communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-00769-7 OPEN

Creating measurement-based oil and gas sector methane inventories using source-resolved aerial surveys

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Critical mitigation of methane emissions from the oil and gas (OG) sector is hampered by inaccurate official inventories and limited understanding of contributing sources. Here we present a framework for incorporating aerial measurements into comprehensive OG sector methane inventories that achieves robust, independent quantification of measurement and sample size uncertainties, while providing timely source-level insights. This hybrid inventory combines top-down, source-resolved, 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 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 OG 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 method and data are used to upper bound the potential influence of source variability/intermittency, 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.

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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]. 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 the potential for episodic emissions—specifically manual liquid unloadings—to skew measurements[19]. Ultimately, the root of these challenges 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 information[21]. 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 Nations 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 Johnson[5] demonstrated the potential to combine aerial LiDAR (light detection and ranging) 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. The present study significantly extends the initial work of Tyner and Johnson[5] to develop and demonstrate a formal protocol for incorporating measurement data directly into source-resolved methane inventories with precisely defined uncertainties. The developed protocol explicitly considers sample size and finite population effects within the context of highly skewed source distributions, while simultaneously accounting for measurement uncertainties and probabilistic detection sensitivities.

The specific goals of this study are: (i) to develop a formal protocol to create a source-resolved, hybrid top-down/bottom-up, 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 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 and intermittency on the derived inventory and share methods to bound the effects of source variability in future studies following the presented inventory protocol. The developed approach is readily extendable to other jurisdictions and demonstrates how a primarily measurement-based methane inventory can be developed, potentially with source- or site-resolved measurement data obtained using a range of technologies, so long as quantified measurement uncertainty and probabilistic detection sensitivity data for that technology are available.

Results and discussion

Figure 1 outlines the developed protocol for creating a hybrid top-down/bottom-up, measurement-based inventory from source- or site-resolved measurement data. For the ideal scenario of a comprehensive and complete measurement survey using a perfectly accurate and infinitely sensitive methane-sensing instrument, all sources would be captured such that the emissions inventory would be the sum of all directly measured emissions. In practice however, there are three notable challenges. Firstly, comprehensive measurement campaigns with complete coverage are generally infeasible. Secondly, source-level emissions inferred from measured (optically, or otherwise) methane concentrations are subject to bias and precision errors resulting from uncertainties in instrument calibration, meteorological data, inversion techniques, etc. Finally, 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 Supplementary 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; for example, 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 precisely defined probabilities of detection (POD) and robustly characterized quantification uncertainties[25] 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

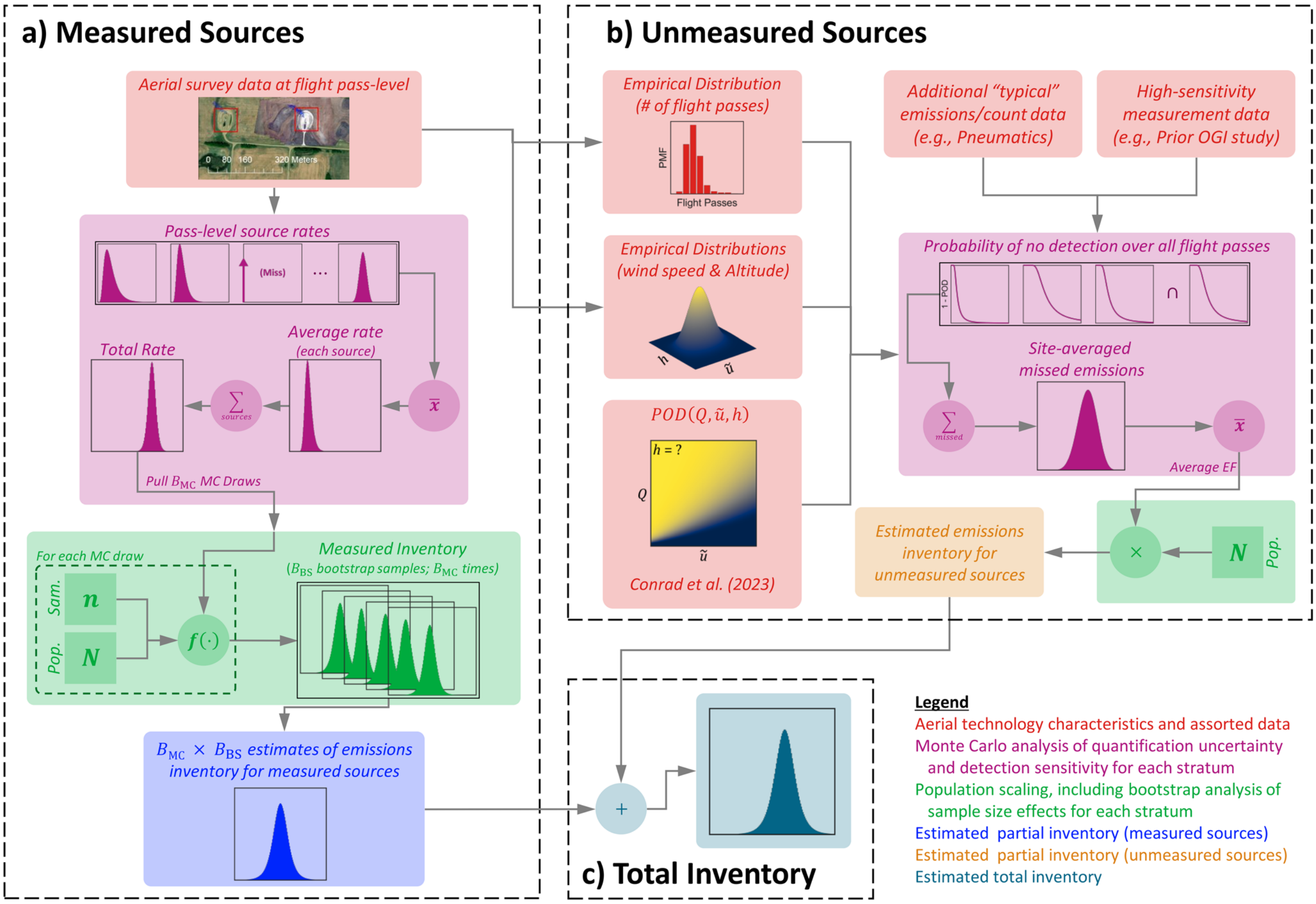

Fig. 1 High-level summary of a protocol for creating hybrid top-down/bottom-up, measurement-based inventories using source-resolved aerial data that considers both quantification and sample-size uncertainties (with finite population corrections) for the measured sources and combines bottom-up inputs for unmeasured sources to create a complete hybrid inventory. a Protocol for the measured source portion of the inventory; **b** protocol for the unmeasured (non-pneumatic, pneumatic instruments, and pneumatic pumps) portion of the inventory; and **c** summation to yield the total inventory.

measured source inventory calculation takes pass-by-pass aerial measurement data from surveyed sites, introduces known measurement uncertainties and detection sensitivities[25] via Monte Carlo and Bayesian analyses, 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 technology[25], 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 112.1 kt/y is computed by summing the measured inventories for each unique strata over 10^4 Monte Carlo draws (B_{MC}) and 10^4 bootstrap resamples (B_{BS}) and reveals overall uncertainties of −18.2% to +21.0% 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

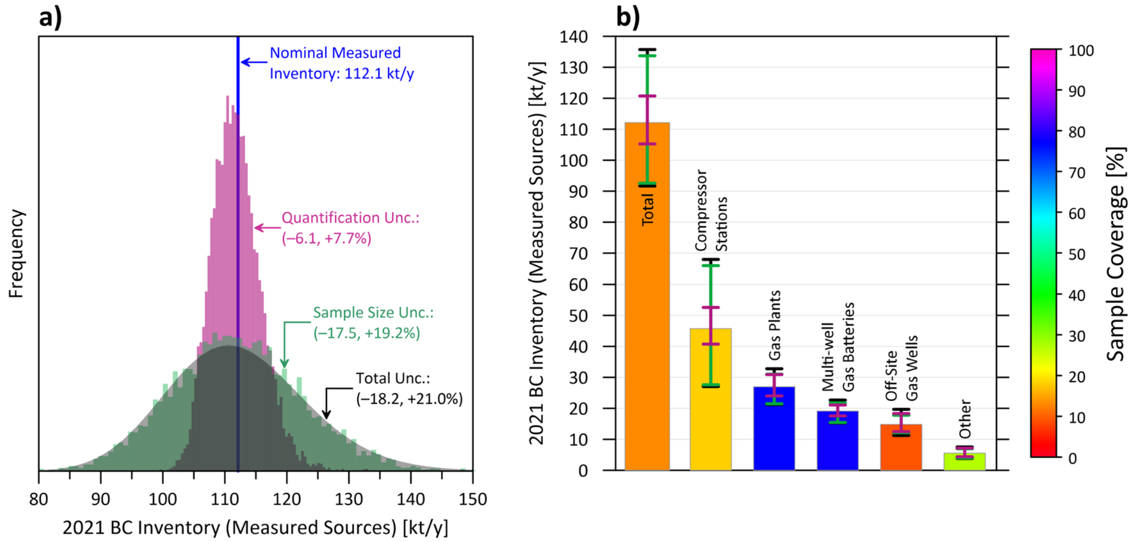

Fig. 2 Quantified uncertainties in the measured-source portion of the BC 2021 methane inventory. a Distribution of quantification uncertainty, sample size uncertainty, and total uncertainty in the measured-source inventory. **b** Measured source emissions and quantification, sample size, and total uncertainties for different facility or well types (strata) with bars shaded according to sample coverage for each stratum.

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 analysis[28] 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 substantial and must be considered during inventory development. Referring to Fig. 1b, this is possible via a parallel Monte Carlo simulation considering site/condition-specific POD[25] using bottom-up equipment count and measurement data from prior studies[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 measurement conditions (generally including meteorological conditions, ground reflectivity, and aircraft 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, for GML, the distributions of wind speeds and altitudes from each pass of the survey; a continuous POD model for the aerial technology[25]; 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 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 2018[32]. 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[29–31,33–37] may be used as in the work of Rutherford et al.[16]. 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 (see section S2.2.1 of the SI) and pneumatic instruments/pumps (see section S2.2.2 of the SI). Detailed results of the unmeasured source analysis for BC are included in the SI.

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 144.5 kt/y, of which 78% is from measured/measurable sources and 22% is from unmeasured bottom-up sources. This high proportion of measured sources reflects the high detection sensitivity of the employed aerial measurement technology and adds confidence in the total estimate. While the developed hybrid top-down/bottom-up inventory protocol could be applied to any technology with well-quantified POD and uncertainty models, it is generally advantageous to choose 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-up 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 presently 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/y for BC in 2019[5]. Although this implies a nominal decrease in emissions of 11% since 2019 consistent with the introduction of new methane regulations in January 2020[39], 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.

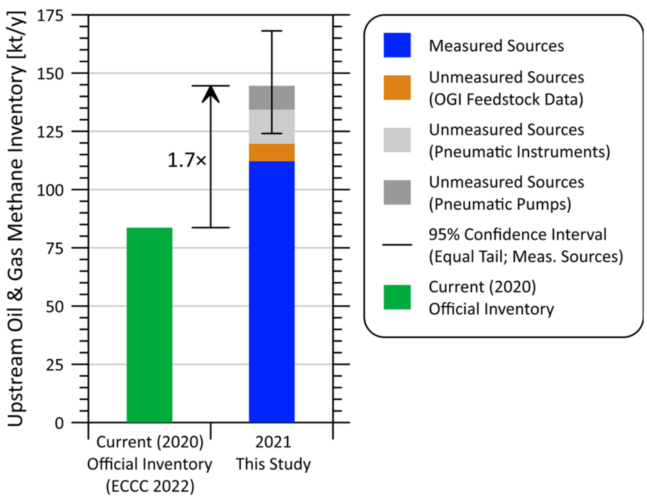

Fig. 3 Comparison of presently derived 2021 hybrid top-down/bottom-up, measurement-based methane inventory for upstream oil and gas production in BC with most recent (2020) official inventory estimate from ECCC. 95% confidence intervals represent the total uncertainty on the measured source fraction 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.

Referring to SI Section S3, methane intensities (also known as 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 protocol[40] 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): 0.33–0.44%). Adding in 14.4 kt/y of methane from downstream sources (i.e., distribution, transmission & storage, and refining; see Table S8) as inventoried by ECCC[38], suggests total annual oil and gas sector methane emissions of 158.9 kt/y, of which 143.7 kt/y 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 measurements[10], 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 a January 2023 limit (impending at the time of the survey) on total site-level tank emissions[39]. Recent ground-based analysis of origins of aerially detected emissions also notes that as much as a quarter of natural gas compressors at upstream facilities are electric-drive in BC[28]. Conversely, these same ground data show that there remains substantial mitigation potential suggesting a plausible pathway for further reductions necessary to reach the federal 75% reduction targets[42] through the Global Methane Pledge[2] 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[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 inventory[38]. 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 an official 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 compressors[28], or no more than 13% of the total inventory. Most importantly, Fig. 4 highlights the value of measured data in enabling 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.

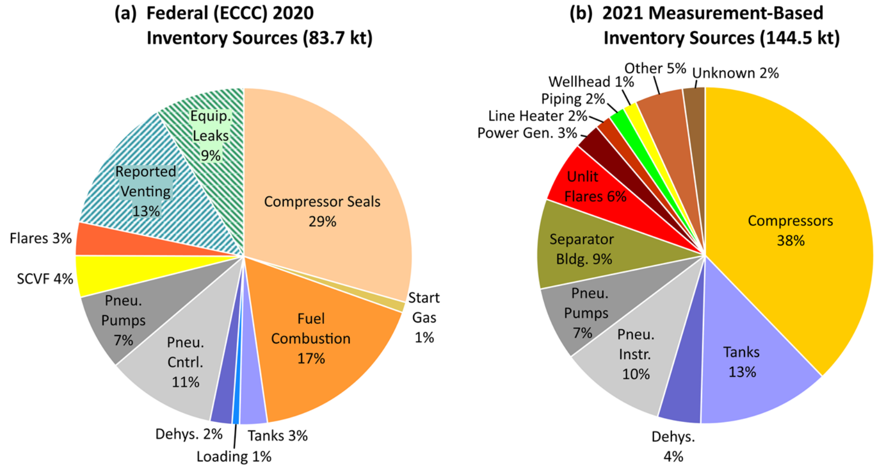

Fig. 4 Comparison of estimated and measured sources contributing to the total upstream oil and gas methane inventory in BC. a Assumed source breakdown in the most recent (2020) official inventory (SCVF = Surface casing vent flow; Dehys. = Glycol Dehydrators). **b** Source breakdown from the presently derived 2021 measurement-based methane inventory.

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 five 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 pass-by-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 quantifying sample size uncertainties for each stratum en 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 112.1 kt/y, the 95% confidence limits are effectively unchanged (91.7–135.7 kt/y vs. 91.9–142.6 kt/y). Closer inspection of the results reveals that, at least for the present sample set, 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 methanol 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 Vaughn et al.[19] and Schwietzke et al.[49] may be a somewhat unique feature of the Fayetteville shale region[8] 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 a separate on-site root cause analysis[28]. 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

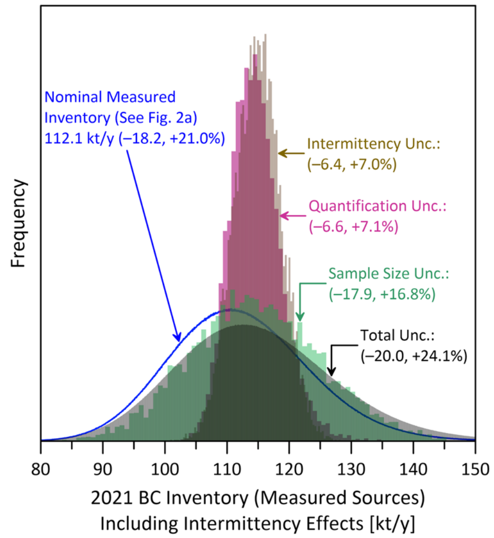

Fig. 5 Analysis to bound the potential effects of source variability and intermittency on the derived methane inventory. Even when overestimating the source variability based on the raw empirical, pass-by-pass measurement data, the potential added uncertainty (brown histogram) is no more than the source quantification error (pink histogram) and has no appreciable effect on the overall inventory uncertainty (black histogram and indicated 95% confidence limits).

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.

Potential limitations, extensions, and recommendations. While the presented comprehensive protocol unlocks new potential for directly incorporating measurements into source-resolved inventories with simultaneous robust characterization of uncertainties, there are several ways this approach could be further improved or potentially extended. First, it is worth restating the importance of high-quality bottom-up field data for estimating the contribution of unmeasured sources in the inventory. Although these sources only account for one-fifth of the present inventory, more generally this approach is best applied in jurisdictions where reliable bottom-up data exist. Future studies reporting on-site measurement and characterization of sources will continue to be especially valuable. Conversely, even in jurisdictions where bottom-up data are constrained to those used to derive official inventories, the present approach for incorporating measurement data is still likely to lead to considerable improvements in inventory accuracy and uncertainty. It is also worth noting that future implementation of proposed regulations eliminating the use of natural gas-driven pneumatics[50] would potentially remove three-quarters of bottom-up sources in the present inventory for BC, further increasing the proportion of directly measured sources and simplifying future application of this method.

The present protocol was developed and demonstrated leveraging the emergence of new aerial survey technologies capable of detecting individual sources with high sensitivity. Although it should again be emphasized that the detailed implementation of the protocol requires robustly characterized probabilities of detection and quantification uncertainties for a chosen measurement technology[25], in principle this hybrid inventory approach should be extendable to other technologies. This could include similar but less sensitive source-level technologies provided that there exist sufficient bottom-up feedstock data to mesh with that technology's detection sensitivity.

At larger spatial scales, measurement data could potentially be used in a similar framework to the presented methodology, subject to possible additional challenges. Firstly, the protocol for estimating unmeasured sources requires the joining of source-level feedstock data with simulated top-down measurements. Section S2.2 of the SI details this for source-level measurement technologies but this approach would need to be formally extended to mesh source-level feedstock data with site-level or worse resolution top-down measurements. At still larger scales relevant to satellite-based imagers, data may be insufficiently resolved to attribute detected emissions to unique facilities or wells. This would likely require aggregation of infrastructure into coarser strata, which would increase uncertainties in the calculated inventory. However, with sufficient, high-sensitivity, source-level data (potentially like that derived in the present study and included with the SI) the hybrid inventory protocol should be generally extendable.

Another possible application of the presented approach would be to explore important questions regarding the optimal design of aerial surveys. As seen in Fig. 2b, the method already permits post hoc examination of uncertainty contribution from different strata in conjunction with sample coverage, and Fig. 5 shows how the entire protocol can be leveraged to bound the potential influence of source variability on a specific derived inventory. However, it would be highly valuable to leverage this protocol to investigate possible guidelines for optimal survey design in the future. While this is beyond the scope of the present work, broader application of the protocol and subsequent analysis and simulation of aggregate data across jurisdictions could provide invaluable insights into anticipated levels of sample coverage necessary to achieve a targeted level of uncertainty. Future investigations leveraging data from broader surveys could explore possible trade-offs or optimization of measurement technology sensitivity, quantification uncertainty, and survey coverage with the goal of minimizing overall uncertainty in a derived inventory. Such questions are especially important for the development of monitoring, reporting, and verification (MRV) protocols such as OGMP2.0[44].

Methods

The presented inventory analysis was completed for the province of British Columbia, Canada, which currently produces 36% of Canadian natural gas[51] and is poised to become a prominent global exporter of liquified natural gas (LNG) with the completion of the LNG Canada terminal[52]. Aerial LiDAR measurements were completed during September 11 to October 8, 2021 at 508 distinct sites (polygons) comprising 601 active facilities and 904 active wells (including 705 offsite wells). As detailed in Table S1, this sample represented 60% of the approximately 1006 active facilities and 10% of the 8995 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 aircraft-mounted, 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[5,25,53], 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) database[54] 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 1.5−7.1 kg/h will be detected with 50% and 90% probability, respectively[25]. 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 work[5], 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 available[28].

Data availability

Oil and gas activity data can be accessed from https://www.petrinex.ca/PD/Pages/BCPD.aspx (Petrinex facility and activity codes), https://data-bcogc.opendata.arcgis.com/datasets/5ace26f614b9435492d679d766430143_0 (permitted facility locations), https://data-bcogc.opendata.arcgis.com/datasets/e2014a76454545abb0509afa2444876b_0 (pre-2016 facility locations), https://data-bcogc.opendata.arcgis.com/datasets/9149cb556e694617970a5774621af8be_0 (permitted well surface hole locations), and https://reports.bcogc.ca/ogc/r/app001/ams_reports/wa_issued (BIL-194: issued well authorizations). Site/operator-anonymized aerial survey data are available as supplementary information in Johnson et al.[28] Data to replicate Figs. 2 through 5 in the main text and Figure S2 in the supplementary information can be accessed at https://doi.org/10.6084/m9.figshare.22251043.v2.

Received: 22 November 2022; Accepted: 21 March 2023;
Published online: 25 April 2023

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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

M.R.J. and D.R.T. conceived the research. M.R.J. acquired funding and supervised and administered the project. B.M.C., M.R.J., and D.R.T. developed the methodology. B.M.C. and D.R.T. developed the software and curated data. M.R.J., B.M.C., and D.R.T. were jointly responsible for the formal analysis, writing (original draft and review & editing), and visualization.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-00769-7.

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Peer review information *Communications Earth & Environment* thanks Grant Allen and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Joshua Dean and Clare Davis. Peer reviewer reports are available.

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