

Preprints are preliminary reports that have not undergone peer review. They should not be considered conclusive, used to inform clinical practice, or referenced by the media as validated information.

Creating Measurement-Based Oil and Gas Sector Methane Inventories using Source-Resolved Aerial Surveys

Matthew Johnson (Matthew.Johnson@carleton.ca)

Carleton University https://orcid.org/0000-0002-3637-9919

Bradley Conrad

Carleton University https://orcid.org/0000-0003-3678-7434

David Tyner

Carleton University https://orcid.org/0000-0002-6500-9888

Article

Keywords: Methane, oil and gas, inventory, uncertainty, source distribution, probability of detection, compressors, tanks, unlit flares, venting, aerial measurements, combustion slip, controlled tanks, uncontrolled tanks, optical gas imaging

Posted Date: December 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2203868/v1

License: (a) This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Version of Record: A version of this preprint was published at Communications Earth & Environment on April 25th, 2023. See the published version at https://doi.org/10.1038/s43247-023-00769-7.

Abstract

We present a new framework for incorporating aerial measurements into comprehensive oil and gas sector methane inventories that achieves robust, independent quantification of measurement and sample size uncertainties, while providing timely source-level insights beyond what is possible in current official inventories. This "hybrid" inventory combines top-down, multi-pass aerial measurements with bottom-up estimates of unmeasured sources leveraging continuous probability of detection and quantification models for a chosen aerial technology. Notably, the combined Monte Carlo and "mirror-match" bootstrapping technique explicitly considers skewed source distributions and finite facility populations that have not been previously addressed. The protocol is demonstrated to produce a comprehensive upstream oil and gas sector methane inventory for British Columbia, Canada, which while approximately 1.7 times higher than the most recent official bottom-up inventory, reveals a lower methane intensity of produced natural gas (< 0.5%) than comparable estimates for several other regions. Finally, the developed method and data are used to upper bound the potential influence of source variability/intermittency on the overall inventory, directly addressing an open question in the literature. Results demonstrate that even for an extreme case, variability/intermittency effects can be addressed by sample size and survey design and have a minor impact on overall inventory uncertainty.

Introduction

Rapid reduction of oil and gas sector methane emissions is an essential part of international efforts to slow global temperature rise^{1,2}. However, mitigation efforts and associated regulations have been hampered by poor understanding of true levels of methane emissions and the underlying distribution of sources. Studies in multiple jurisdictions have repeatedly found significant underestimation of methane emissions in official inventories using a range of approaches^{3–10}. While proposed reasons for these discrepancies include the failure of bottom-up emission factor calculations to account for strongly skewed source distributions and "super-emitters"^{8, 11–15}, the limited data sets behind bottom-up emission factors and associated measurement uncertainties in creating these emission factors^{4,5, 16–18}, and potential for episodic emissions – specifically manual liquid unloadings – to skew measurements¹⁹, the root of the challenge is the lack of direct measurement data in current inventories. Moreover, missing in the discussion is how quickly inventories can be expected to evolve and how quickly they will need to evolve if we are to accurately track progress toward reduction targets. Most critically, the expectation for rapid methane reductions and need to monitor and verify the extent of these reductions requires incorporation of direct, real-time measurement data in inventories.

Indeed the U.S. National Academies have concluded that "(i)mprovements in the accuracy and precision of methane emission estimates will be maximized through the use of both top-down and bottom-up measurements"²⁰ and recently launched a fast-track study to develop a framework for evaluating emissions inventories and information²¹. In parallel, the Intergovernmental Panel on Climate Change (IPCC) Task Force on National Greenhouse Gas Inventories (TFI) – which publishes the international

guidelines for emissions reporting under the United National Framework Convention on Climate Change (UNFCCC) – has initiated meetings on the "Use of Atmospheric Observations Data in Emissions Inventories"²². Notably, although the existing IPCC methodology includes text allowing for the use of measurements in official inventories^{23,24}, current Tier 3 protocols (the most accurate recommended approach) are still solely based on bottom-up activity and emission factor calculations. As also noted by Rutherford et al.¹⁶, a key challenge in incorporating measured data into inventories is the need to preserve the source-level resolution of current bottom-up methodologies, which are critical for guiding regulations and to a lesser extent to meeting IPCC reporting requirements. Recently, Tyner and Johnson⁵ demonstrated the potential to combine aerial LiDAR measurements with ground-based survey data to create a source-resolved, "hybrid" top-down/bottom-up measurement-based methane inventory for the upstream oil and gas sector in British Columbia, Canada. This study significantly extends this work to develop and demonstrate a formal protocol that explicitly considers sample-size uncertainties and finite population effects within the context of highly skewed source distributions, while simultaneously accounting for aerial measurement uncertainties and probabilistic detection sensitivities.

The goals of this study are: (i) to develop a protocol to create a "hybrid" measurement-based oil and gas sector methane inventory combining comprehensive source-resolved aerial survey data with bottom-up inputs and prior ground-based study data; (ii) to develop and describe a robust method to calculate uncertainties in the measured component of the inventory that, to the authors' knowledge, is the first to explicitly consider both sample size and finite population effects as well as aerial measurement uncertainties and condition-dependent detection sensitivities; (iii) to demonstrate this approach by creating a source-resolved measurement-based methane inventory for the British Columbia (BC) upstream oil and gas sector sufficient for use in IPCC reporting; and (iv) to analyze potential influence of source variability in future studies following the presented inventory protocol. The developed approach is readily extensible to other jurisdictions and demonstrates how source- or site-resolved measurement data obtained using a range of technologies could be directly included in inventories so long as quantified measurement uncertainty and probabilistic detection sensitivity data for that technology are available.

Results

Figure 1 outlines the developed protocol for creating a measurement-based inventory from source- or siteresolved measurement data. For the ideal scenario of a comprehensive measurement survey using a perfectly accurate and infinitely sensitive instrument, all sources would be captured such that the emissions inventory would be the sum of all directly measured emissions. In practice however, the finite detection sensitivity of methane-sensing instrumentation necessitates a piecewise approach considering two nonoverlapping subsets – measured/measurable and unmeasured/unmeasurable sources – that sum to the whole. *Measured* sources are those that were detected and quantified at the surveyed sites as well as sources that would be detected/quantified at sites not included in the survey sample. By contrast, *unmeasured* sources are those that were not successfully detected during the survey and those that would not be detected/quantified at sites not included in the sample.

Importantly, the diverse facility types within the upstream oil and gas sector (e.g., isolated wells, multi-well batteries, compressor stations, gas plants, etc.) are treated as separate strata within the overall sample; Fig. 1 is thus separately applied in parallel to each stratum as defined in Table S1 of the Supplemental Information (SI) for the demonstration inventory in BC along with associated sample and population sizes for each. Aggregation of like entities into homogeneous strata tends to reduce the variance of desired statistics, improving the precision in each stratum's calculated mean emission rate (i.e., emission factor) and total emissions (i.e., emissions inventory). This approach can also permit stratum-dependent methodologies leveraging prior information about the strata – e.g., pneumatic equipment at gas plants in BC are almost exclusively air-driven and may be ignored in the methane inventory. Finally, this approach provides the *relative* contribution of each stratum to the whole, which is important data for regulation and mitigation. While the present demonstration of this approach uses aerial measurement data collected using Bridger Photonics Gas Mapping LiDAR (GML), the protocol is generally applicable to any technology with well-characterized probabilities of detection (POD) and quantification uncertainties²⁵ and sufficient spatial resolution to resolve individual facilities.

Protocol for Quantifying Measured Sources and Uncertainties

As outlined in Fig. 1a and more fully detailed in the SI, the measured source inventory calculation takes pass-by-pass aerial measurement data from surveyed sites, introduces known measurement uncertainties and detection sensitivities²⁵ via Monte Carlo and Bayesian analysis, and scales via bootstrapping to consider sites not included in the sample. This approach solves three key challenges. First, the joint Monte Carlo and Bayesian approach (see Section S2.1) provides a formal framework for objectively considering any "missed" detections of a source seen in one or more other passes of the aircraft, noting that this could be due to both variability/intermittency of the source and/or the finite detection sensitivity of GML. Notably, this approach allows explicit consideration of the condition-specific probability of detection during each measurement pass along with available information about a source from all passes where it had a potential to be measured. Second, the Monte Carlo analysis robustly considers the source quantification uncertainty during each pass, leveraging detailed uncertainty models for the aerial technology²⁵, permitting direct analysis of measurement uncertainties at the source, site, and inventory level. Third, the mirror-match bootstrapping technique^{26,27} enables robust scaling of emissions in each sample stratum to the population in a way that considers the actual distribution of emissions at sites in the stratum (which are generally non-smooth and highly skewed) as well as finite population effects (which are critically important since the *population* of facilities and wells in each stratum is finite, and the size of the sample can be large relative to the population, see Table S1 of the SI). Stated in terms of a specific example, it would not be reasonable to consider methane emissions at a gas plant as indicative of emissions at a well site when developing an inventory, which shows the importance

of stratified sampling. Even at the source level, where both types of sites may have some similar equipment, it is also unlikely these would be from equivalent populations given expected differences in controls, sizing, and throughput. Conversely, within any region of interest such as the province of BC, the total population of gas plants is finite (60 active facilities in 2021) and "standard" statistics based on assumed (non-Gaussian) distributions for an infinite population are not accurate or relevant. Notably, the implemented mirror-match bootstrapping approach overcomes these challenges to permit independent and robust analysis of sample size uncertainties for each stratum and for the total inventory.

Figure 2 illustrates the power of this approach in producing a measured-source methane inventory using the present analysis of BC, Canada as an example. The total measured inventory of 112.2 kt/yr is computed by summing the measured inventory for each unique strata over $B_{MC} = 10^4$ times $B_{BS} = 10^4$ estimates, and reveals overall uncertainties of – 18% to + 21% at 95% confidence. Interestingly, despite the relatively large sample sizes (see Table S1), the combined uncertainties are still dominated by sample size effects. A key innovation of this approach is a robust framework for considering sample size requirements in future inventory studies and regulated monitoring, reporting, and verification (MRV) efforts.

Figure 2b demonstrates how the method can also be used to calculate separate inventory uncertainties for different facility types (strata) and their relative contributions to the overall uncertainty of the measured portion of the inventory. The bars of Fig. 2b are shaded by the percentage of each stratum's population included in the sample, which highlights important effects that may not be automatically anticipated. For example, while the relatively large uncertainty contribution of compressor stations might be expected from the comparatively low sample coverage of 18% for that stratum, the large uncertainty for gas plants relative to its magnitude is potentially unexpected, especially the large sample size uncertainty given the 77% sample coverage. This can ultimately be explained by the strongly skewed distribution of sources at gas plants, where parallel root cause analysis²⁸ has shown that emissions tend to be driven by controlled tank sources that generally do not emit but can emit large volumes when they do. Conversely, uncertainties at off-site gas wells are nearly equally affected by quantification uncertainty and sample size uncertainty despite lower sample coverage (9%) implying less internal variability within the off-site gas well stratum. Most importantly, the results of Fig. 2b demonstrate how the presented protocol yields useful data to optimize the design of future measurement campaigns to maximize precision and minimize sampling effort. It should also be noted that any temporal variability among sites in each stratum, in addition to being empirically considered through measurement flights over separate days each with potentially multiple passes, should manifest as increased variability in emissions among sites in the sample and thus is also inherently captured in the uncertainty analysis. This is further analyzed in the Discussion below.

Protocol for Estimating Unmeasured Sources

The preceding measured source protocol quantifies the contribution of all sources that are detected and quantified during *at least one* flight pass. However, due to source intermittency and the probabilistic and

finite sensitivity of aerial methane-detection technologies, some quantity of sources may not be detected during *any* flight pass of the survey. Depending on the sensitivity of the employed aerial technology and the jurisdiction's underlying source distribution, these *unmeasured* sources may be significant and must be considered during inventory development. Referring to Fig. 1b, this is possible via a parallel Monte Carlo simulation considering site/condition-specific POD²⁵ using "bottom-up" equipment count and measurement data from prior studies (e.g., refs 29–33) as inputs. This new "unmeasured source" protocol allows robust derivation of stratum-dependent, average, emission factors for unmeasured sources on a per-site basis.

Briefly, for an aerial survey of N unique flight passes over a source, where each pass has a unique POD that depends on the conditions (e.g., wind and altitude) and source rate at the time of the pass, the source is *unmeasured* if it is probabilistically missed during all N passes. This problem is ideally suited to Monte Carlo analysis as shown in Fig. 1b and more fully detailed in S2.2 of the SI. Inputs (shown in red) include the actual empirical distribution of the number of flight passes over a source and the distributions of wind speeds and altitudes from each pass of the survey; continuous POD data from the aerial technology²⁵; and relevant bottom-up data from the literature for the distribution of potential sources near and below the aerial technology's sensitivity limit. These bottom-up feedstock data may include measurement data from surveys using more-sensitive technologies and/or the combination of counts and typical (manufacturer-rated) emissions of underlying equipment, similar to those used to derive the emission factors underpinning traditional bottom-up inventories.

For the presently derived inventory for BC in 2021, supplemental feedstock data were sourced from a ground survey of 149 unique sites (including 62 facilities and 205 wells) in BC performed in 2018³². This data set includes 1) estimated emission rates from non-pneumatic equipment detected by optical gas imaging and measured where possible using Hi-Flow sampling, 2) counts and identification (manufacturer and model) of pneumatic equipment, and 3) estimated vent rates for identified pneumatics based on prior field measurements and manufacturer data. More generally, in the absence of region-specific feedstock data, other general data sets (such as refs. 29–31, 33–37) may be used as in the work of Rutherford¹⁶. The Monte Carlo analysis then outputs final average site-level emission factors which are applied to the stratum's population to yield the unmeasured inventory for the stratum, optionally parsed by non-pneumatics (orange, see section S2.2.1 of the SI) and pneumatic instrument/pumps (gray, see section S2.2.2 of the SI). Detailed results of the unmeasured source analysis for BC are included in the SI.

Discussion

Upstream Oil and Gas Methane Inventory for British Columbia in 2021

Figure 3 plots the measured and unmeasured components of the presently derived 2021 methane inventory for BC and compares with the official 2020 (most recent available) federal inventory estimate from Environment and Climate Change Canada (ECCC)³⁸. For 2021, total estimated upstream oil and gas sector methane emissions are 144.6 kt/yr, of which 78% is from measured/measurable sources and 22% is from unmeasured "bottom-up" sources. This high proportion of measured sources reflects the low detection sensitivities of the employed aerial measurement technology and adds confidence in the total estimate. While the developed hybrid inventory protocol could be applied to any technology with well-quantified POD and uncertainty models, there is an obvious advantage in choosing technologies with better detection and quantification thresholds such that a higher portion of total sources are directly measured.

The plotted 95% confidence interval indicates the total quantified uncertainty in the measured sources from Fig. 2, noting that it is not possible to create a similarly robust estimate of the uncertainty in the bottom-estimate of unmeasured sources derived using existing data. However, because the official bottom-up ECCC inventory leverages these same count and field data, any bias or uncertainty in these bottom-up sources should be equivalent such that the two inventories are directly comparable considering the error bars as indicated. The nominal factor of 1.7 times higher methane emissions (range of 1.5–2.0 times) seen in the newly derived measurement-based inventory is consistent with a broad range of previous studies throughout North America^{4–10, 18}. This underscores the importance of incorporating direct measurements into official estimates to accurately track and reduce oil and gas sector methane emissions. The present 2021 calculation is also consistent with the authors' previous estimate of 162.6 kt/yr for BC in 2019⁵. Although this implies a nominal decrease in emissions of 11% since 2019 consistent with the introduction of new methane regulations in January 2020³⁹, it should be noted that the previous sample size was three times smaller and the difference is well within the error bars of the present calculation.

Referring to SI, Section S3, methane intensities ("leakage rates") of marketed natural gas were calculated by attributing quantified methane emissions on a produced energy basis consistent with the Natural Gas Sustainability Initiative protocol⁴⁰ and Schneising et al.⁴¹. Considering first sources captured in the present upstream methane inventory, the upstream methane intensity of BC natural gas was 0.38% (95% confidence interval (CI): 0.33–0.45%). Adding in 14.4 kt of methane from downstream sources (i.e., distribution, transmission & storage, refining, see Table S8) as inventoried by ECCC³⁸, suggests total oil and gas sector methane emissions of 159.0 kt of which 143.7 kt are attributable to natural gas production. This results in an overall natural gas methane intensity of 0.42% (95% CI: 0.37–0.48%), which is lower than a 2019 Western Canadian average of 0.63–1.11% and a 2019 U.S. average of 1.08–1.51% derived from satellite measurements¹⁰, a 2015 U.S. range of 1.45–1.94% derived from Alvarez et al.⁸, and 2018/2019 ranges of 0.55–5.59% for five different U.S. basins from Schneising et al.⁴¹ (note all ranges have been recalculated using a consistent set of assumptions as detailed in SI Section S3). This comparatively low intensity is presumably indicative of 2020 regulations in BC which include mandatory three times per year leak detection and repair (LDAR) surveys at most facilities as well as an impending

(January 2023) limit on total site-level tank emissions³⁹. Recent ground-based root-cause analysis of aerially detected emissions also notes that as much as a quarter of natural gas compressors at upstream facilities are electric-drive in BC²⁸. Conversely, these same ground data show that there remains significant mitigation potential suggesting a plausible pathway for further reductions necessary to reach the federal 75% reduction targets⁴² through the Global Methane Pledge² as well as international 0.2 – 0.25% intensity targets^{43,44}.

Beyond having potential to track and verify necessary reductions much faster than it would be possible to update bottom-up inventories and associated emission factors, the present measurement-based inventory protocol can also provide source-level breakdowns critical to the ongoing regulatory efforts (e.g., refs. 45, 46) intended to meet these goals. This is illustrated in Fig. 4, which compares source breakdowns in the presently derived inventory with those in the latest official federal inventory³⁸. Noting that the colours are matched for equivalent sources, there are several stark differences beyond the factor 1.7 difference in total magnitude. Notwithstanding the generic categories of venting and leaks in the official inventory that are traced to industry reported volumes and not attributed to specific sources, emissions from tanks, dehydrators, and separators are notably underrepresented in the official inventory. Similarly, unlit flares – a prominent source in several recent studies^{5,28,47,48} – do not appear as a source category despite constituting 6% of total methane emissions in the measurement-based inventory. If compressor seal emissions, start gas, and a generic estimate for methane from fuel combustion in the official inventory are combined to compare with the compressor category from the present survey, their proportional total notably exceeds the present measurement. However, this surely overestimates the importance of compressor seal emissions given results of parallel ground inspections suggesting these are likely at most one-third of the present attribution to compressors²⁸, or no more than 13% of the total inventory. More importantly, Fig. 4 highlights the value of measured data in permitting effective regulatory and mitigation actions that efficiently target the sources that matter most. Conversely, this result also reveals the associated risks in relying on regulations that are based on incorrectly assumed source distributions to achieve necessary reduction targets.

Bounding the Potential Effects of Source Intermittency on Inventory Uncertainty

A potential limitation of any measurement study taken over a short window in time, is the effect of source variability and intermittency on the calculated inventory. Certainly, if the overall emission processes are ergodic, such that the ensemble average of random samples during a measurement campaign are equal to the time-average total, then the challenge is simply one of sample size. However, this has not been possible to directly test and to the authors' knowledge, remains an open question in the literature. The present inventory protocol and uncertainty analysis procedures provide a framework to put an upper bound on the potential influence of source variability/intermittency on the measured inventory.

During the present aerial survey, all sites with detected sources were re-flown at least once, 1–10 days after the initial flight, where each flight contained up to 5 passes over each source. The raw variation in the estimated source rates for each pass on each day (including estimates of zero when a source was within the measurement swath but not detected) is a convolution of measurement uncertainty, probabilistic detection sensitivity, and source variability/intermittency. However, if the former two contributions are purposely neglected, then the observed variation can be used as a conservative overestimate of the source variability/intermittency. Building on this concept, a bootstrapping analysis was designed in which the actual measured emission rates from each pass of each source were substituted with a random sample (with replacement) from all relevant passes (including zeroes) for that source. In other words, the entire inventory analysis was repeated multiple times as the individual passby-pass measurements for all sources were randomly varied in an intentional overestimate of possible source variability based on the raw data. The rest of the analysis then proceeded as in Fig. 1a, adding in measurement uncertainties for each randomly drawn pass value and guantifying sample size uncertainties for each stratum on route to constructing an overall inventory. The additional uncertainty contribution from this intentional overestimate of source variability/intermittency could then be compared to the individual component and overall uncertainties.

As shown in Fig. 5, even grossly overestimating the variability and intermittency of sources using the pass-by-pass empirical data has a negligible effect on the measured source inventory. Although the mean measured source total increases slightly to 114.9 kt/y in this scenario from 112.2 kt/y, the 95% confidence limits are effectively unchanged (91.7–135.9 kt/y vs. 91.9–142.6 kt/y). Closer inspection of the results reveals that the uncertainty contribution of source variability/intermittency is within the range attributable to quantification error. This illustrates how a protocol combining multi-pass measurements over separate days inherently addresses source variability within this timescale across a large sample.

However, there is still a possibility of temporal variation at time scales not captured by the survey. This may include seasonal variations in emissions (e.g., driven by increased use of methanol injection pumps and catalytic heaters in colder months) or diurnal variations driven by servicing activities limited to workday hours (e.g., due to manual liquid unloadings as specifically suggested from measurements and analysis for the Fayetteville shale region of Arkansas^{19,49}). Seasonal variations might ideally be addressed by conducting regular measurement surveys at different times of the year but could also easily be bounded given the likely small contribution of seasonally varying sources within the total inventory (Fig. 4). For the present inventory specifically, aerial measurements were performed during the "shoulder" season of September to October, such that the portion of non-operating and operating methane pumps and heaters may to first approximation be representative of broader operations during the year.

While manual liquid unloadings vented to atmosphere of the scale suggested in refs. 19 and 49 may be a somewhat unique feature of the Fayetteville shale region⁸ and are not thought to be a typical component of operations in BC, the potential influence of workday-specific activities was nevertheless considered in two separate ways. First, the present source-based measurements permitted review of each detected source including a subset that were investigated in separate on-site root cause analysis²⁸. Only 2 of 527

aerial quantified sources were notably linked to service operations – a 22.6 kg/h source from well completion equipment which typically operates continuously day and night until the well is completed, and a 16 kg/h truck loading event which would likely only occur during workday hours but is still inconsequential relative to the > 5500 kg/h of measured sources in the survey. Second, the potential for differences in measured emissions magnitudes between workdays and weekends was investigated statistically. As detailed in Section S4 of the SI, null hypothesis testing confirmed there was no statistical difference (at 5% significance) in emission magnitudes nor distributions measured on weekdays vs. weekends for tanks, flares, separators, compressor buildings, dehydrators, power generators, piping, unknown, and other sources, i.e., all sources with sufficient data to run the analysis. Most importantly, although this result is not necessarily generalizable to other regions which may have different source characteristics, the variability analysis summarized in Fig. 5 and the subsequent statistical analysis discussed here represents a framework for quantitatively bounding the effects of source variability and intermittency in each region where this new measurement-based inventory protocol might be applied.

Methods

The presented inventory analysis was completed for the province of British Columbia, Canada, which currently produces 36% of Canadian natural gas ⁵⁰ and is poised to become a significant global exporter of liquified natural gas (LNG) with the completion of the LNG Canada terminal ⁵¹. Aerial LiDAR measurements were completed during September 11 to October 8, 2021 at 508 distinct sites (polygons) comprising 601 active facilities and 702 active wells. As detailed in Table S1, this sample represented 60% of the approximately 1006 active facilities and 8% of the 8726 active wells in the province at that time. More importantly, the stratified sample achieved broad representation across the range of unique facility subtypes as necessary to create a robust inventory.

The aerial measurements used Bridger Photonics' Gas Mapping LiDAR (GML) technology, a light aircraftmounted, active-scanning optical sensor capable of providing high-resolution (~ 1-2 m) geo-located imagery of methane abundance over an approximately 100-m wide measurement swath. Briefly, as detailed elsewhere^{5,25,52}, emission rates of detected sources are estimated combining measured plume height and methane concentrations between the aircraft and the ground with locally estimated wind speed data (e.g., High-Resolution Rapid Refresh (HRRR) database⁵³ or Meteoblue (meteoblue.com) depending on coverage in the region of interest). Most critically, detailed independently-derived POD and quantification uncertainty models are available for this technology. These suggest that at the typical altitude of 175 m above ground level and 3-m windspeeds between 1.7 and 8.3 m/s (95% equal tail confidence interval) seen during the present survey, sources between 0.7 – 3.5 kg/h and 1.5 – 7.0 kg/h will be detected with 50% and 90% probability, respectively²⁵. At the median wind speed of 4.5 m/s from the survey, the 50% and 90% PODs are 1.7 kg/h and 3.5 kg/h.

All sites with detected sources were flown at least twice on separate days 1–10 days apart, where each flight included multiple overlapping passes as necessary to fully cover the facility or previously detected

sources. Average emission rates for each source were derived using data from multiple measurement passes and pass-specific POD data according to the inventory protocol summarized in Fig. 1 and fully detailed in the SI. As in previous work⁵, all detected sources were manually reviewed and attributed to specific equipment and facility subtypes using a combination of high-resolution aerial imagery, facility plans, and industry-reported production accounting data, as well as information from parallel ground inspections when available²⁸.

Declarations

Acknowledgements

The authors are especially grateful for the leadership of Don D'Souza and Peter Kos (British Columbia Ministry of Environment and Climate Change Strategy) and members of the BC Oil and Gas Methane Emissions Research Collaborative (MERC) in overseeing this work. Technical input of the BC Oil & Gas Commission (including Kevin Parsonage, Marie Johnson, Laurie Welch, Raman Sanghera, Dana Lockinger, James Gladysz, and James Nazareth) in helping fill data gaps to determine locations and active status of facilities and wells during the design phase of the aerial surveys was essential to the success of the project. We are also grateful for the assistance of Steve Smyth (Environment & Climate Change Canada) in developing the source-level comparisons with the official ECCC inventory. This work was supported by the British Columbia Oil and Gas Research and Innovation Society (BC OGRIS, contract number ER-Meth-2022-02), Natural Resources Canada (NRCan, grant number EIP2-MET-001), and Natural Sciences and Engineering Research Council of Canada (grant numbers 06632 and 522658).

Author Contributions

MRJ and DRT conceived the research; MRJ acquired funding and supervised and administered the project; BMC, MRJ, and DRT developed the methodology; DRT and BMC developed the software and curated data; MRJ, BMC, and DRT were jointly responsible for the formal analysis, writing (original draft and review & editing), and visualization.

Declaration of Competing Interest

The authors have no competing interests to declare.

Supporting Information

The online version contains supplemental material available on the publisher's website.

References

- 1. IEA. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. (International Energy Agency (IEA), 2021).
- 2. CCAC. Global Methane Pledge. (2021). Available at: https://www.globalmethanepledge.org/. (Accessed: 28th April 2022)
- 3. Chen, Y. *et al.* Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey. *Environ. Sci. Technol.* **56**, 4317–4323 (2022).
- 4. MacKay, K. *et al.* Methane emissions from upstream oil and gas production in Canada are underestimated. *Sci. Rep.* **11**, (2021).
- 5. Tyner, D. R. & Johnson, M. R. Where the Methane Is—Insights from Novel Airborne LiDAR Measurements Combined with Ground Survey Data. *Environ. Sci. Technol.* **55**, 9773–9783 (2021).
- Chan, E. *et al.* Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada Are Nearly Twice Those Reported in Inventories. *Environ. Sci. Technol.* acs.est.0c04117 (2020). doi:10.1021/acs.est.0c04117
- Hmiel, B. *et al.* Preindustrial 14CH4 indicates greater anthropogenic fossil CH4 emissions. *Nature* 578, 409–412 (2020).
- 8. Alvarez, R. A. *et al.* Assessment of methane emissions from the U.S. oil and gas supply chain. *Science (80-.).* **361**, 186–188 (2018).
- 9. Zhang, Y. *et al.* Quantifying methane emissions from the largest oil-producing basin in the United States from space. *Sci. Adv.* **6**, 1–10 (2020).
- Shen, L. *et al.* Satellite quantification of oil and natural gas methane emissions in the US and Canada including contributions from individual basins. *Atmos. Chem. Phys.* 22, 11203–11215 (2022).
- 11. Brandt, A. R., Heath, G. A. & Cooley, D. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. *Environ. Sci. Technol.* **50**, 12512–12520 (2016).
- 12. Brandt, A. R. *et al.* Methane Leaks from North American Natural Gas Systems. *Science (80-.).* **343**, 733–735 (2014).
- 13. Zavala-Araiza, D. *et al.* Reconciling divergent estimates of oil and gas methane emissions. *Proc. Natl. Acad. Sci.* **112**, 15597–15602 (2015).
- 14. Zavala-Araiza, D. *et al.* Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites. *Environ. Sci. Technol.* **49**, 8167–8174 (2015).
- 15. Lyon, D. R. *et al.* Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region. *Environ. Sci. Technol.* **49**, 8147–8157 (2015).
- 16. Rutherford, J. S. *et al.* Closing the methane gap in US oil and natural gas production emissions inventories. *Nat. Commun.* **12**, 1–12 (2021).
- Festa-Bianchet, S. A., Tyner, D. R., Seymour, S. P. & Johnson, M. R. 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. *Environ. Sci. Technol.* (2022).

- Johnson, M. R., Tyner, D. R., Conley, S. A., Schwietzke, S. & Zavala-Araiza, D. Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector. *Environ. Sci. Technol.* **51**, 13008–13017 (2017).
- Vaughn, T. L. *et al.* Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region. *Proc. Natl. Acad. Sci.* 201805687 (2018). doi:10.1073/pnas.1805687115
- 20. National Academies of Sciences. *Improving Characterization of Anthropogenic Methane Emissions in the United States. Improving Characterization of Anthropogenic Methane Emissions in the United States* (National Academies Press, 2018). doi:10.17226/24987
- 21. National Academies. Development of a Framework for Evaluating Global Greenhouse Gas Emissions Information for Decision Making. (2022). Available at: https://www.nationalacademies.org/ourwork/development-of-a-framework-for-evaluating-global-greenhouse-gas-emissions-information-fordecision-making. (Accessed: 24th August 2022)
- 22. IPCC TFI. Task Force on National Greenhouse Gas Inventories: Meetings. (2022). Available at: https://www.ipcc-nggip.iges.or.jp/meeting/meeting.html. (Accessed: 30th August 2022)
- 23. IPCC. 2019 Refinement To the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy. in (eds. Calvo Buendia, E. et al.) 200 (2019).
- 24. IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy. in (eds. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K.) **2**, (IPCC National Greenhouse Gas Inventories Programme, 2006).
- 25. Conrad, B. M., Tyner, D. R. & Johnson, M. R. Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies. *Remote Sens. Environ.* (2022). doi:https://doi.org/10.31223/X5S05F
- 26. Sitter, R. R. A resampling procedure for complex survey data. J. Am. Stat. Assoc. 87, 755–765 (1992).
- 27. Sitter, R. R. Comparing three bootstrap methods for survey data. *Can. J. Stat.* **20**, 135–154 (1992).
- 28. Johnson, M. R., Tyner, D. R. & Conrad, B. M. Root Causes of Oil and Gas Sector Methane Emissions: On-Site Investigations of Aerial Measured Sources. *Environ. Sci. Technol.* (2022).
- 29. Star Environmental. *Fugitive Hydrocarbon Emissions from Oil and Gas Production Operations*. (American Petroleum Institute (API), 1993).
- 30. Pacsi, A. P. *et al.* Equipment leak detection and quantification at 67 oil and gas sites in the Western United States. *Elementa* **7**, (2019).
- 31. ERG. City of Fort Worth Natural Gas Air Quality Study. (Eastern Research Group (ERG), 2011).
- Robinson, C., Driver, K. & D'Antoni, M. D. *Cap-Op Energy British Columbia Oil and Gas Methane Emissions Field Study*. (2018). doi:https://www.bcogc.ca/files/resources/bc-cas-mefs-chapters-1-3-err2-20200224.pdf
- 33. Clearstone Engineering Ltd. Update of Equipment, Component and Fugitive Emission Factors for Alberta Upstream Oil and Gas. (Alberta Energy Regulator (AER), 2018).

- 34. Bell, C. S. *et al.* Comparison of methane emission estimates from multiple measurement techniques at natural gas production pads. *Elem. Sci. Anthr.* **5**, (2017).
- 35. Allen, D. T. *et al.* Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. *Environ. Sci. Technol.* **49**, 633–640 (2015).
- 36. Allen, D. T. *et al.* Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci.* **110**, 18023–18023 (2013).
- 37. Thoma, E. D. *et al.* Assessment of Uinta Basin Oil and Natural Gas Well Pad Pneumatic Controller Emissions. *J. Environ. Prot. (Irvine,. Calif).* **08**, 394–415 (2017).
- 38. ECCC. 2020 National Inventory Report (NIR) Part 3. (Environment and Climate Change Canada (ECCC), 2022).
- 39. BCOGC. *Oil and Gas Activities Act Drilling and Production Regulation*. (British Columbia Oil and Gas Commission (BCOGC), 2021).
- 40. NGSI. *NGSI Methane Emissions Intensity Protocol Version 1.0*. (Natural Gas Sustainability Initiative (NGSI), 2021).
- 41. Schneising, O. *et al.* Remote sensing of methane leakage from natural gas and petroleum systems revisited. *Atmos. Chem. Phys.* **20**, 9169–9182 (2020).
- 42. ECCC. 2030 Emissions Reduction Plan. (2022).
- 43. OGCI. Oil and Gas Climate Iniative. (2022). Available at: https://www.ogci.com/.
- 44. OGMP2.0. Oil and Gas Methane Partnership (OGMP) 2.0 Framework. (2020).
- 45. ECCC. *Reducing Methane Emissions from Canada's Oil and Gas Sector*. (Environment and Climate Change Canada (ECCC), 2022).
- 46. Ramseur, J. L. *Inflation Reduction Act Methane Emissions Charge: In Brief*. (Congressional Research Service, 2022).
- 47. Lyon, D. R. *et al.* Concurrent variation in oil and gas methane emissions and oil price during the COVID-19 pandemic. *Atmos. Chem. Phys.* **21**, 6605–6626 (2021).
- 48. Plant, G. *et al.* Inefficient and unlit natural gas flares both emit large quantities of methane. *Science* (80-.). **377**, 1566–1571 (2022).
- Schwietzke, S. *et al.* Improved mechanistic understanding of natural gas methane emissions from spatially-resolved aircraft measurements. *Environ. Sci. Technol.* acs.est.7b01810 (2017). doi:10.1021/acs.est.7b01810
- 50. CER. 2021 Marketable Natural Gas Production in Canada. (2022).
- 51. LNG Canada. LNG Canada. (2022). Available at: https://www.lngcanada.ca/. (Accessed: 30th August 2022)
- 52. Johnson, M. R., Tyner, D. R. & Szekeres, A. J. Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR. *Remote Sens. Environ.* **259**, 112418 (2021).
- 53. NOAA. High-Resolution Rapid Refresh (HRRR) Model. (2020). Available at: https://rapidrefresh.noaa.gov/. (Accessed: 9th June 2022)



Figure 1

High-level summary of a protocol for creating measurement-based inventories using aerial data that considers both quantification and sample-size uncertainties (with finite population corrections) for the measured sources and combines bottom-up inputs for unmeasured sources to create a complete "hybrid" inventory.



Quantified uncertainties in the measured-source portion of the BC 2021 methane inventory. (a) Distribution of quantification uncertainty, sample size uncertainty, and total uncertainty in the measured-source inventory. (b) Measured source emissions and quantification, sample size, and total uncertainties for different facility or well types (strata) with bars shaded according to sample coverage for each stratum.



Comparison of presently derived 2021 measurement-based "hybrid" methane inventory for upstream oil and gas production in BC with most recent (2020) official inventory estimate from ECCC. The 95% confidence intervals represent the total uncertainty on the measured source fraction of the inventory. Uncertainties on the unmeasured source component should be equivalent between the present and ECCC inventories since they are derived from similar bottom-up data.



Comparison of estimated and measured sources contributing to the total upstream oil and gas methane inventory in BC. (a) Assumed source breakdown in the most recent (2020) official inventory (SCVF = Surface casing vent flow; Dehys. = Glycol Dehydrators). (b) Source breakdown from the presently derived 2021 measurement-based methane inventory.



Analysis to bound the potential effects of source variability and intermittency on the derived methane inventory. Even when overestimating the source variability based on the raw empirical, pass-by-pass measurement data, the potential added uncertainty (brown histogram) is no more than the source quantification error (pink histogram) and has no appreciable effect on the overall inventory uncertainty (black histogram and indicated 95% confidence limits).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

• EERLAerialMethaneInventoryNatureCommunicationsSISUBMIT.pdf