Using Source-Resolved Aerial Surveys to Create Measurement-Based Methane Inventories

IPCC TFI Meeting, Geneva, September 5–7, 2022

Prof. Matthew R. Johnson, Ph.D., P.Eng

Professor & Scientific Director
Energy & Emissions Research Lab.,
Mechanical & Aerospace Engineering,
Carleton University, Ottawa, ON
Matthew.Johnson@carleton.ca
https://carleton.ca/eerl

Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

Why We Need to Incorporate Measurements in (Methane) Inventories

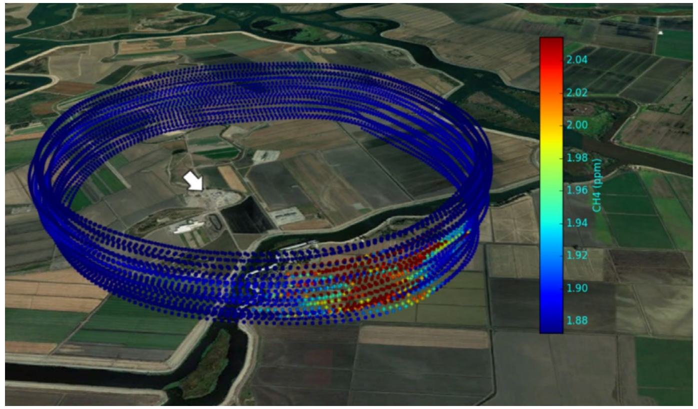
- *Multiple* studies, in *multiple* jurisdictions, using *multiple* techniques consistently show current oil and gas sector methane inventories are underestimated
  - **Airplane source/site-resolved** (e.g., Tyner & Johnson, EST 2021; Chen et al., EST 2022)
  - **Airplane mass balance** (e.g., Johnson et al., EST 2017; Karion et al., EST 2015; Peischl et al., J. Geophys. Res., 2015, 2016; Alvarez et al., Science 2018)
  - **Mobile (truck) measurements** (e.g., Mackay et al., Sci. Reports, 2021)
  - **Inverse modelling of ground station data** (e.g., Chan et al., EST 2020; Miller et al., PNAS 2013)
  - **Satellite measurements** (e.g., Zhang et al., Sci. Adv., 2020)
  - **Isotope measurements** (e.g., Hmiel et al., Nature, 2020)

- **Emissions must be expected to rapidly change!**
  - <u>Emission factors</u> and inventories must be <u>***continually updated***</u> if we are to track reductions

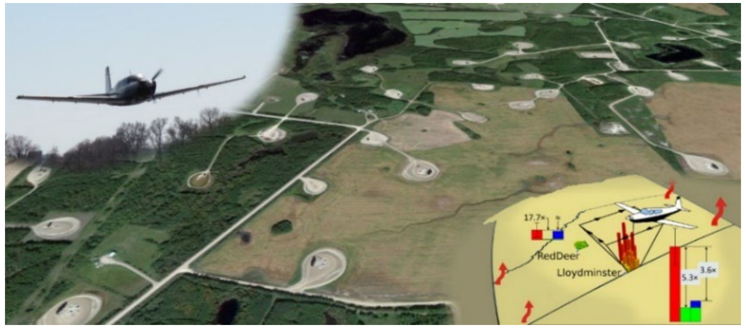
Key Challenges: Why We Don't Generally Use Measurements in Inventories

- **Inventories must preserve source / site / facility-type resolution**
  - Bottom-up resolution is critical for regulatory and mitigation decisions
  - Simple-scaling of bottom-up totals to match some other total measurement misses a key part of the problem
- **Unknown / unverified capabilities of available measurement technologies**
  - What is the Probability of Detection (POD) of a source under general conditions?
  - What is the quantification uncertainty of a source/site under general conditions?
- **Protocols to incorporate measurements?**
  - What about unmeasured sources?
  - How do determine required sample sizes with skewed distributions?
  - Finite sample effects
  - Etc.

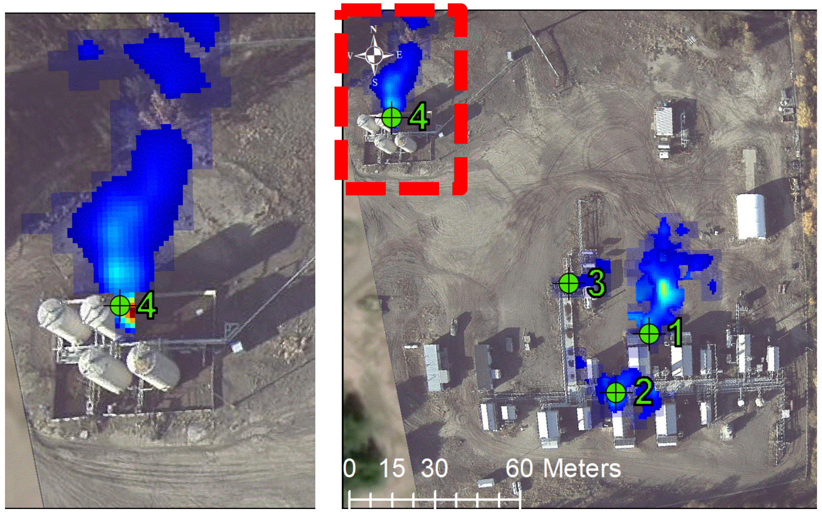
Potential for Airborne Measurement Approaches



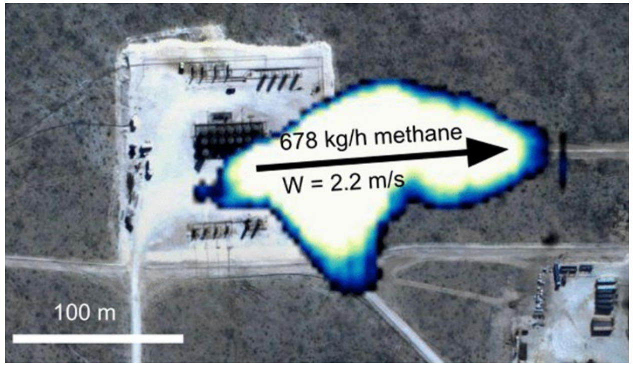
Scientific Aviation (Conley et al., AMT 2017)



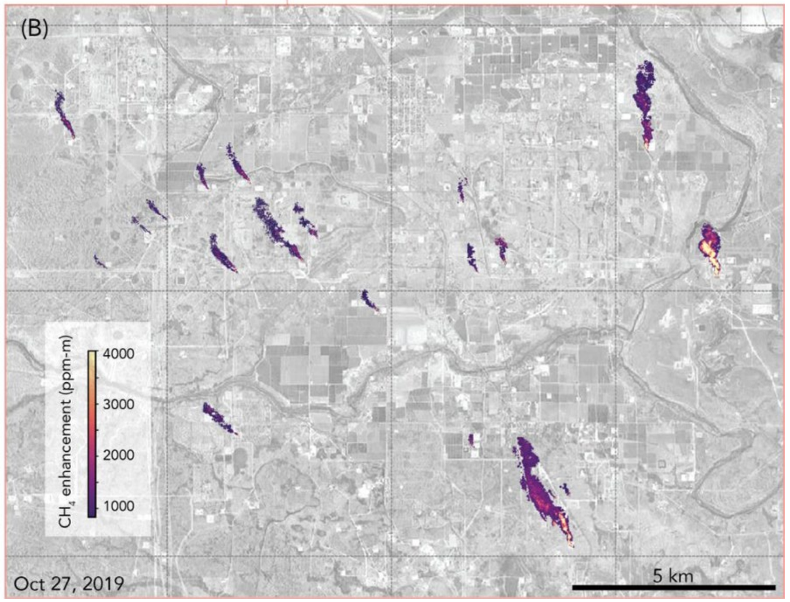
Scientific Aviation (Johnson et al., EST 2017)



Bridger Photonics (Tyner & Johnson, EST 2021)



Kairos Aerospace (Chen et al., EST 2022)



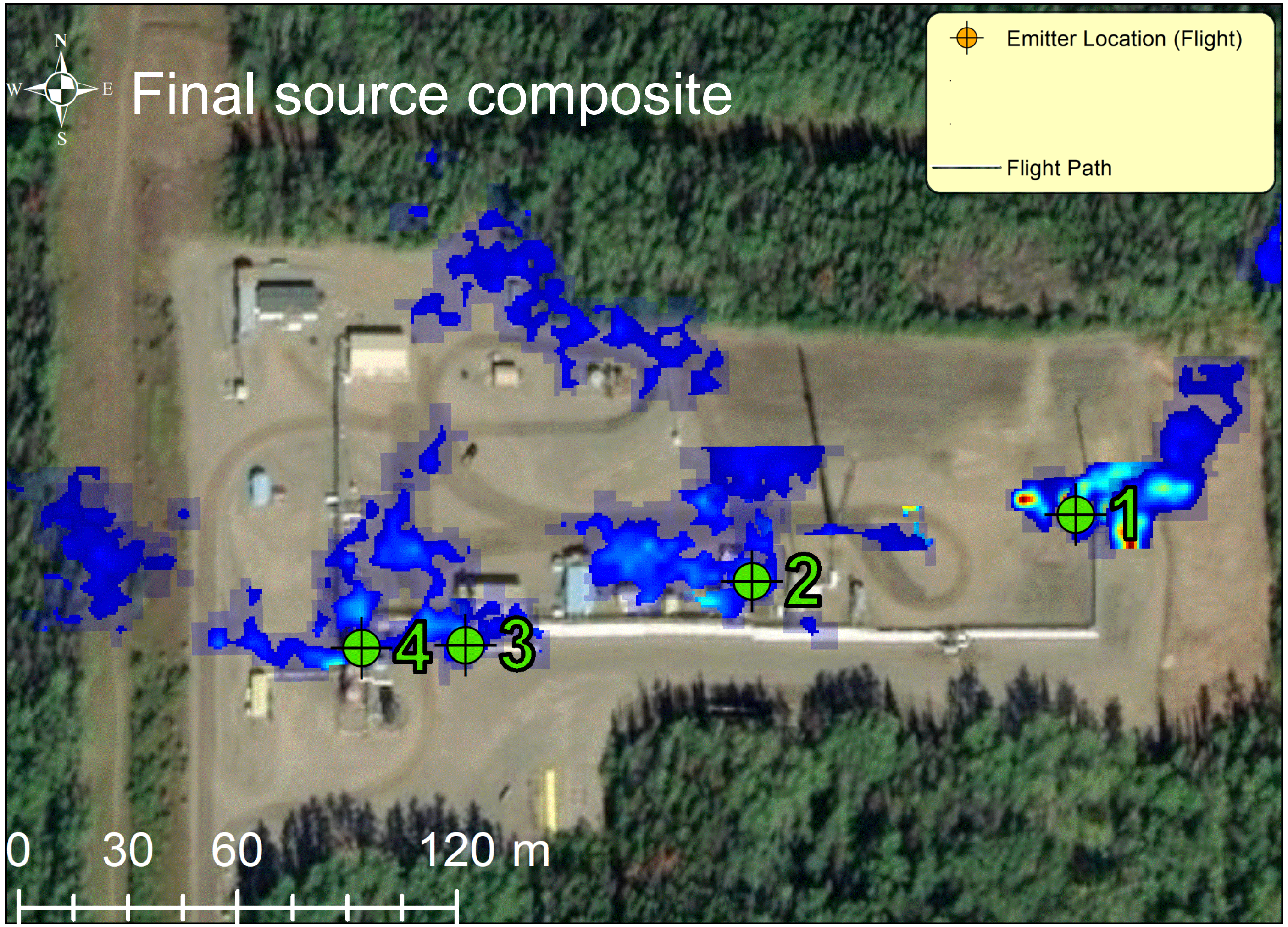
AVIRIS-NG (Cusworth et al., Energy & Climate 2021)

Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

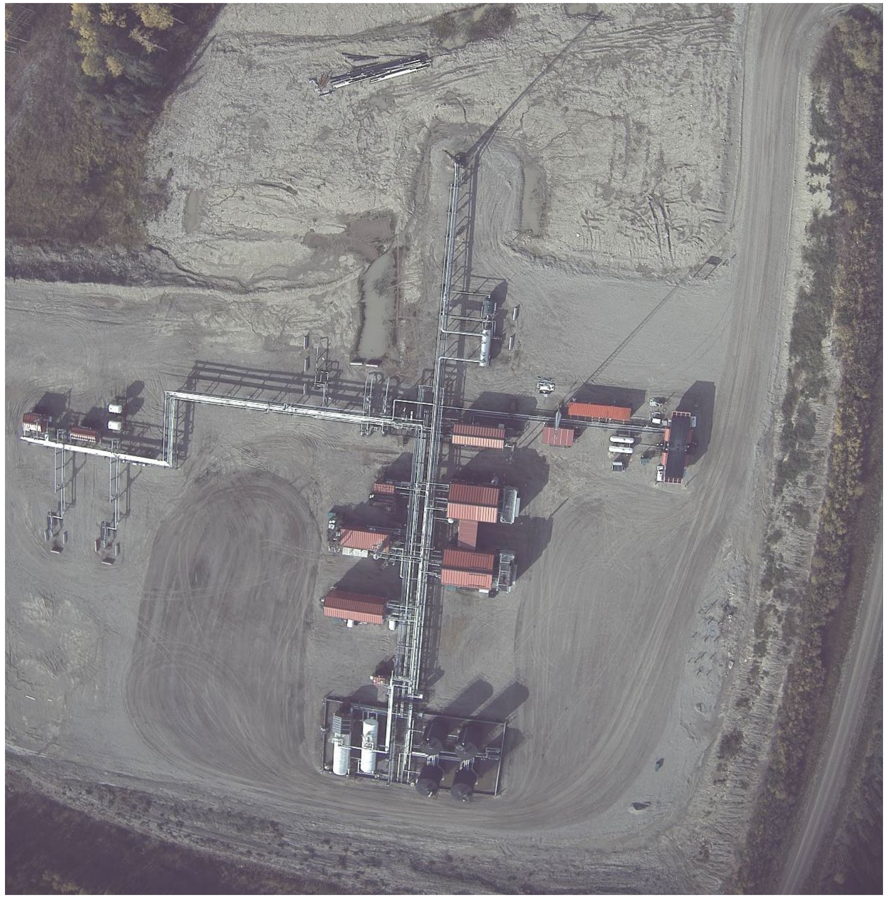
Example Aerial Technology: Bridger Photonics Gas Mapping LiDAR

- 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



Source Attribution: Geo-locating Aerial Survey Imagery

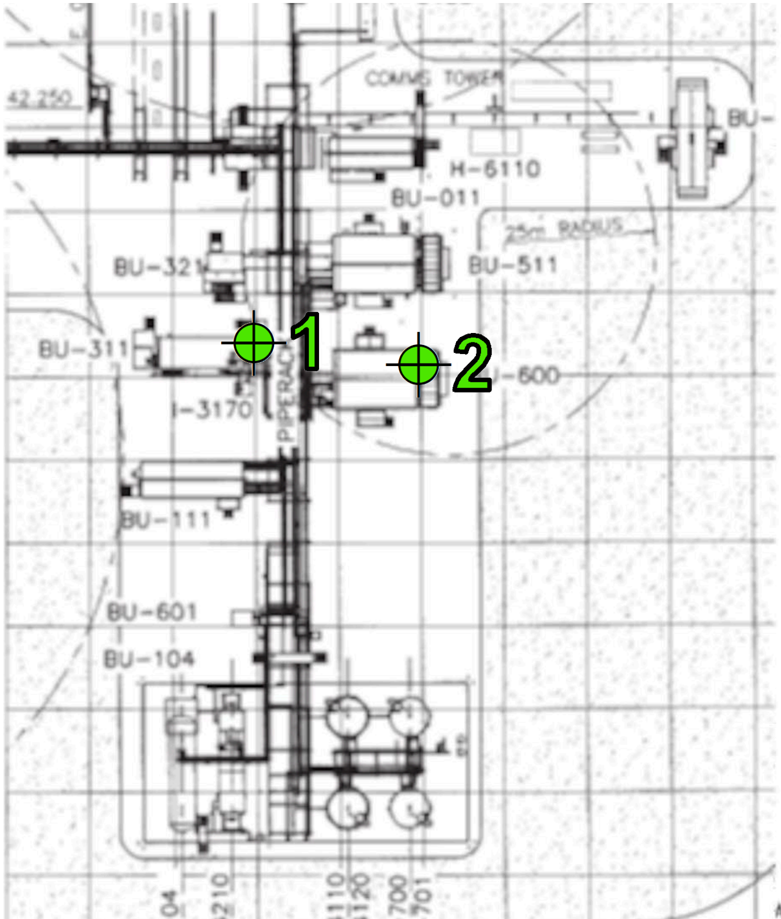
- Combining satellite imagery, geo-located aerial photos, plot plans, & ground survey data to attribute



Carleton UNIVERSITY eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

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

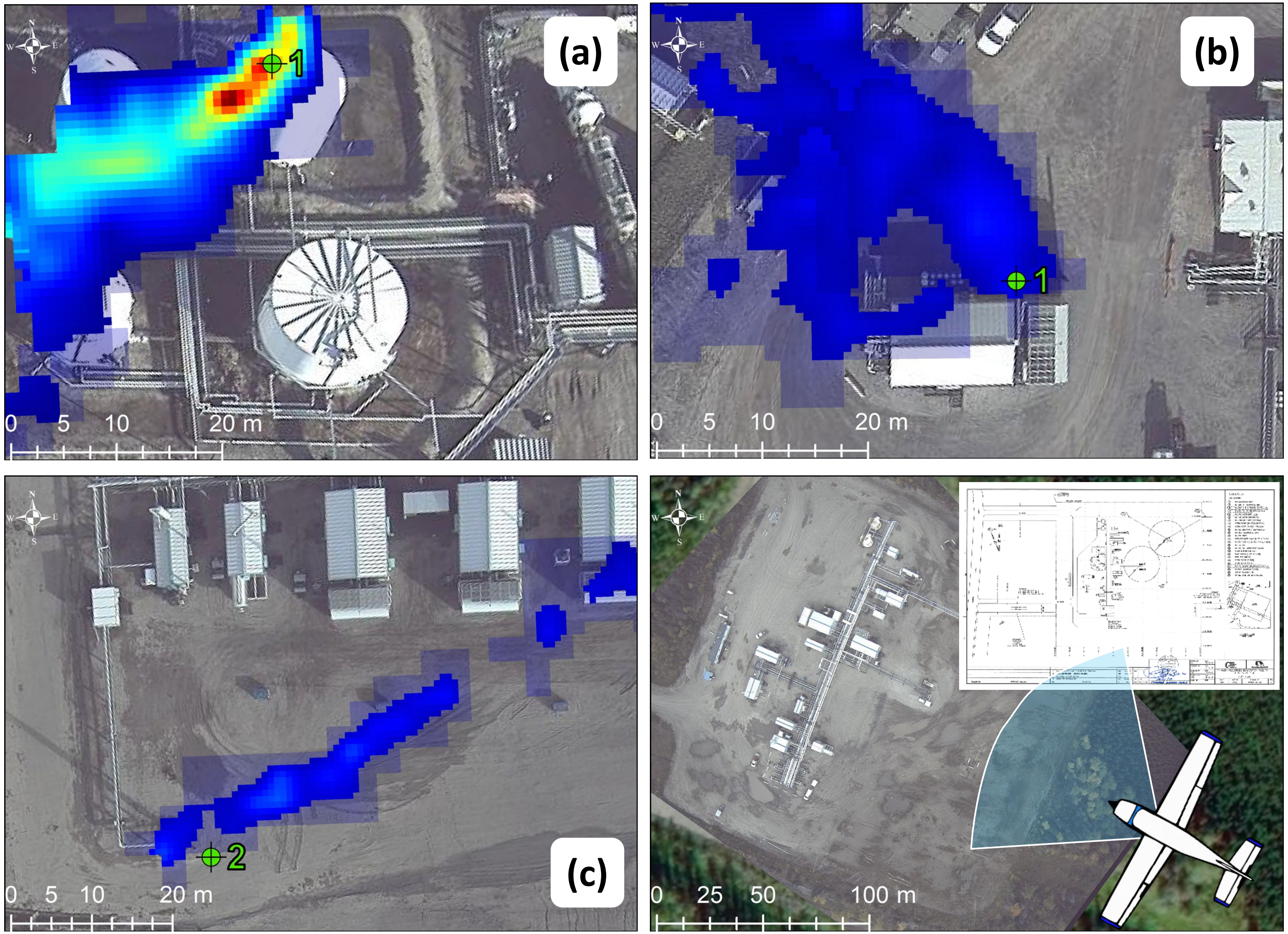
TAG NO.	DESCRIPTION
BU-011	MCC/IA BUILDING
BU-111	SLUG CATCHER BUILDING
BU-131	SEPARATOR BUILDING
BU-311	DEHYDRATION UNIT BUILDING
BU-321	FUEL GAS DEHY BUILDING
BU-511	COMPRESSOR #1 BUILDING
BU-521	COMPRESSOR #2 BUILDING
BU-541	RECYCLE COMPRESSOR BUILDING
BU-921	GENERATOR BUILDING
BU-931	METERING BUILDING
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

Carleton UNIVERSITY

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

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

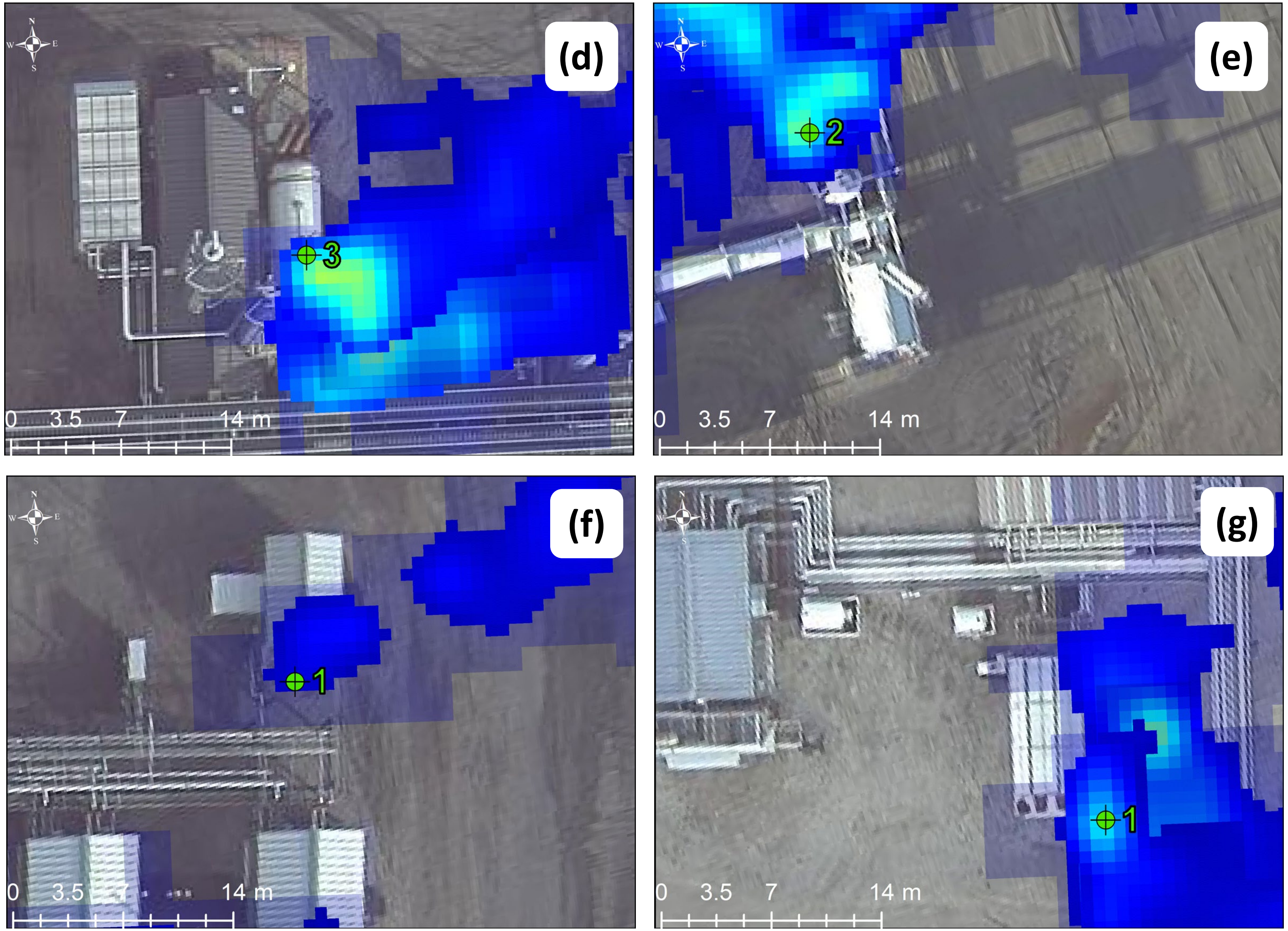
- Key sources:
  a) Tanks
  b) Compressors
  c) Unlit flares



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

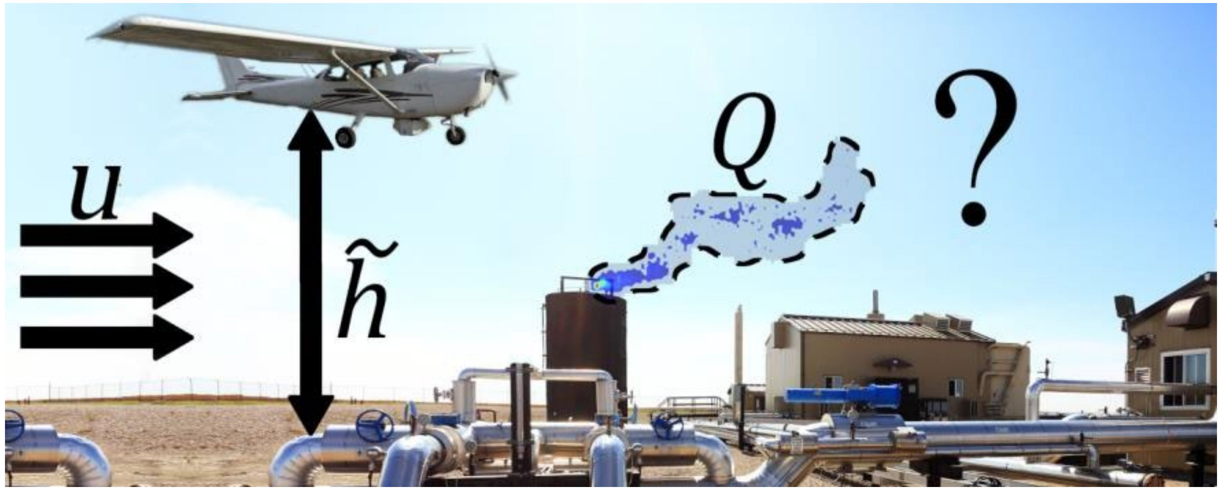
High Resolution (~1m) Data Enables Attribution to Specific Sources

- 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)

Robust, Critical Evaluation of Measurement Technologies



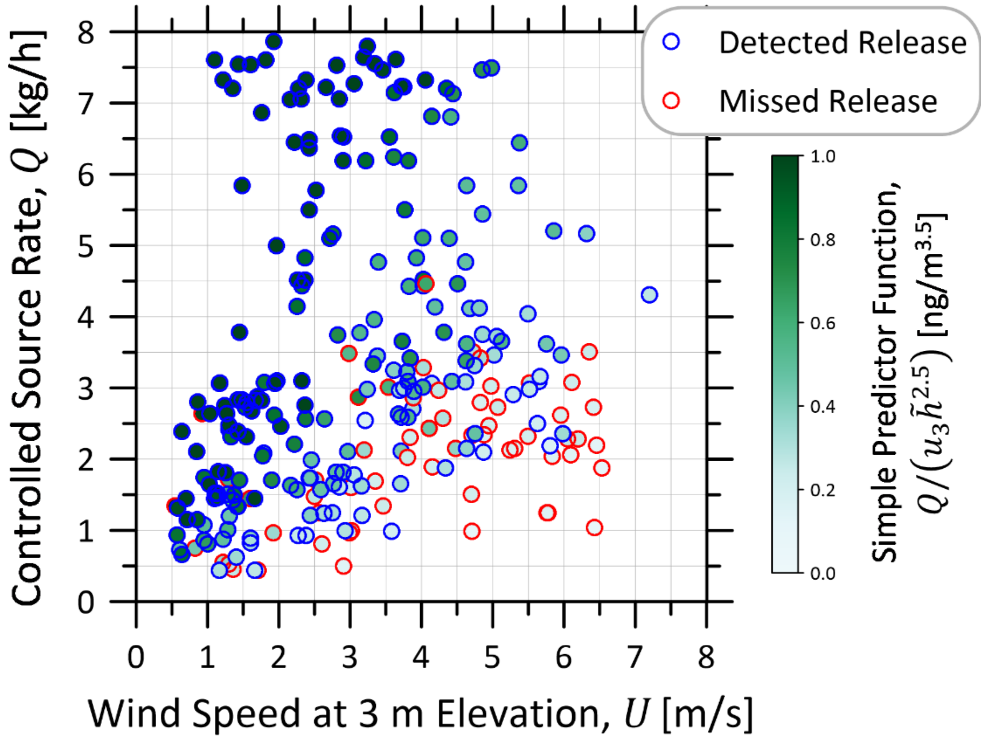
- Fully- and semi-blinded controlled release testing

- 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)

Carleton University
eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

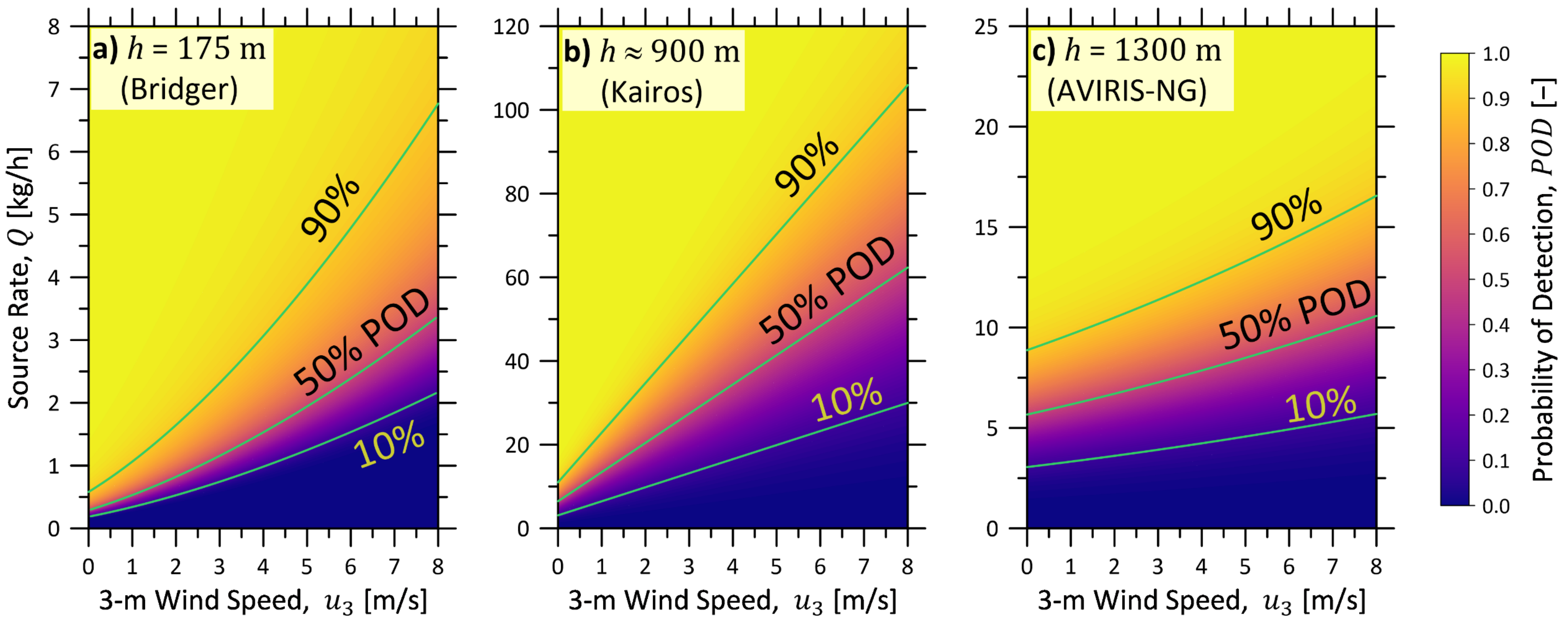
1. Fully-Blinded Controlled Release Testing of *Sensitivity Limits*

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



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)

Continuous Probability of Detection (POD) Functions



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

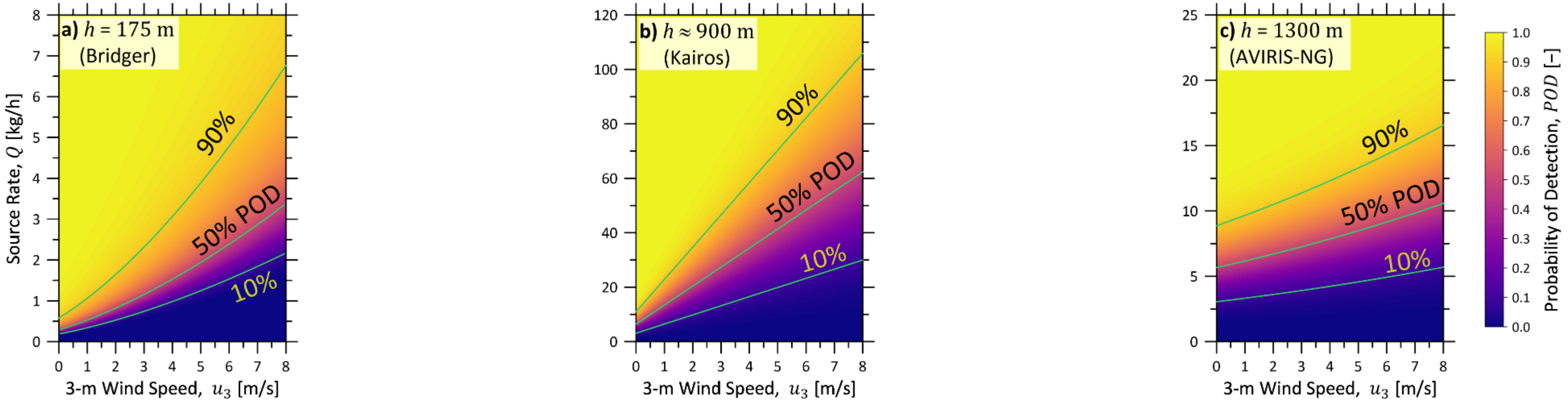
B.M. Conrad, D.R. Tyner, M.R. Johnson (2022) Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies, *Remote Sensing of Environment* (under review: preprint)

Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

Continuous Probability of Detection (POD) Functions

	Bridger GML™	Karios Leaksurveyor™	NASA AVIRIS-NG



	Bridger GML™	Karios Leaksurveyor™	NASA AVIRIS-NG
Typical Altitude:	175 m	900 m	3000 m
50% POD @ 3m/s:	1.2 kg/h	27 kg/h	13 kg/h
Measurement Swath:	100 m	800 m	1800 m

- 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)

Carleton University | eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

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

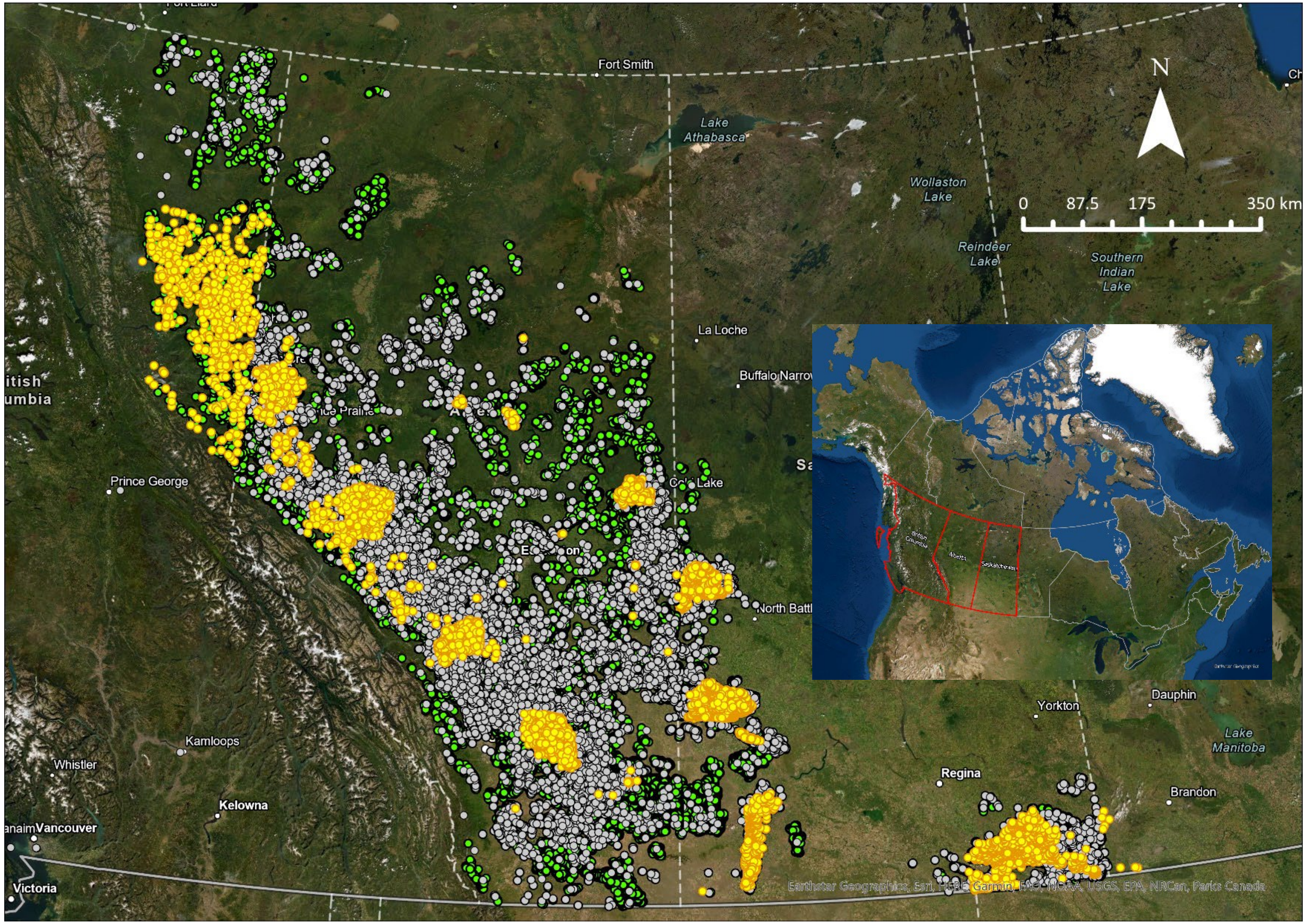
Environment and Climate Change Canada / Environnement et Changement climatique Canada

BRIDGER PHOTONICS

GREENPATH ENERGY LTD

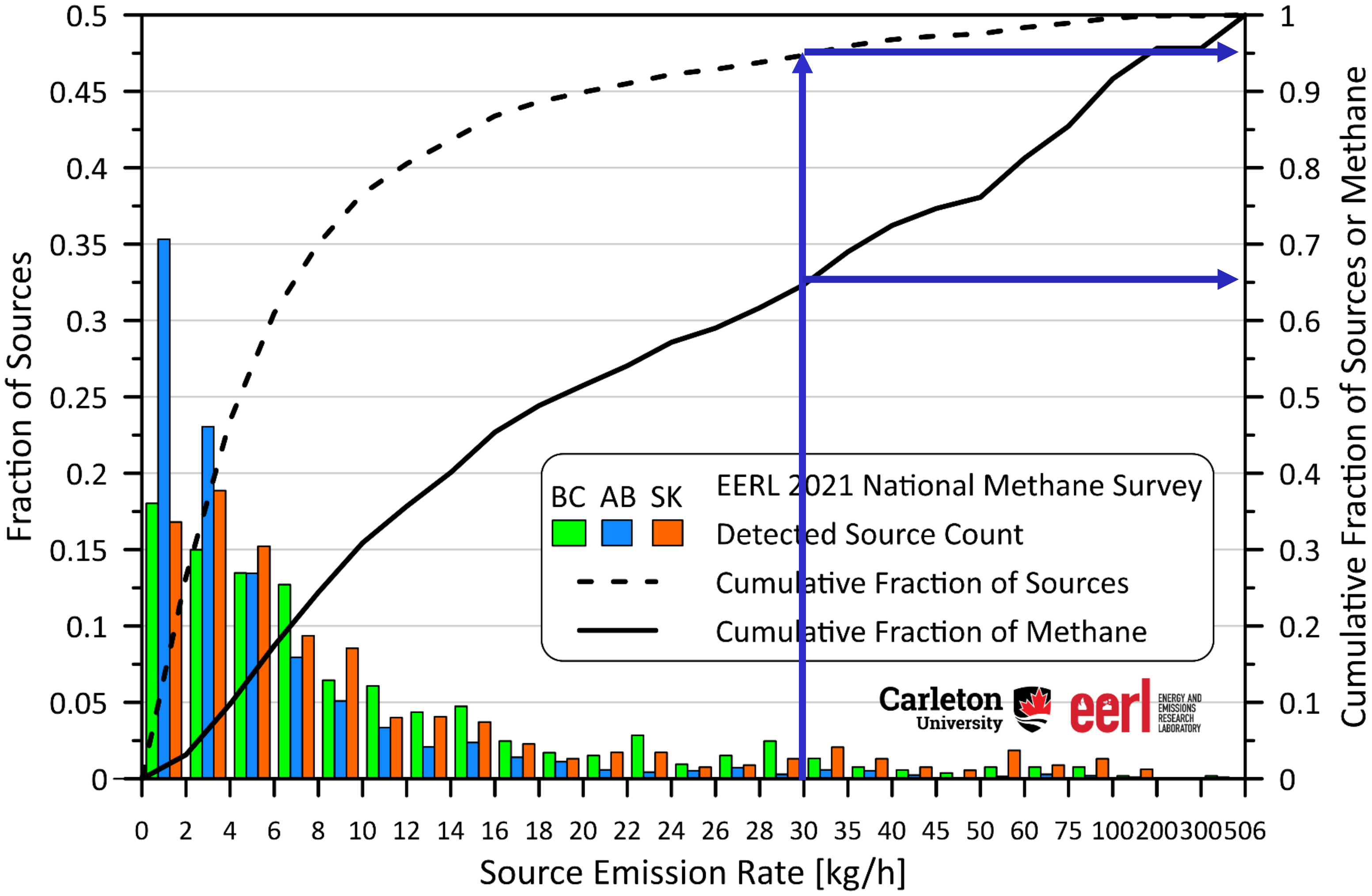
Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY



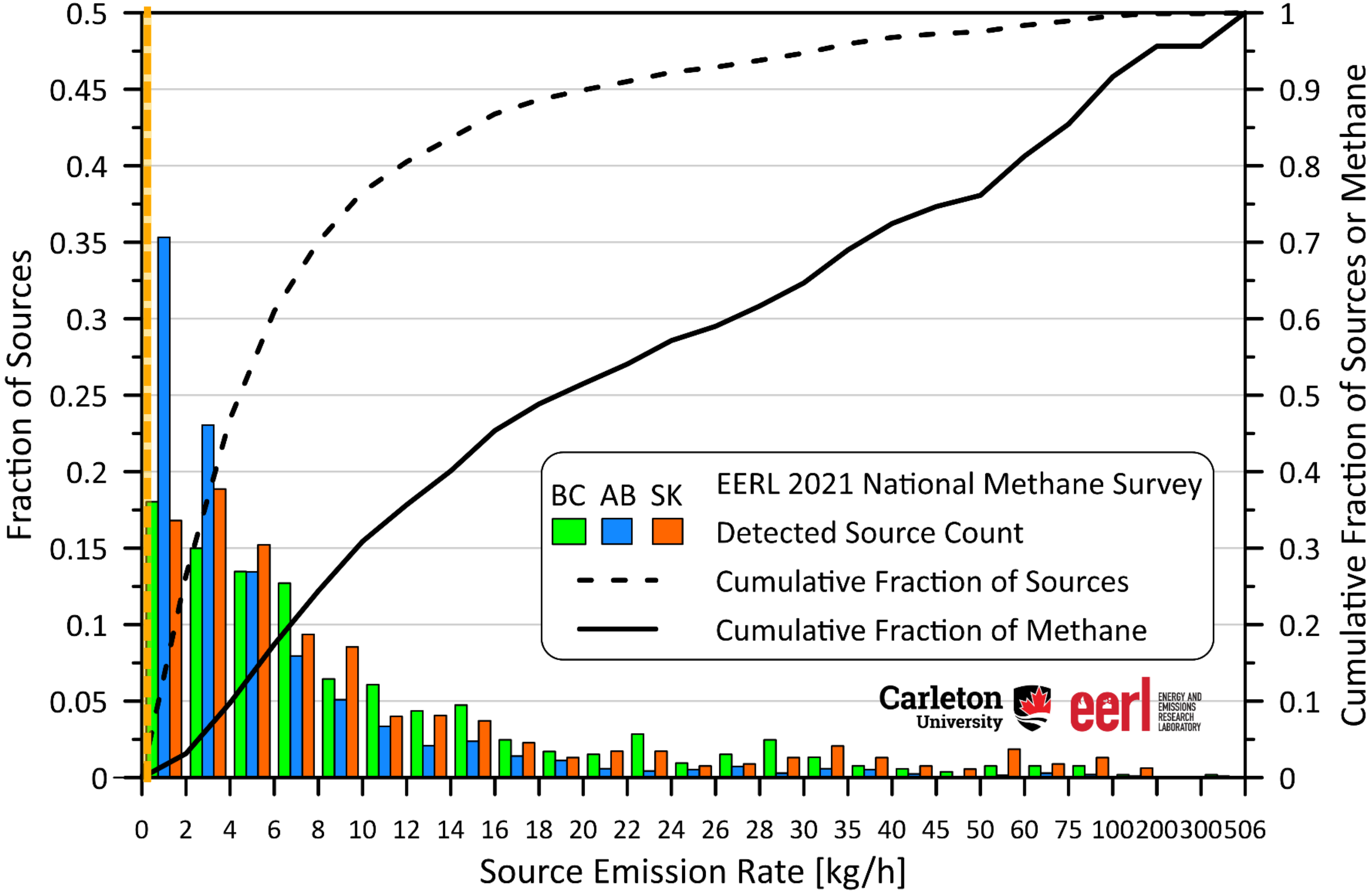
EERL 2021 National Survey: Distributions of Detected Sources

- 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 measure methane / ~81% of all methane
  - Not just about "super-emitters"
  - Mid-sized source key and will become more important as mitigation efforts succeed



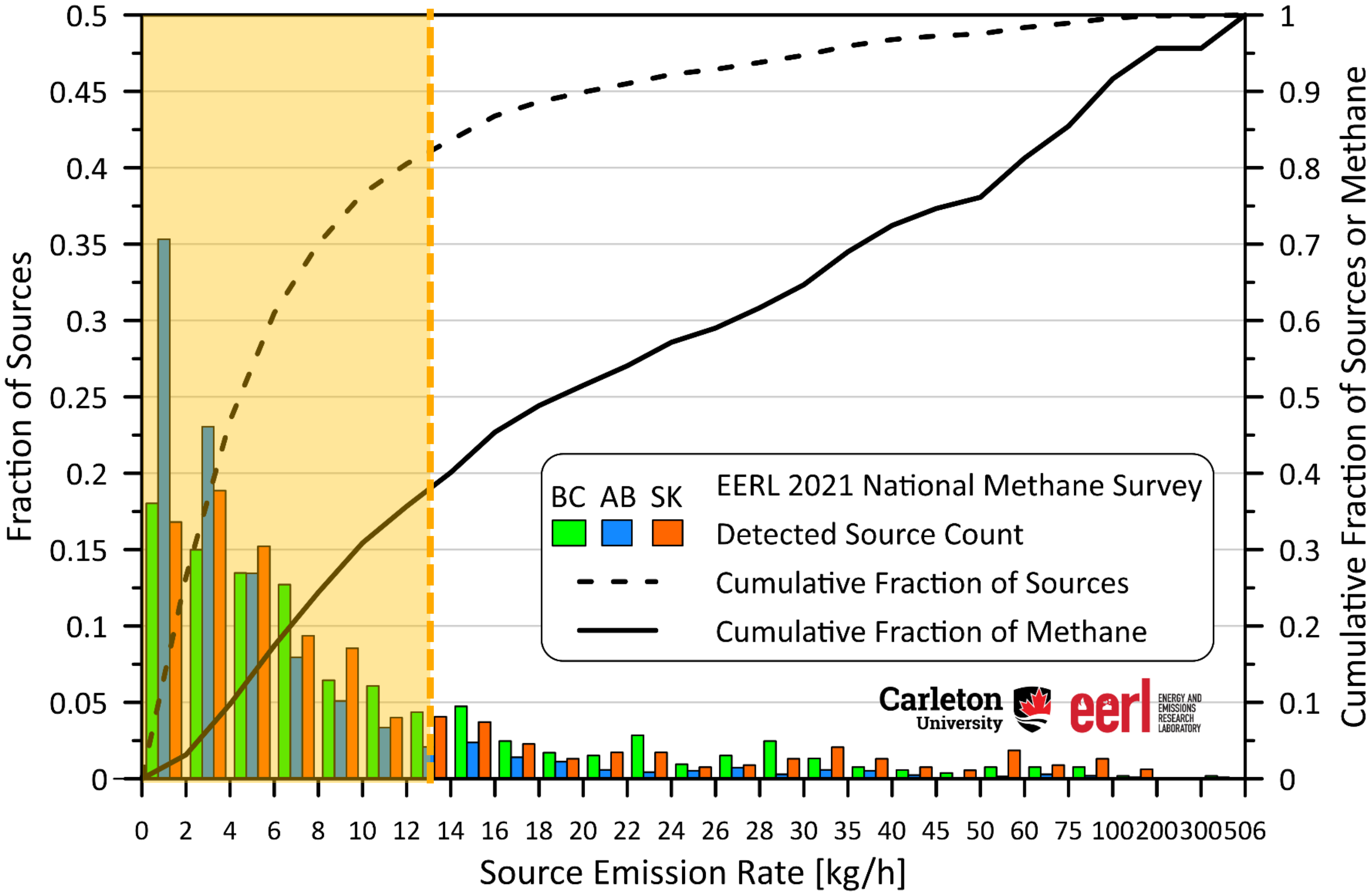
EERL 2021 National Survey: Distributions of Detected Sources

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



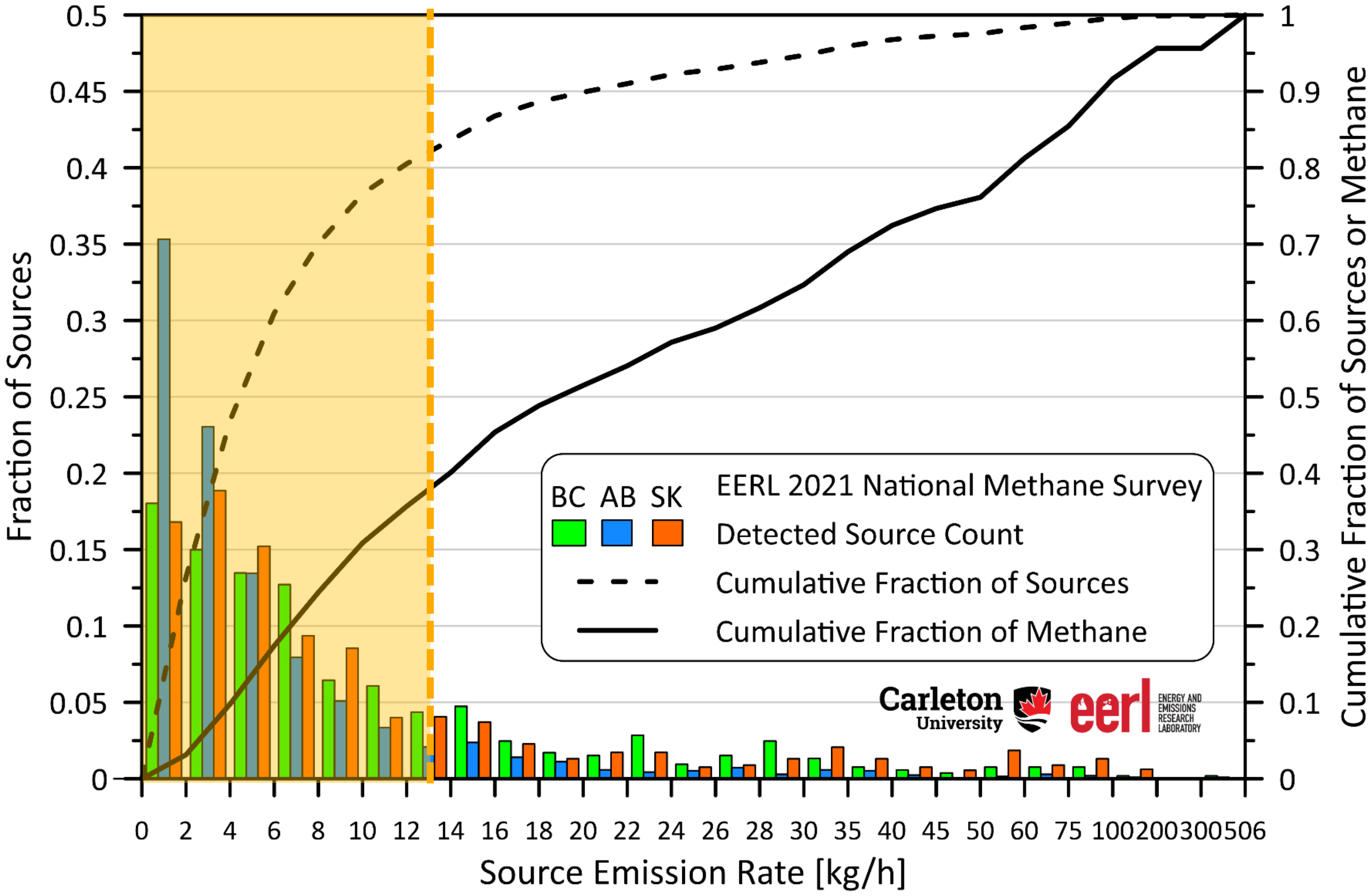
EERL 2021 National Survey: Distributions of Detected Sources

- Measured distributions represent ~80% of total methane *(shown later)*
- At 13 kg/h sensitivity can see:
  - ~18% of these sources / 62% of this methane
  - ~50% (0.62*0.8) of all methane



EERL 2021 National Survey: Distributions of Detected Sources

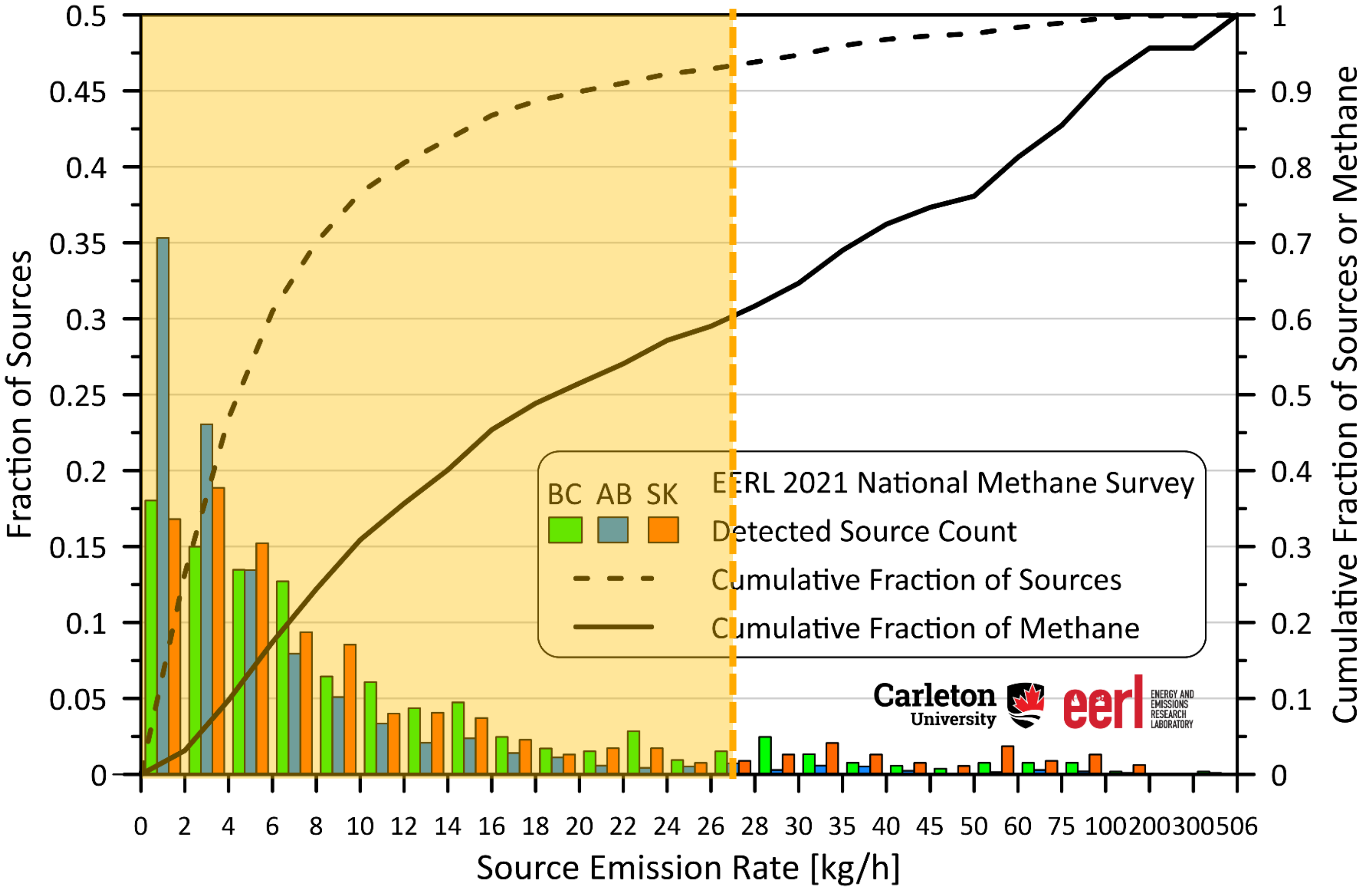
- Measured distributions represent ~80% of total methane *(shown later)*
- At 13 kg/h sensitivity can see:
  - ~18% of these sources / 62% of this methane
  - ~50% (0.62*0.8) of all methane
- At 27 kg/h sensitivity can see:



Carleton University eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

EERL 2021 National Survey: Distributions of Detected Sources

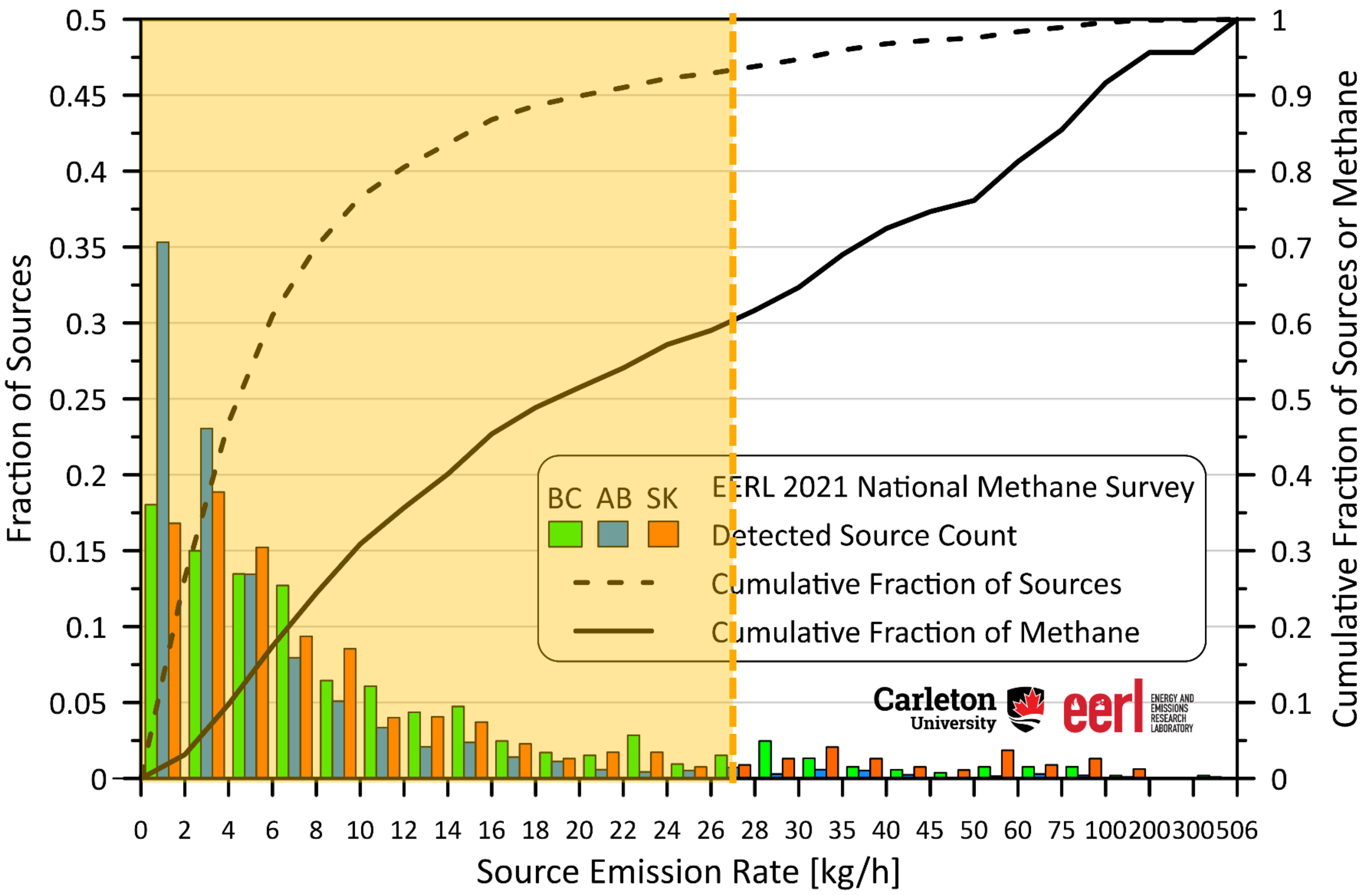
- Measured distributions represent ~80% of total methane *(shown later)*
- At 13 kg/h sensitivity can see:
  - ~18% of these sources / 62% of this methane
  - ~50% (0.62*0.8) of all methane
- At 27 kg/h sensitivity can see:
  - ~7% of these sources / 40% of this methane
  - ~32% (0.4*0.8) of all methane



Carleton University eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

EERL 2021 National Survey: Distributions of Detected Sources

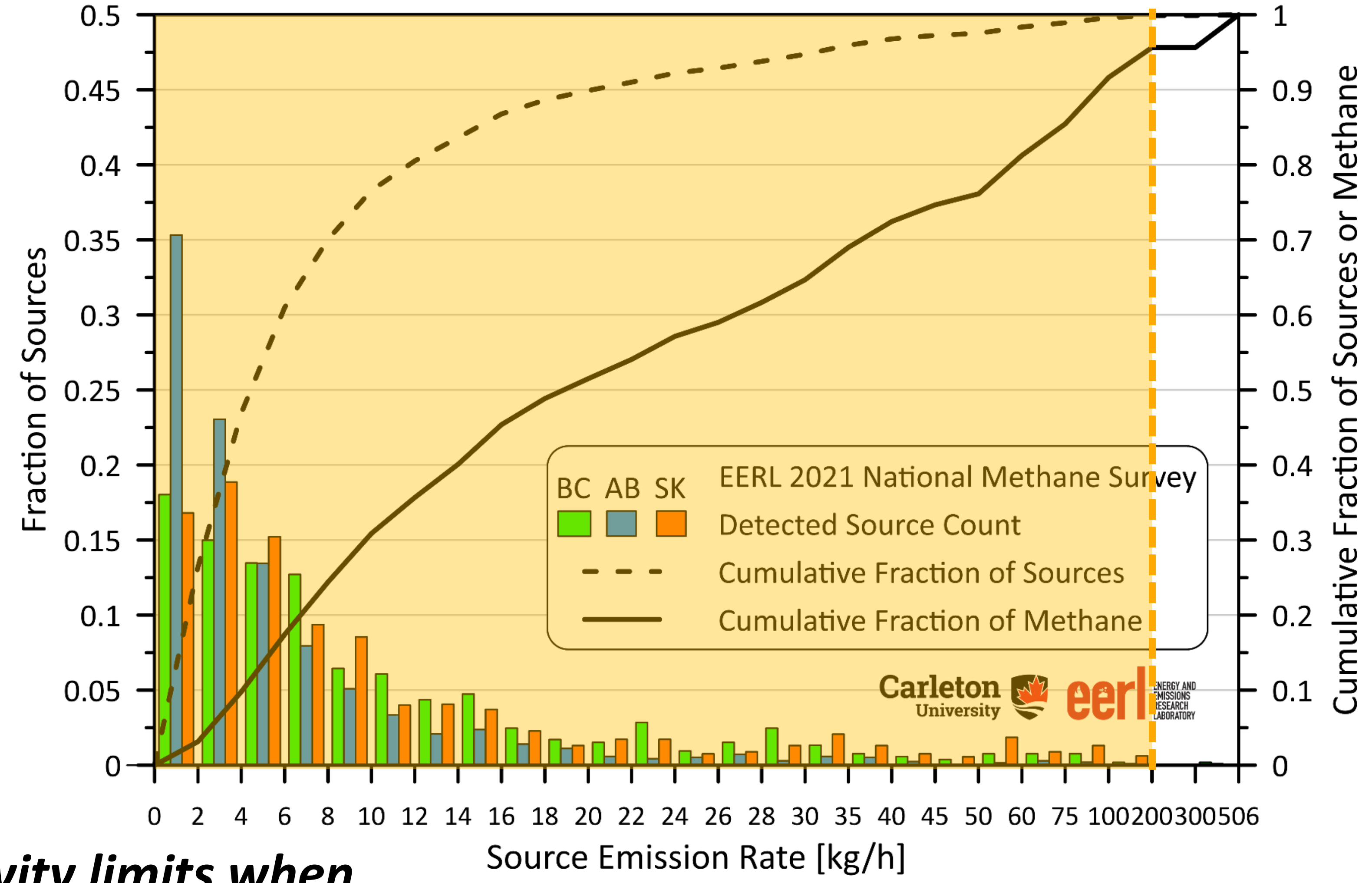
- Measured distributions represent ~80% of total methane *(shown later)*
- At 13 kg/h sensitivity can see:
  - ~18% of these sources / 62% of this methane
  - ~50% (0.62*0.8) of all methane
- At 27 kg/h sensitivity can see:
  - ~7% of these sources / 40% of this methane
  - ~32% (0.4*0.8) of all methane
- At 200 kg/h sensitivity can see:



Carleton University eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

EERL 2021 National Survey: Distributions of Detected Sources

- Measured distributions represent ~80% of total methane *(shown later)*
- At 13 kg/h sensitivity can see:
  - ~18% of these sources / 62% of this methane
  - ~50% (0.62*0.8) of all methane
- At 27 kg/h sensitivity can see:
  - ~7% of these sources / 40% of this methane
  - ~32% (0.4*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

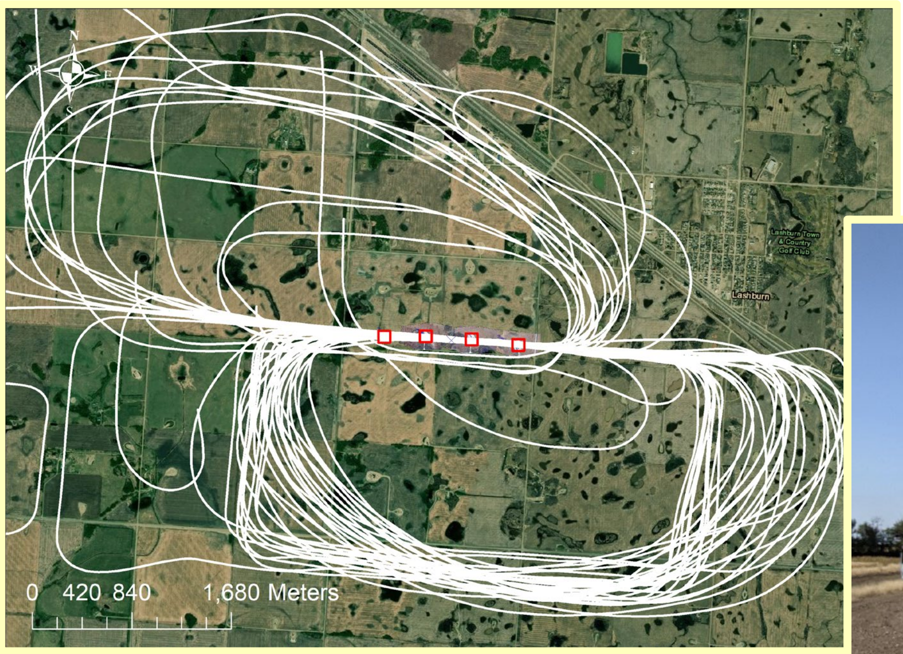


- ***Critical to understand sensitivity limits when incorporating measurements from different technologies***

Carleton University | eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

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

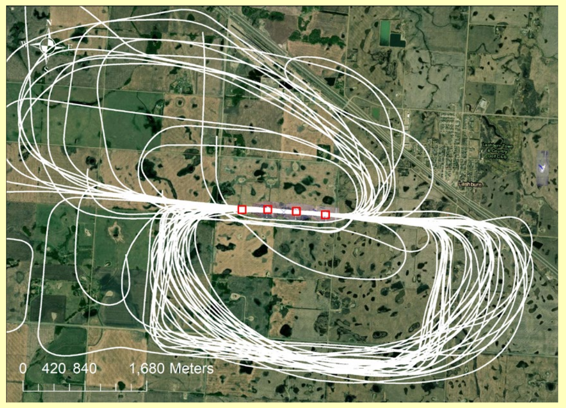


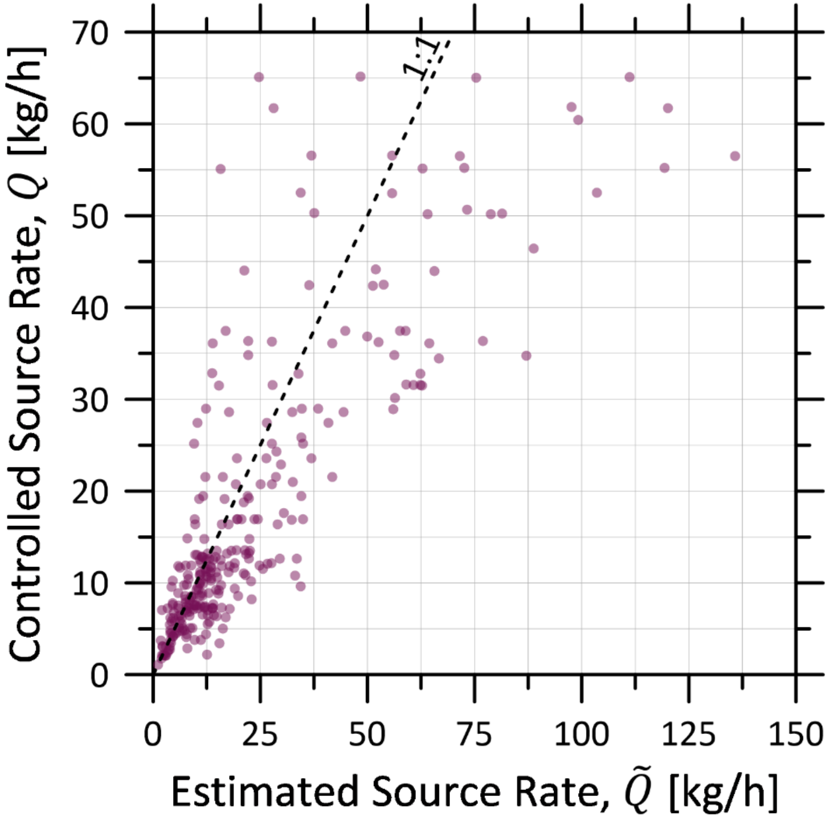
Carleton University

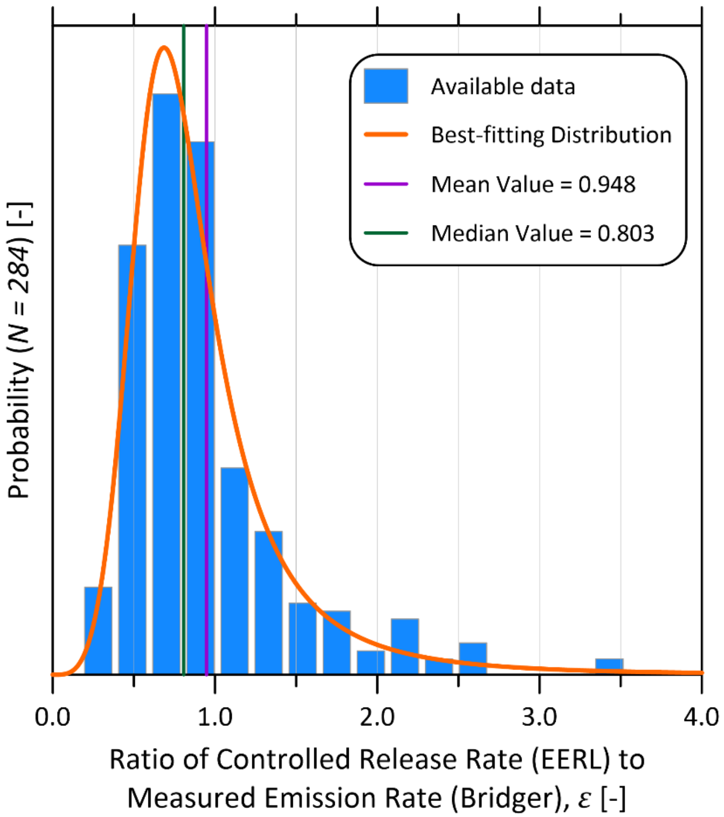
eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

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







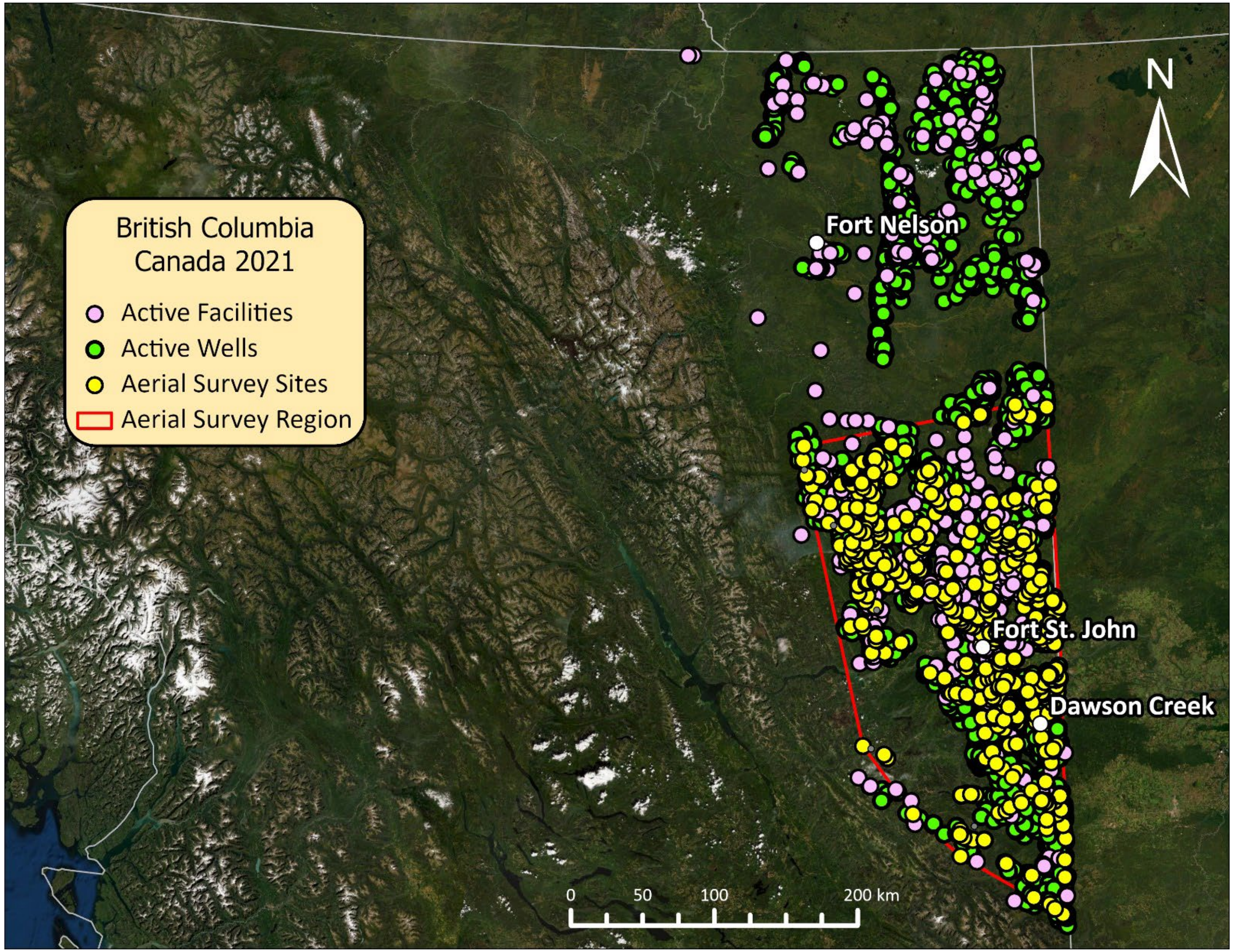
B.M. Conrad, D.R. Tyner, M.R. Johnson (2022) Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies, *Remote Sensing of Environment* (under review: preprint)

Carleton University | eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

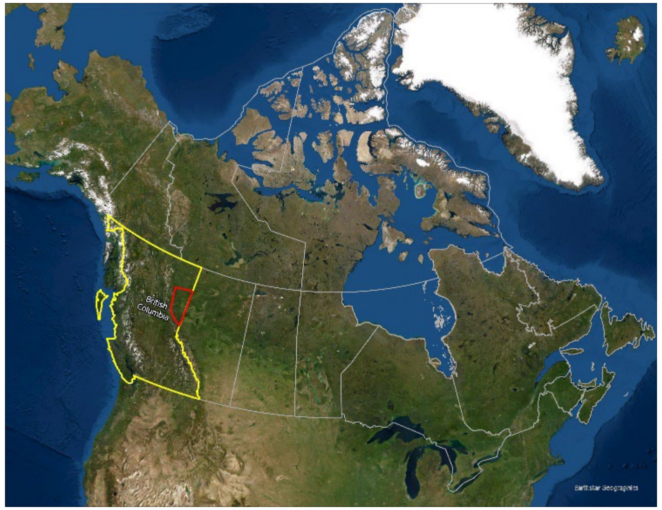
A Measurement-Based Methane Inventory for British Columbia (BC), Canada

- 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

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



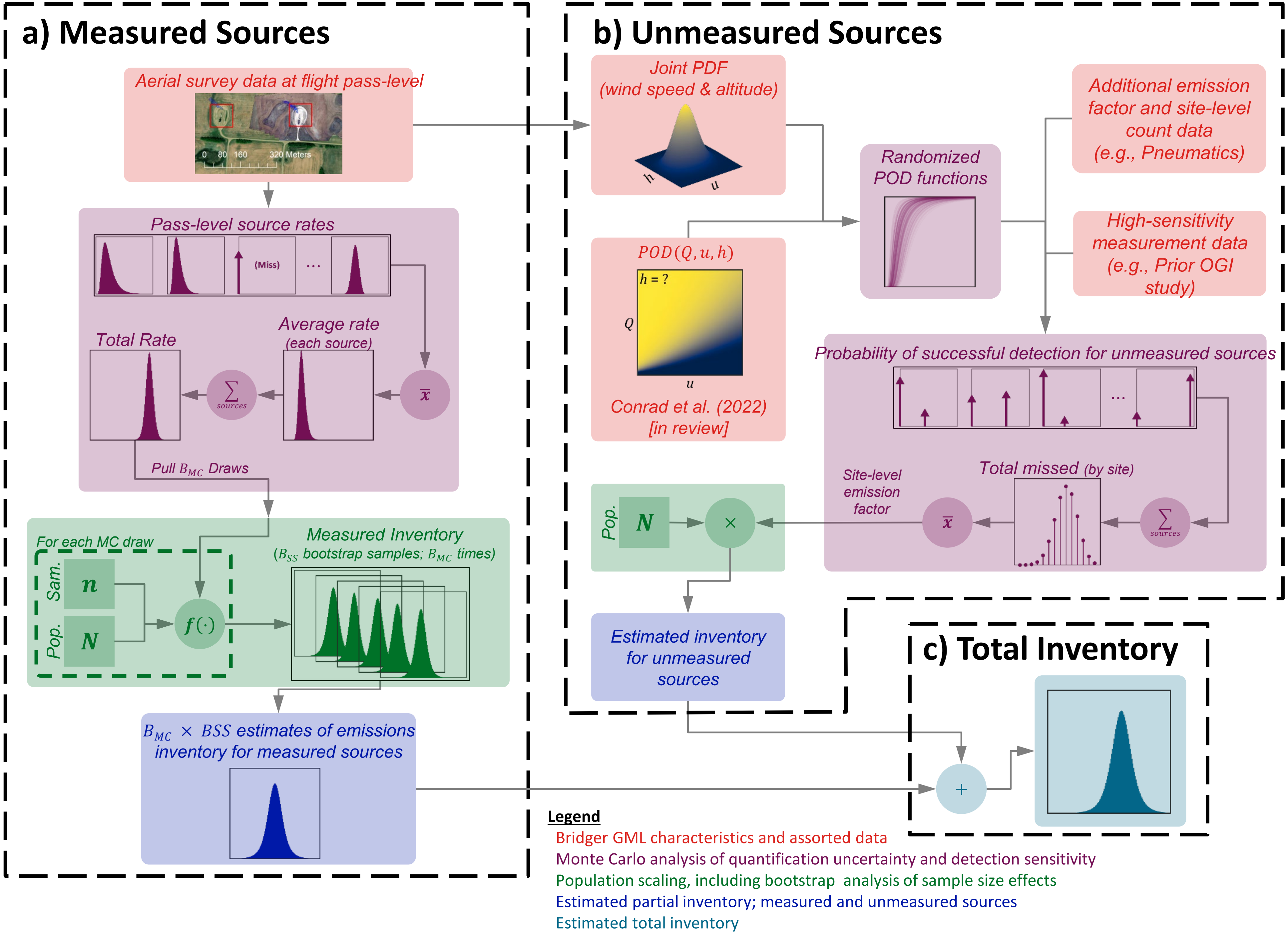
- Survey includes:
  - 59% of all active facilities
  - 8% of all active wells



Carleton University

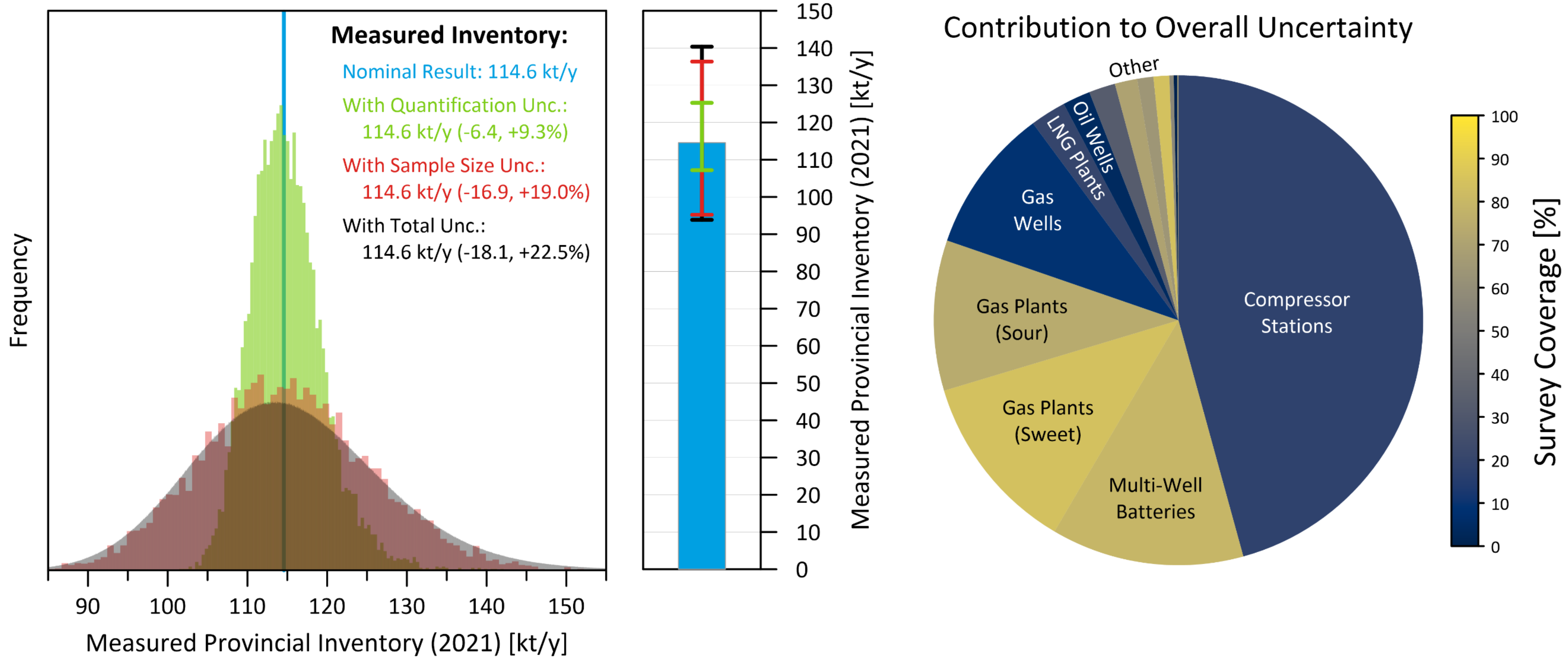
eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

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



Johnson et al., (2022) to be submitted

Quantification and Sample Size Uncertainties in *Measured* Inventory Sources

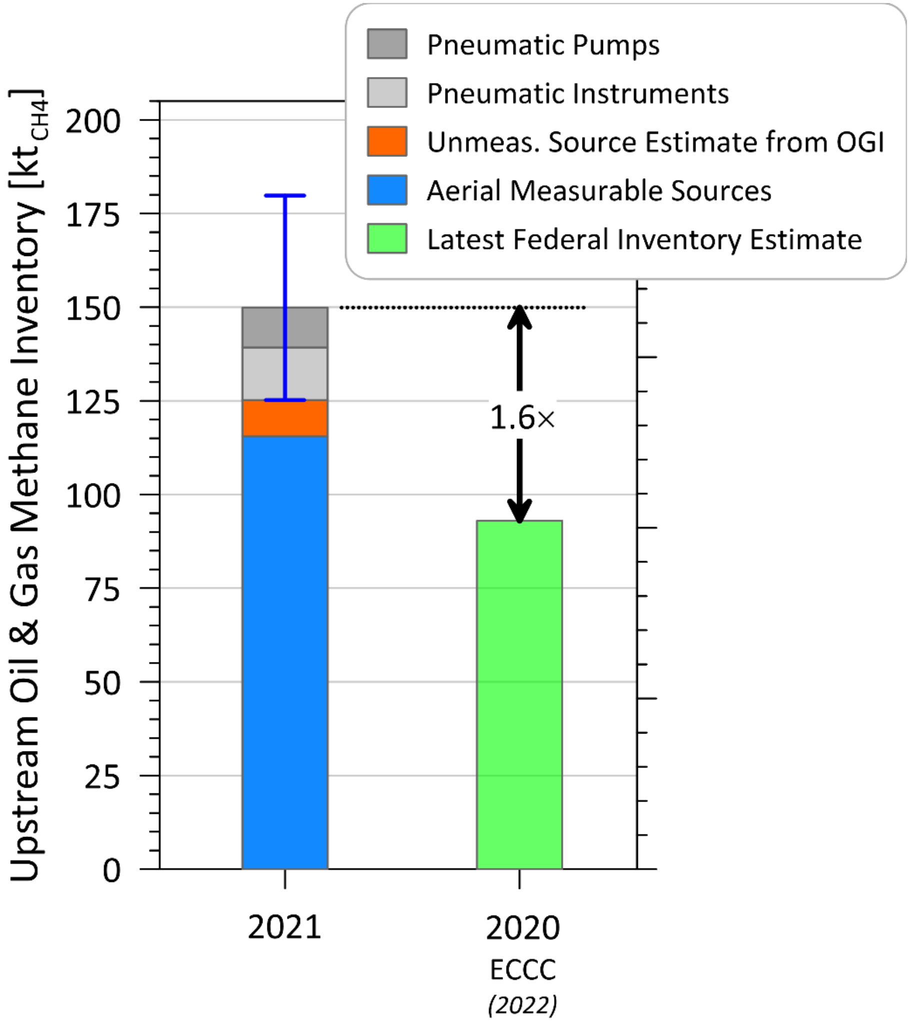


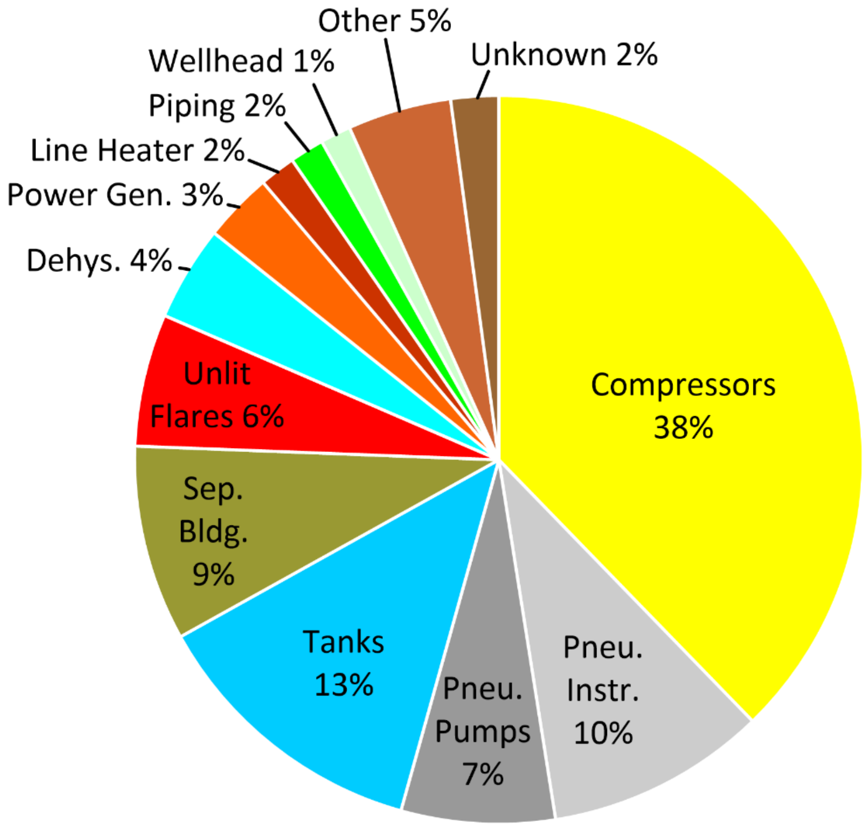
- Very powerful approach to quantify, analyze, and *minimize* uncertainty

Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

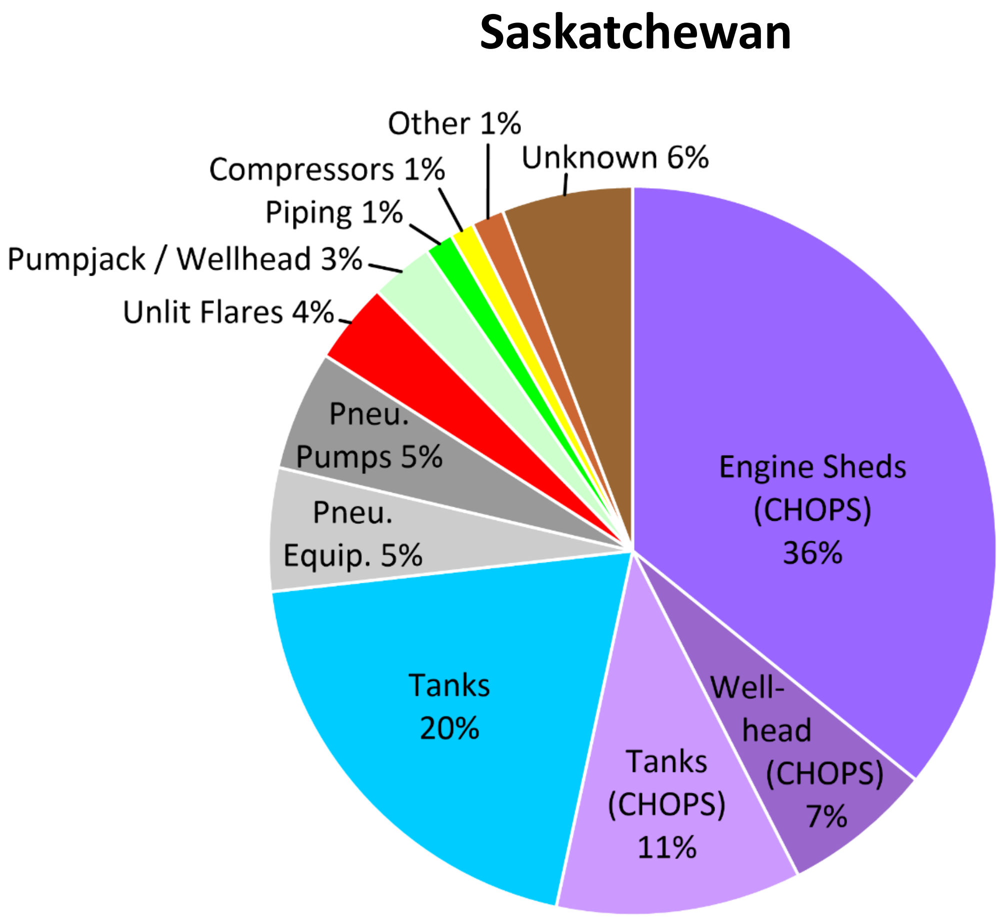
2021 Measurement-Based Methane Inventory for BC

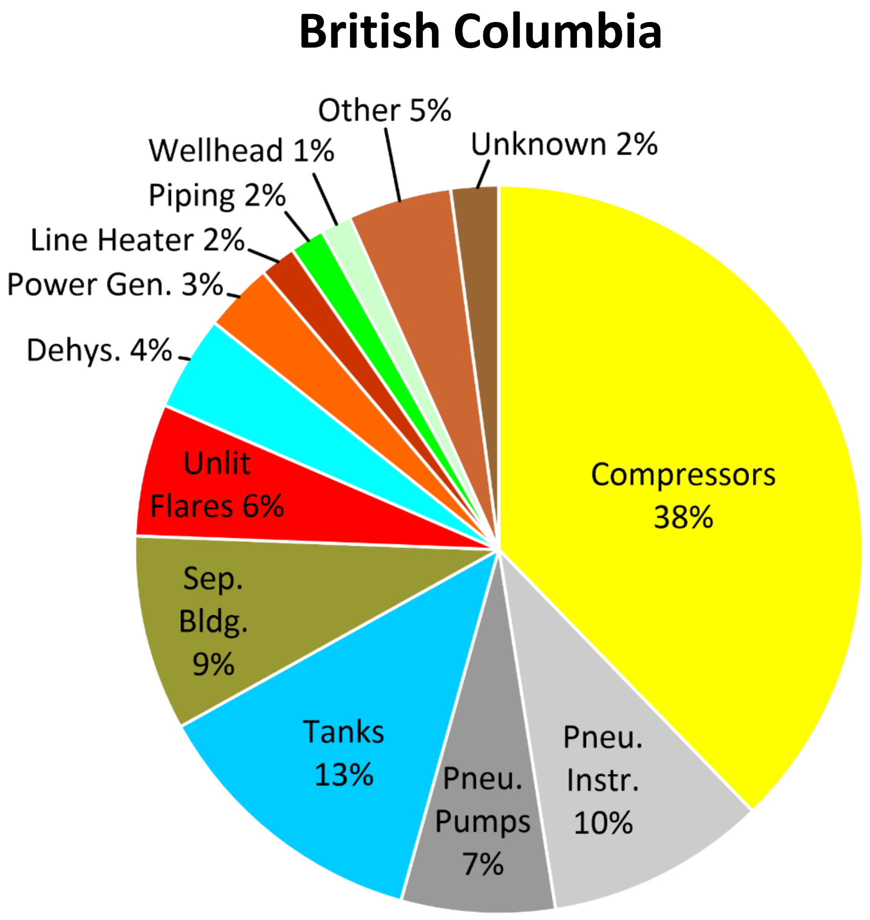




Carleton University
eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

Stark Differences in Sources Among Provinces

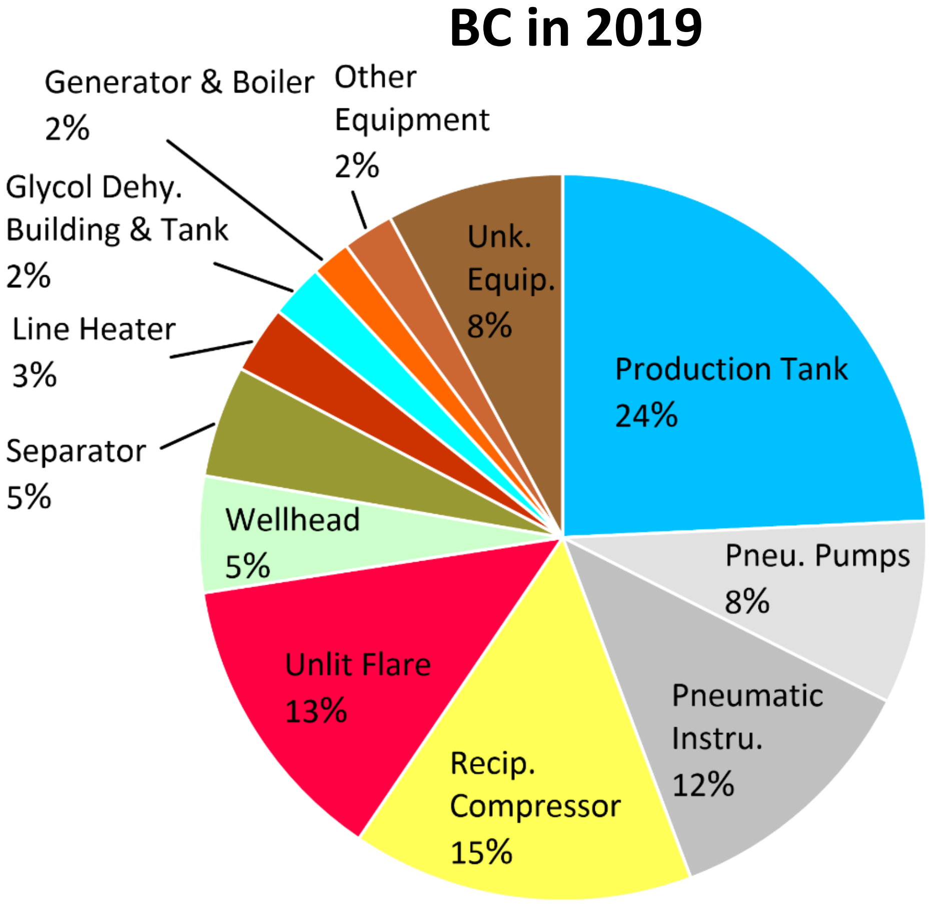


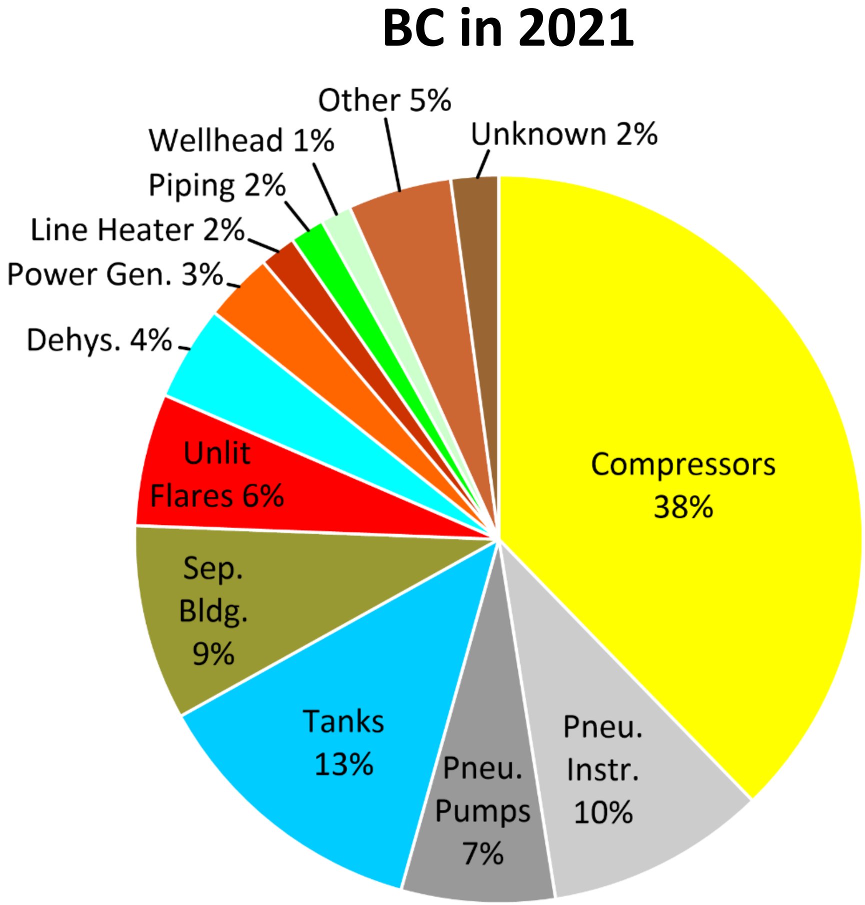


Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

Rapid Changes as Sources Evolve and Regulations Take Effect





Carleton University
eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

Conclusions

- Traditional bottom-up, emission factor based inventories face many challenges
  - Persistent underestimation
  - Rapid evolution of sources and source distributions as regulations take hold
- New aerial technologies are a revolution in possibilities, but:
  - Robust, independently-proven probabilistic sensitivity and uncertainty models are critical
  - Not all technologies are interchangeable and not all are sufficient for creating source- and site-resolved inventories
- Measurement-based methane inventories are possible *now* using careful application of statistical methods using current technologies
  - Province of BC Canada looking to transition to measurement-based inventories this year!

Acknowledgements

Natural Resources Canada | Ressources naturelles Canada

Canada

EDF ENVIRONMENTAL DEFENSE FUND™

BC OGRIS
BC Oil and Gas Research and Innovation Society

BC Oil & Gas COMMISSION

NSERC CRSNG

UN environment programme 50 1972-2022

BRIDGER PHOTONICS

GREENPATH ENERGY LTD

Environment and Climate Change Canada | Environnement et Changement climatique Canada

Carleton University

eerl ENERGY AND EMISSIONS RESEARCH LABORATORY

Website: https://carleton.ca/eerl
Email: Matthew.Johnson@carleton.ca

Selected References

- 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)
- 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)
- D.R. Tyner, M.R. Johnson (2021) **Where the Methane Is—Insights from Novel Airborne LiDAR Measurements Combined with Ground Survey Data**, *Environmental Science & Technology*, 55, 14, 9773–9783 (doi: 10.1021/acs.est.1c01572)
- 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*, Volume 259, 112418. (doi: 10.1016/j.rse.2021.112418)
- M.R. Johnson*, D.R. Tyner (2020) **A case study in competing methane regulations: Will Canada's and Alberta's contrasting regulations achieve equivalent reductions?** *Elementa: Science of the Anthropocene*, 8(1), p.7. (doi: 10.1525/elementa.403)
- 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)
- T.A. Fox, A.P. Ravikumar, C.H. Hugenholtz, D. Zimmerle, T.E. Barchyn, M.R. Johnson, D. Lyon, T. Taylor (2019) **A methane emissions reduction equivalence framework for alternative leak detection and repair programs**, *Elementa*, 7(1), p.30 (doi: 10.1525/elementa.369)
- C.A. Brereton, L.J. Campbell, M.R. Johnson* (2019) **Computationally Efficient Quantification of Unknown Fugitive Emissions Sources**, *Atmospheric Environment*, 3(100035):1-13 (doi: 10.1016/j.aeaoa.2019.100035)
- D.R. Tyner, M.R. Johnson* (2018), **A Techno-Economic Analysis of Methane Mitigation Potential from Reported Venting at Oil Production Sites in Alberta**, *Environmental Science & Technology*, 52(21):12877-12885 (doi: 10.1021/acs.est.8b01345)