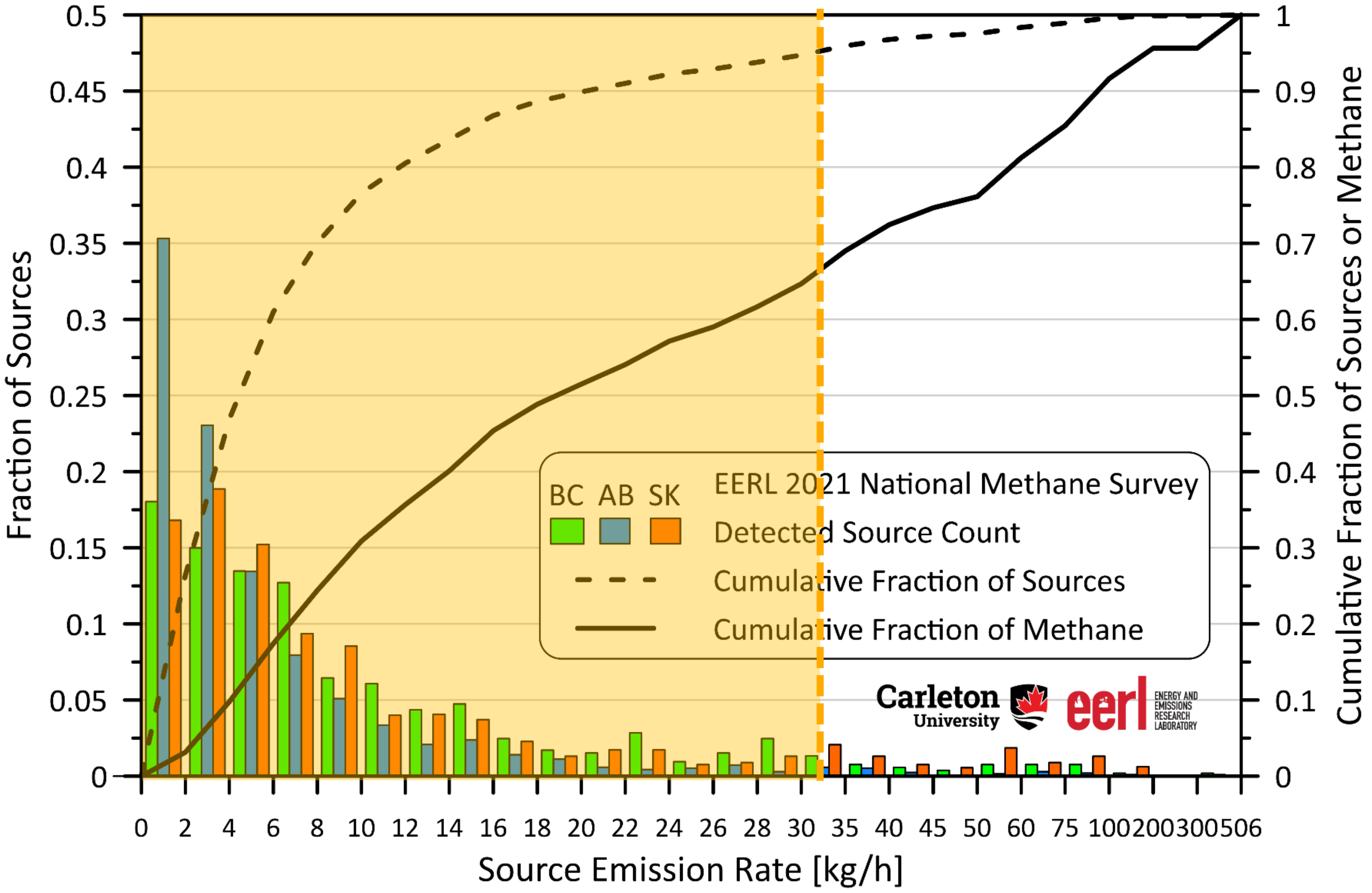
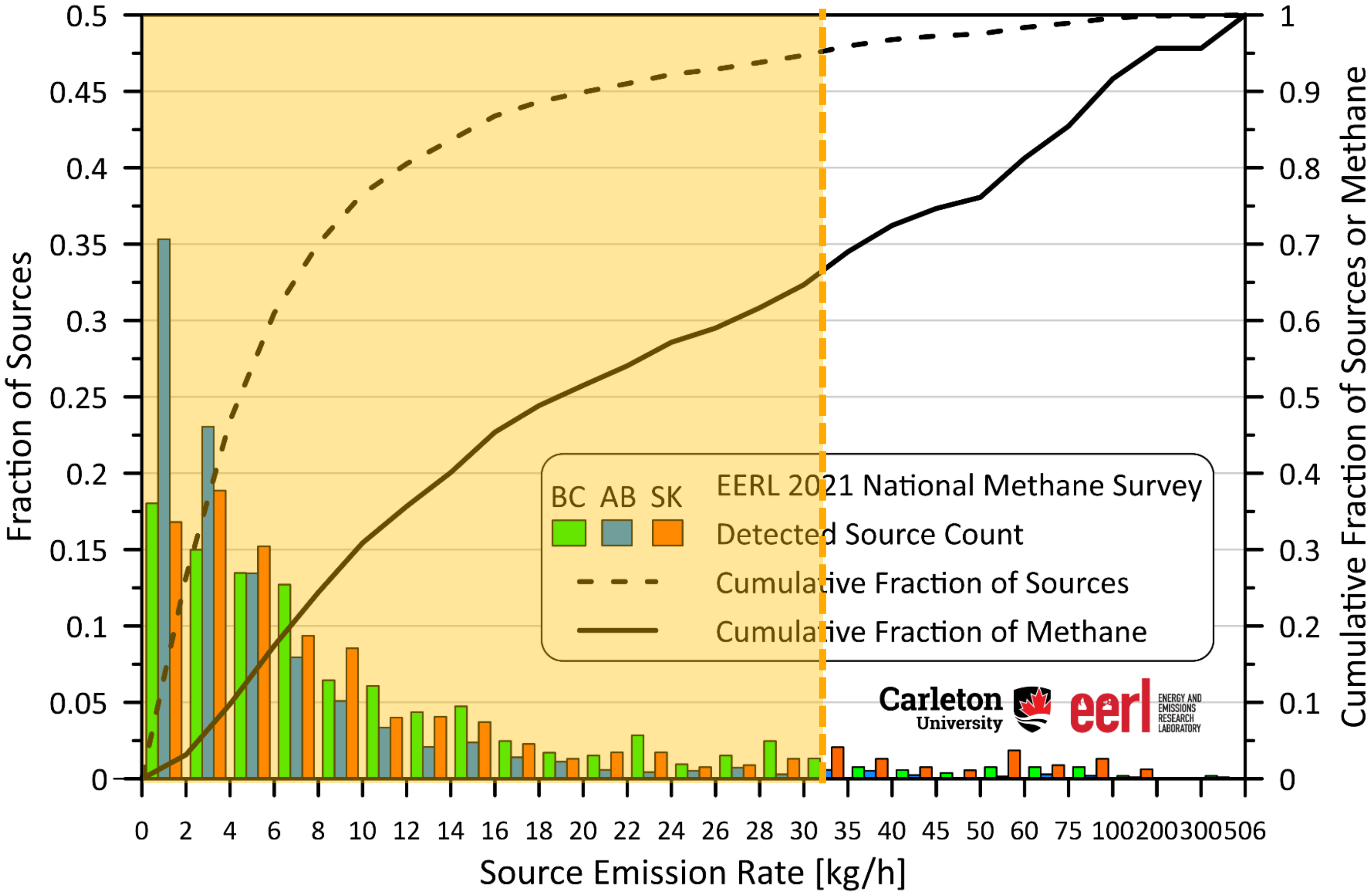
  - ~38% (0.48*0.8) of all methane
- At 32 kg/h sensitivity can see:
  - ~5% of these sources / 33% of this methane
  - ~26% (0.33*0.8) of all methane



EERL 2021 National Survey: Distributions of Detected Sources

- Measured distributions represent ~80% of total methane *(shown later)*
- At 20 kg/h sensitivity can see:
  - ~10% of these sources / 48% of this methane
  - ~38% (0.48*0.8) of all methane
- At 32 kg/h sensitivity can see:
  - ~5% of these sources / 33% of this methane
  - ~26% (0.33*0.8) of all methane
- At 200 kg/h sensitivity can see:



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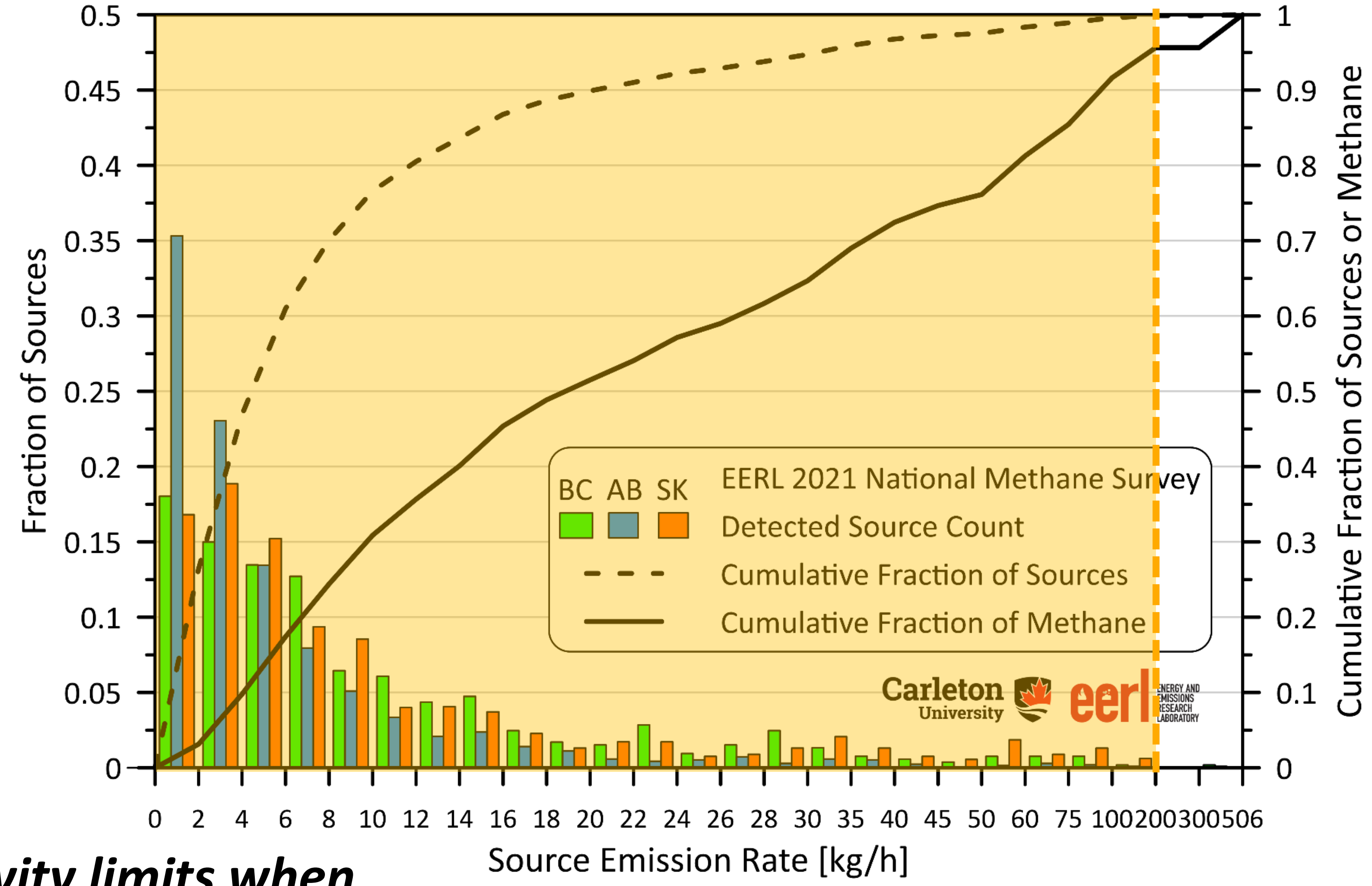
EERL 2021 National Survey: Distributions of Detected Sources

- Measured distributions represent ~80% of total methane *(shown later)*
- At 20 kg/h sensitivity can see:
  - ~10% of these sources / 48% of this methane
  - ~38% (0.48*0.8) of all methane
- At 32 kg/h sensitivity can see:
  - ~5% of these sources / 33% of this methane
  - ~26% (0.33*0.8) of all methane
- At 200 kg/h sensitivity can see:
  - <1% of these sources / 5% of this methane
  - ~4% (0.05*0.8) of all methane



- ***Critical to understand sensitivity limits when incorporating measurements from different technologies***

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