Vehicle-Based Fugitive Emission Detection and Attribution Within Alberta Energy Developments

AUPRF Final Report

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Abstract

Accurate and spatially-extensive methane emission data can help operators and regulators meet new reduction targets. Vehicle-based monitoring uses a truck equipped with laser-based, multi-gas analyzers that measure methane and associated thermogenic gases to a precision of ~1 ppb, as well as algorithms that detect plumes on the basis of methane and associated gases. Plumes can be attributed known upwind infrastructure using back-trajectory algorithms. Travelling at roughly 80km/hr, we can routinely detect emissions of ~10 m^3/d per day from hundreds of meters away, while sampling an average of 100 (on-pad) to 400 (roadside sampling) well pads/facilities per day. The aim of this Alberta Upstream Petroleum Research Fund (AUPRF) study was to collect field air chemistry data in three Alberta Energy Developments (Medicine Hat, Lloydminster, Peace River) that would:

1) Provide development-specific geochemical (CH_4, C_2H_6, $\delta^{13}CH_4$, CO_2, H_2S) fingerprints for the vehicle-based gas monitoring system, to increase immediate applicability in Alberta;
2) Quantify methane concentrations and drivers of variation, across several developments;
3) Allow us to evaluate vented and fugitive emissions frequency and severity from several thousand pieces of infrastructure.

We collected data near thousands of wells and facilities within Lloydminster, Peace River, and Medicine Hat, Alberta during fall 2016. Over the course of six weeks, we measured CH_4 (methane), C_2H_6 (ethane), $\delta^{13}CH_4$ (isotopic methane), CO_2 (carbon dioxide), and H_2S (hydrogen sulfide) concentrations simultaneously at 1 Hz intervals, while following pre-planned routes along public roads. Over 6.7 million geo-located ambient gas and climate measurements were collected during this time. Using these data, we identified geochemical emission signatures of industrial-sourced plumes. We also generated statistical summaries of methane concentration variability in dense areas of infrastructure, and in the background. We ran a Generalized Additive Model (GAM) to understand how different variables influence ambient background methane. Finally, using geochemical emission signatures, we enumerated plumes detected on-road and attributed them to nearby infrastructural sources within several hundred meters. If a piece of infrastructure was measured upwind and within a defined radius of an on-road anomaly (as determined by gas ratio signatures), it was tagged as a potential emitter.

Absolute raw concentrations differed between developments. We observed only mild enrichments of several tenths of a ppm CH_4 in the Peace River and Medicine Hat regions, relative to the atmospheric background of methane (~1.85 ppm, NOAA 2017), whereas enrichments were markedly higher in the Lloydminster area. In Lloydminster, we occasionally measured average concentrations exceeding 6 ppm for an hour of driving (covering tens of km). We saw several hundred plumes (super-ambient air downwind of infrastructure), the relative gas ratios of which were within expected ranges for these developments. For example, we measured similar C1(CH_4):C2(C_2H_6) ratios of 1-2% for Peace River and Medicine Hat, whereas the Lloydminster

C1:C2 ratio was just below 1%. We measured appreciably higher ratios of associate gases at Peace River, and relative to CH_4, the CO_2 and H_2S values were higher than in other developments.

Outside of plumes, a statistical model showed that methane concentrations in the background air were controlled mostly by the time in which they were recorded. Other factors such as wind speed, topography, geography, and temperature were comparatively less important in predicting background variation.

Applying geochemical and geospatial filters to the data, we could attribute plumes more specifically to known upwind oil and gas infrastructure. These were the result of fugitive *and* vented emissions. Overall our routes passed ~1200 wells in each development, in triplicate. We found that emission frequencies varied amongst developments, but were the most common in Lloydminster, where 56% of wells were emitting methane-rich gas above the minimum detection range of 10.3 – 25.9 m^3/day (dependent on atmospheric conditions each day). Active wells in Medicine Hat and Peace River followed, with 28% and 29% of wells tagged as a potential emission sources, respectively. Although active wells were the predominant source of emissions, other classes of infrastructure, including abandoned and suspended infrastructure, also contributed. Both episodic and persistent emissions were measured in each development, owing to the sporadic and unpredictable nature of oilfield related emissions. Lloydminster emissions were the most episodic.

This study demonstrates the practicality of mobile surveying as a practical, large-scale screening solution to address high-priority air quality concerns in Alberta. We hope the project outcomes will inform the development of smart policies, regulations, and best practices for the sustainable development and monitoring of Alberta's hydrocarbon resources.

Background

Alberta is the greatest greenhouse gas emitter amongst Canadian provinces, where oil and gas sector methane emissions alone totaled 31 megatonnes of carbon dioxide equivalents in 2014 (Alberta Government Climate Change Leadership Plan, 2015). Of these, 48% are venting related, whereas 46% originate from fugitives and leaks. The remaining 6% are from flares or other sources (Alberta Government Climate Change Leadership Plan, 2015). It is important for the energy industry to understand the sources of such emissions, as they primarily contain high concentrations of methane, a greenhouse gas with a radiative heating potential 28 times that of carbon dioxide over a 100-year timespan (Myrhe et al., 2013).

In 2012, we developed and patent-protected a technology for detecting the presence and origin of fugitive and vented gas emissions across large geographic areas. This vehicle-based technology consists of hardware and computing algorithms, and is referred to as ExACT, for *Emissions Attribution via Computational Techniques*. Multi-gas measurements are used to identify and attribute emissions to specific sources algorithmetrically, including well pads, batteries, and facilities. Emission plumes can be identified at a deviation of only tens of parts per billion from the background. It is therefore possible to detect emissions from much farther away than with current techniques, after which they can be quickly localized. The technique can be used for screening, and for quickly (100-400 well pads/day) identifying anomalous sites that forward looking infrared (FLIR) operators should visit. Originally developed on commission by an operator of a large, enhanced oil recovery operation, ExACT has since been used in major energy developments but also in research related to coal bed CH_4, oil and gas exploration, natural gas, shale gas, oil sands, carbon capture and storage, and in fence-line investigations. The technique is tailored to conventional and unconventional environments.

Over the past five years, our laboratory has conducted vehicle-based fugitive emission studies across Canada and the United States. While we have worked extensively with operators headquartered in Calgary, a relatively small portion of our data has been procured within Alberta – despite some areas where air quality and emissions are of concern, and where the technique would be useful. This gap was the major motive behind our AUPRF project. We wish to tune our approach for key developments in Alberta, and to develop best practice recommendations for its use. This research will allow us to make the technology available for cost-effective, short-term projects in the province. Additionally, it will help generate a baseline understanding of fugitive and vented emissions occurrence and severity within Alberta. Three target areas for research include:

1) **Emission geochemistry:** Identify geochemical signatures of AB's oil and gas operations and establish appropriate monitoring gases for each development. *Outcome: Development-specific geochemical (CH_4, C_2H_6, $\delta^{13}CH_4$, CO_2, H_2S) fingerprints for the vehicle-based gas monitoring system, to increase immediate applicability in Alberta.*

2) **Ambient background:** Determine how ambient background gas concentrations vary as a function of time, biological, geographical, and atmospheric influences. *<u>Outcome:</u> Statistical analysis of methane variation, across several developments*.
3) **Emission attribution:** Allocate on-road plumes to nearby infrastructure, to see how emissions are distributed across developments, and/or classes of infrastructure. *<u>Outcome:</u> Vented and fugitive emissions frequency and severity from several hundred pieces of infrastructure*.

Methodology

Peace River, Medicine Hat, and Lloydminster, Alberta were chosen for these vehicle-based campaigns. Air monitoring and quality issues are a concern at these sites, and were a factor in our site selection.

a) Field Measurements

Data were collected during extensive vehicle-based field surveys of air composition. A series of 45 air monitoring surveys were conducted between October 17th and November 22nd, 2016. In each of the three regions, all surveys followed one of 5 preplanned routes on off-lease grid roads, specific to the region (Appendix, Figures 1-4). The routes were designed to optimize coverage and accessibility, and were guided by an infrastructural GIS (facility and wellhead) database provided by Altus Geomatics. For the purpose of this study, a facility is considered as any piece of oil and gas infrastructure within the database that is not a well. Facilities include compressor stations, tank batteries, gas gathering systems, etc. During a campaign, each route was repeated three times to capture diurnal variability, to capture the degree of variation in emissions, and to obtain higher confidence overall.

Gas concentrations were collected at ~1m height via cavity ring-down spectroscopy (CRDS) using high-precision, ppb-level truck-mounted Picarro G2210-*i* CRDS (CO_2, CH_4, C_2H_6, and $\delta^{13}CH_4$) and Teledyne T101 (H_2S) analyzers that record at 1 - 2 Hz. A tubing system connected to an air pump drew atmospheric gas through an inlet at the front of the survey vehicle (to eliminate gas from the vehicle's own tail pipe), where it was fed to the analyzers situated in the truck cab. Here, gas is analyzed in real-time which makes for near- instantaneous measurements, viewable from a monitor within the vehicle.

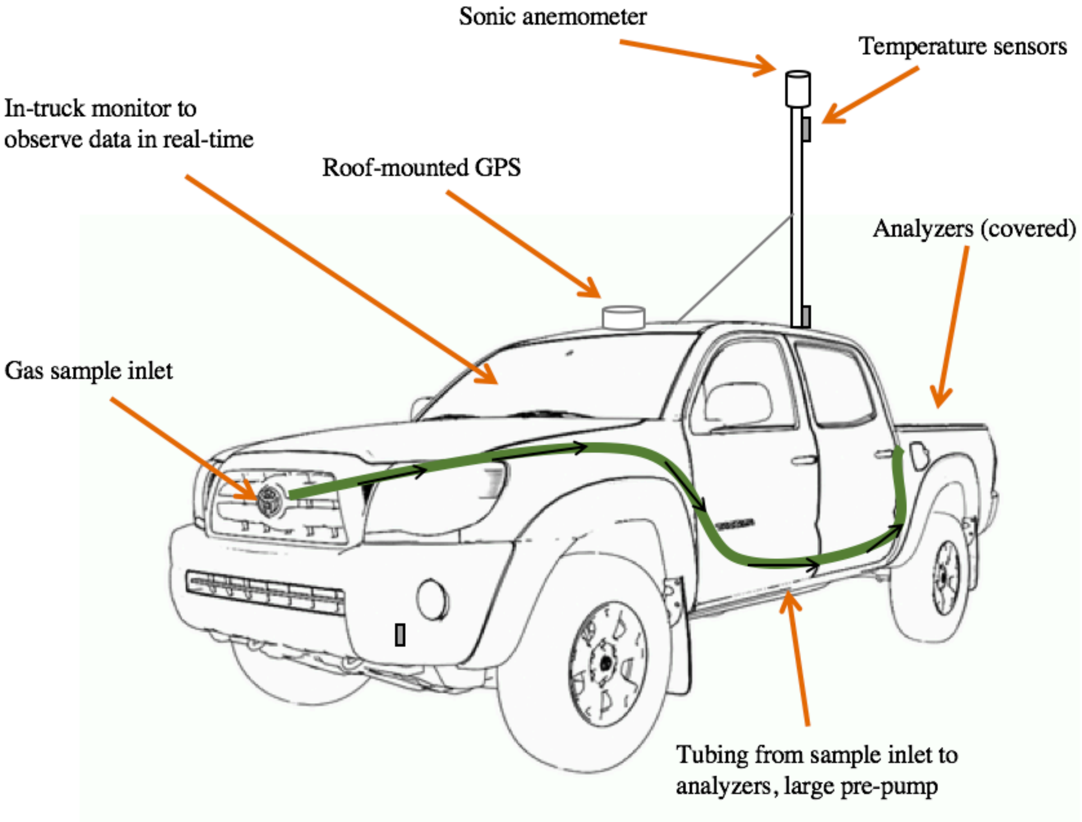


Figure 5. ExACT mobile survey set up.

A 7 liter/min pumping rate kept residence time in the tubing to 1-2 seconds. The concentration data were tied to coordinates recorded by a Garmin 16x Vehicle Rooftop GPS and Tacoma anemometer. We recorded meteorological parameters using an RM Young 2-D sonic anemometer, and thermal gradient temperature sensors (Campbell Scientific 107B, 0.01ºC accuracy) mounted on the bottom air dam and anemometer mast of the truck. Data from the Garmin GPS and the meteorological sensors were recorded at 1Hz with a cab-mounted Campbell Scientific CR1000x datalogger under vehicle power. Subsequent statistical analyses, including plume detection and source attribution, were performed using R 3.2.5 statistical software.

b) Site Descriptions

Lloydminster

The Lloydminster area straddles the border of Alberta and Saskatchewan, and contains vast amounts of heavy oil deposits. The reserve of heavy oil is estimated at 5.2 billion cubic meters (33 billion barrels). Oil is found in multiple zones of thin, unconsolidated sandstones with high oil saturation mostly found at depths of 400-600m. Much of the oil originates within the Lower Cretaceous Mannville Formation (*Coskuner et al., 2015*). The Cold Heavy Oil Production with Sand (CHOPS) production technique is common in this region to improve recovery of the heavy, viscous oil.

Peace River

With an area of 8000 km^2, the Peace River oil sands in northwestern Alberta are the smallest of the province's four major oil sand deposits situated within the Western Canadian Sedimentary Basin. Here, roughly 155 billion barrels of bitumen are contained within the Mississippian, Permian, and Lower Cretaceous reservoir beds. Geology in the Peace River area is unique in that the bitumen deposits produce heavy oil that has higher levels of sulphur and aromatic compounds compared to other areas of the province, which has led to a series of public complaints. This prompted the Alberta Energy Regulator (AER) to take action and address emission-related odors from heavy oil operations in the region. In April 2014, the AER accepted an independent panel of hearing commissioners' recommendations that are within the AER's jurisdiction. As a result, the AER introduced Bulletin 2014-17: New Requirements for the Capture and Flaring, Incinerating, or Conserving of All Casing Gas and Tank-Top Gas by New and Existing Operations in the Peace River Area, which are region-specific revisions to Directive 060 and 056. Updated regulations required that heavy oil and bitumen operations in the Peace River area capture and flare, incinerate, or conserve all casing gas and tank-top gas, effectively eliminating venting in the area.

Medicine Hat

The first gas discovery in Western Canada was made near Medicine Hat, Alberta in the late 1800s. The Medicine Hat sandstone is the largest and most mature natural gas pool in Canada. This sandstone formation, upper Coniacian to lower Santonian in age, is close to the Colorado Group strata in southeast Alberta and southwest Saskatchewan (*Giboy, 1989*). Sweet, shallow gas production is predominant in the Medicine Hat region, yet there also exists a minimal number of oil production wells. Although the Medicine Hat region accounts for only 7% of provincial natural gas production, the area accounts for approximately half of the operating gas wells in the province (Asualt, 2016).

c) Geochemical Analysis of Emission Plumes / Super-ambient Concentrations

False positives are minimized in emission detection when a geochemical fingerprint is incorporated into the detection strategy. Most oil and gas emission sources are rich in CH_4, but accessory gases (CO_2, H_2S, C2+ volatile organic compounds (VOCs)) are also present as a function of the produced fluid chemistry of the reservoir, or the process that emits the gas. The CH_4 itself is sometimes also distinct from the background as a function of the $\delta^{13}C$ value. Since the ExACT technique generally uses at least one geochemical fingerprint for detection, we were interested in understanding the concentrations of these accessory ratios in the background air. This affects the ExACT setup for different developments – both the combination of analyzers onboard, and the gas ratios used for source attribution in the algorithms. In this study, we harvested geochemical fingerprints for each study area by aggregating data from inside CH_4-rich areas, of which we witnessed hundreds.

We defined methane-rich areas as ones in which 1) concentrations of CH_4 and other gases were enriched above the ambient background (to any degree), and 2) where ratios of these super-ambient (excess) concentrations had a CO_2:CH_4 ratio that was highly depressed relative to the global atmospheric average of ~215. Specifically, we looked for ratios <100 in order to define methane-rich areas. This approach works better than a simple CH_4 concentration threshold, because ratios are relatively insensitive to pooling of gases in valleys and other factors that contribute to natural (non-oilfield) methane enrichment in air. As part of the process, we determine the concentration of the ambient background of each gas, which fluctuates at some temporal scale depending on route, speed, atmospheric conditions, terrain, and land use. We must reset the ambient background concentration of each gas at a specified time interval, called the Running Minimum Reset Interval (RMRI). We iteratively scale the RMRI until we maximize the number of consecutive multi-point excess ratio emission anomalies. This process helps to separate (deconvolute) the background from the anomalies. A unique optimal RMRI was determined for each survey. Generally, RMRI resets at ~5-minute timescales are best for enhancing excess ratio departures. At road speeds, 5-minutes equates to about 5-7 km of driving.

For these methane-rich areas, we aggregated all super-ambient, or excess, concentrations. The ratios of excess concentrations act like a fingerprint, and should ideally reflect the ratios of gas sources in these developments, as outlined further in Hurry et al. (2015), and within a US Patent application (Risk et al. 2014). The excess ratio fingerprint (all gases) is development-specific, but also varies within a development. Understanding this fingerprint leads to more definitive detection and fewer false positives. Since most gas sources originate from the produced fluids, the excess concentration ratio fingerprint should reflect the produced fluid fingerprint. However, onsite processing or gas migration from nearer-surface strata may occasionally alter the measured airborne excess concentration ratio fingerprint. In this report, we expressed gas excess concentration ratios normalized to CH_4 = 10. We also calculated Keeling plot intercepts to determine the source signature of $\delta^{13}CH_4$. As part of this work, we were also looking for evidence of significant additional methane sources in these areas, which would appear as substantial standard deviation in fingerprint ratios, and/or complex Keeling plots showing several mixing lines and/or poor regression statistics. If significant additional methane sources (agriculture, etc.) are not present, we could use more simplistic criteria for plume detection.

d) Drivers of Variability in Background Methane by Generalized Additive Model (GAM)

GAMs are used to describe non-linear relationships between response and predictor variables over time. GAMs are adaptable for non-normally distributed variables, and are easily interpreted due to their additive structure (De Brogniez, 2015). In this study, we used a GAM to determine the primary drivers of ambient methane, in case there were significant natural sources present, or elevated concentrations within particular areas of land use. The relative influence of different variables such as temperature and elevation was determined through R^2, F, and P values outputted from the model. The mgcv package from R statistical software was used for all calculations. The GAM model used took the following form,

$$g(E(Y)) = \beta_0 + S_1(\chi_1) + S_2(\chi_2) + \ldots + S_p(\chi_p)$$

where $S_i(X_i), i = 1, 2...p$ are non-parametric smooth functions for the independent variable X_i. The function S_i is estimated in a flexible manner and does not have to be nonlinear for all independent variables in the GAM. Smooth functions developed using cubic regression splines expressed the non-parametric relationships between response and predictor variables (Wood, 2006). Longitude and latitude were also incorporated into each model for spatial autocorrelation. The GAM was applied to our RMRI reset time series, which excludes the methane-rich plume areas.

e) *Plume Identification and Attribution*

Since our results suggest that only one broad type of methane source type was present within each development, we could simply use our $e\text{CO}_2{:}e\text{CH}_4$ ratio (where *e* represents excess concentration above ambient) as an indicator of plumes. Other accessory gases are not required for general work within developments with straightforward air chemistry, though they might be useful in discriminating deep wells from old, or operators from one another. We did, however, slightly tune the numerical $e\text{CO}_2{:}e\text{CH}_4$ search values according to kernel density plots shown in Figure 8, and discussed below. Even at distance, the measured $\text{eCO}_2{:}\text{eCH}_4$ ratio closely reflects that of the source.

Following geochemical attribution, a geospatial attribution that incorporates back-trajectory analyses of each plume is conducted. To flag a nearby piece of oil and gas infrastructure as a potential emitter, it must meet geochemical, geospatial, and persistence criteria:

a) Infrastructure is upwind of on-road data points
b) Within a defined radius of on-road data points
c) Series of a minimum three anomalous on-road data points within the source's radius
d) The source must be tagged as a potential emitter (i.e. meet above criteria) > 50% of the times it is surveyed.

These geospatial attribution criteria are visualized below, where a back-trajectory of a plume observed on-road leads us to a piece of infrastructure that is upwind, and within the radius of the on-road measurements. A nearby piece of infrastructure, also within the radius, is not considered a source because it is downwind.

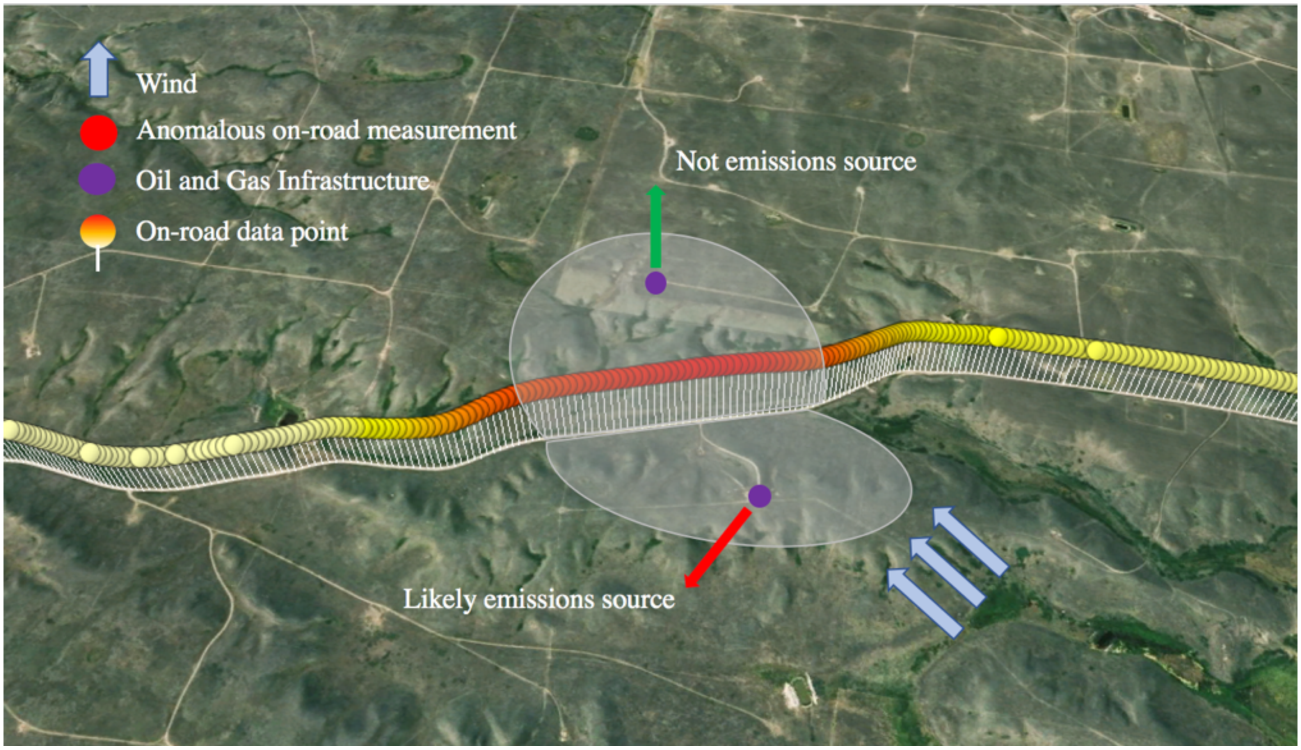


Figure 6. Geospatial attribution – tagging a source as an emitter.

It is important to note that all sources tagged are 'potential emitters'. Based on plume transport dynamics, it is possible for a shadow effect to occur. This occurs when a plume from a distant source is detected on road, but blows towards and past another more proximal piece of infrastructure, causing the most proximal infrastructure within the radius to be falsely flagged as the emitter. Our multi-gas approach to detecting anomalies reduces false positives, leading us to a 95-99% confidence in plume detection, even for anomalies as minor as 10 ppb CH_4. Although there are continual improvements to our geospatial methods of flagging an emitter, assumptions must be made, and we are hence less confident about geospatial attribution compared to emissions detection. The best way to decrease geospatial attribution uncertainty is to gain access to wellpads, although we are working on various methods to detect shadow plumes in an automated fashion.

Batteries containing multiple pieces of infrastructure were common in all campaigns, but in Lloydminster, upwards of 10 wells on a pad would be common. When ExACT is used from the roadside, it does not pinpoint which well on a multi-well pad is emitting, but instead flags all sources as potential emitters. In such cases, a small-scale infrared imaging tool is best suited to narrow in on the source. This is important to consider when interpreting results, as multi-well pads in Lloydminster could be biased towards greater emitting frequencies. The best way to decrease this uncertainty is to get closer, where back-trajectories are more accurate, or potentially not even needed if full loops can be driven around the infrastructure in question.

Under normal wind conditions, the Minimum Detectable Limit (MDL) for fast (several second) transits through plumes, at 130m distance from source, is roughly 1.034 m^3 d^{-1}, a level significantly beneath the allowable combined venting and flaring threshold of 900 m^3 d^{-1} (per site) in most Canadian developments (Alberta Energy Regulator: Directive 060, 2016). Despite driving quickly, we can therefore still locate and enumerate emissions above and below regulatory limits. In-place oil and gas infrastructure is itemized in Altus Geomatics datasets, which then allows us to geospatially attribute any emissions detected on-road, to potential upwind sources within 200 or 400m (depending on campaign). In summary, the routes are driven, data from varying sources are combined, a geochemical excess ratio is defined, data is processed further to correct for a fluctuating background, and finally, a geospatial analysis attributes observed on-road anomalies to a probable source. Any summary statistics such as emissions dependence on operator, or infrastructure type and age, are calculated using R, and further spatial analyses or mapping are conducted in ESRI's ArcGIS 10.2.

The campaign-specific eCO_2/eCH_4 ratios and radii are summarized below. Anomalous eCO_2/eCH_4 ratios were chosen based on density plots, as described in the following discussion section. The radius is extended for Peace River due to the increased average distance of infrastructure from road.

Table 1. Anomalous gas ratio and radius values per campaign

	Anomalous eCO_2/eCH_4 ratio	Radius
Lloydminster	60	200
Peace River	100	400
Medicine Hat	100	200

Results and Discussion

During 45 mobile surveys in Lloydminster, Peace River, and Medicine Hat, we collectively surveyed 2065 wells and 1137 facilities (in triplicate) over the course of eight weeks, during which high precision, laser-based gas analyzers recorded over 6.7 million unique, geo-located gas concentration and climate data points. Survey route statistics by campaign are shown in Table 2 below. A piece of infrastructure is considered sampled if it is passed downwind a minimum two times during the entirety of a campaign, within a defined distance of the on-road measurement. Infrastructure passed only once was filtered out during analysis. Geo-located data points were totaled from raw datasets, prior to processing.

Table 2. Summary route statistics

	Lloydminster	***Peace River***	***Medicine Hat***
Total km surveyed	2,684	2,881	2,784
Total surveys	15	15	15
Geolocated data points collected *	2,593,304	2,064,258	2,051,518
Sampled wells	783	456	826
Sampled facilities	589	237	311

Infrastructure surveyed during this study included a diverse set of wells and facilities operated by 59 unique, major to small, oil and gas production companies in Alberta. The distinctive nature and layout of each energy development presents a comparative look at emissions, their concentrations, severity, and impacts per region.

a) Emission Geochemistry

Summary statistics for five gases, including isotopic methane, are summarized in Table 3. Concentrations are raw, or "as recorded," and ambient background was not subtracted. Concentrations shown were averaged over the entirety of a campaign. This is useful to characterize the average, or expected geochemistry of background gases for each campaign, and to understand how extreme values differ per region.

Table 3. Summary gas statistics

Lloydminster

Statistic	N	Mean	St. Deviation	Minimum	Maximum
CH_4 (ppm)	185,236	2.41	1.77	1.94	64.1
CO_2 (ppm)	185,236	412	12.7	400	525
$\delta^{13}CH_4$	185,236	-50.5	2.38	-80.4	-34.3
H_2S (ppb)	185,236	0	3.19	0	53.8
C_2H_6 (ppm)	185,236	0.01	0.02	0	0.57

Peace River

Statistic	N	Mean	St. Deviation	Minimum	Maximum
CH_4 (ppm)	147,447	1.97	0.1	1.91	3.69
CO_2 (ppm)	147,447	413	16.3	398	683
$\delta^{13}CH_4$	147,447	-47.9	1.19	-63.1	-36.1
H_2S (ppb)	130,213	0.752	2.49	0	23.3
C_2H_6 (ppm)	147,447	0.002	0.005	0	0.11

Medicine Hat

Statistic	N	Mean	St. Deviation	Minimum	Maximum
CH_4 (ppm)	146,537	2.03	0.13	1.92	5.47
CO_2 (ppm)	146,537	412	21.41	399	698
$\delta^{13}CH_4$	146,537	-48.8	1.34	-61.6	-34.6
H_2S (ppb)	146,537	0	1.94	0	18.9
C_2H_6 (ppm)	146,537	0.001	0.003	0	0.06

Oil and gas emissions carry a unique geochemical signature, that varies by region, geologic formation, and type of development (practice, tank or pipeline, etc.). We measured plumes that typically lasted several seconds, but we saw several hundred of them during the campaigns. Geochemical signatures of the most severe gas plumes within Medicine Hat, Peace River and Lloydminster, are presented in Table 4 below.

Table 4. Relative excess concentrations of the top five most severe plumes, normalized relative to an excess methane concentration of 10 ppm.

	eCO_2 (ppm)	**eCH_4 (ppm)**	**eH_2S (ppm)**	**eC_2H_6 (ppm)**
Lloydminster	10.224	10	0.003	0.088
Peace River	187.203	10	0.015	0.126
Medicine Hat	22.960	10	0.002	0.164

Here, we show the relative excess concentration of each gas, in equivalent units of ppm, normalized to CH_4=10. In the plumes, Peace River and Medicine Hat had C1(CH_4):C2(C_2H_6) excess ratios of 1-2%, whereas Lloydminster C1:C2 was just below 1%. We measured appreciably higher ratios of associate gases like CO_2 and H_2S at Peace River.

We were initially surprised at the C2 fraction in the Medicine Hat region, which was higher than published values for Medicine Hat (Research Council of Alberta, 1962). However, Taylor *et al.* (2000) has since shown that the values we measured are not unrealistic, as higher C2+ gases are common for gases extracted from deeper within the formation. Ratios of fugitive and vented emissions for Mannville group oil sands were consistent with values published in Rowe and Muehlenbachs (1999). Hydrogen sulfide concentrations are more difficult to tie directly to produced fluids, because tight air quality regulations for this gas result in mitigation measures that reduce H_2S relative to reservoir values. However, we did see that the relative fraction of H_2S to CH_4 was higher in Peace River than other developments, which is consistent with the known regional sour gas odors that have resulted in additional monitoring requirements for operators. Keeling plots (Figure 7 below) of raw gas concentrations suggest that the $\delta^{13}CH_4$ values of plumes are ~ -65, -62, -50 for Lloydminster, Medicine Hat, and Peace River, respectively (indicated by the y-intercept). The first two are within a few points of values published Rowe and Muehlenbachs (1999) and Taylor *et al.* (2000). We could not find published values for Peace River's formation to compare.

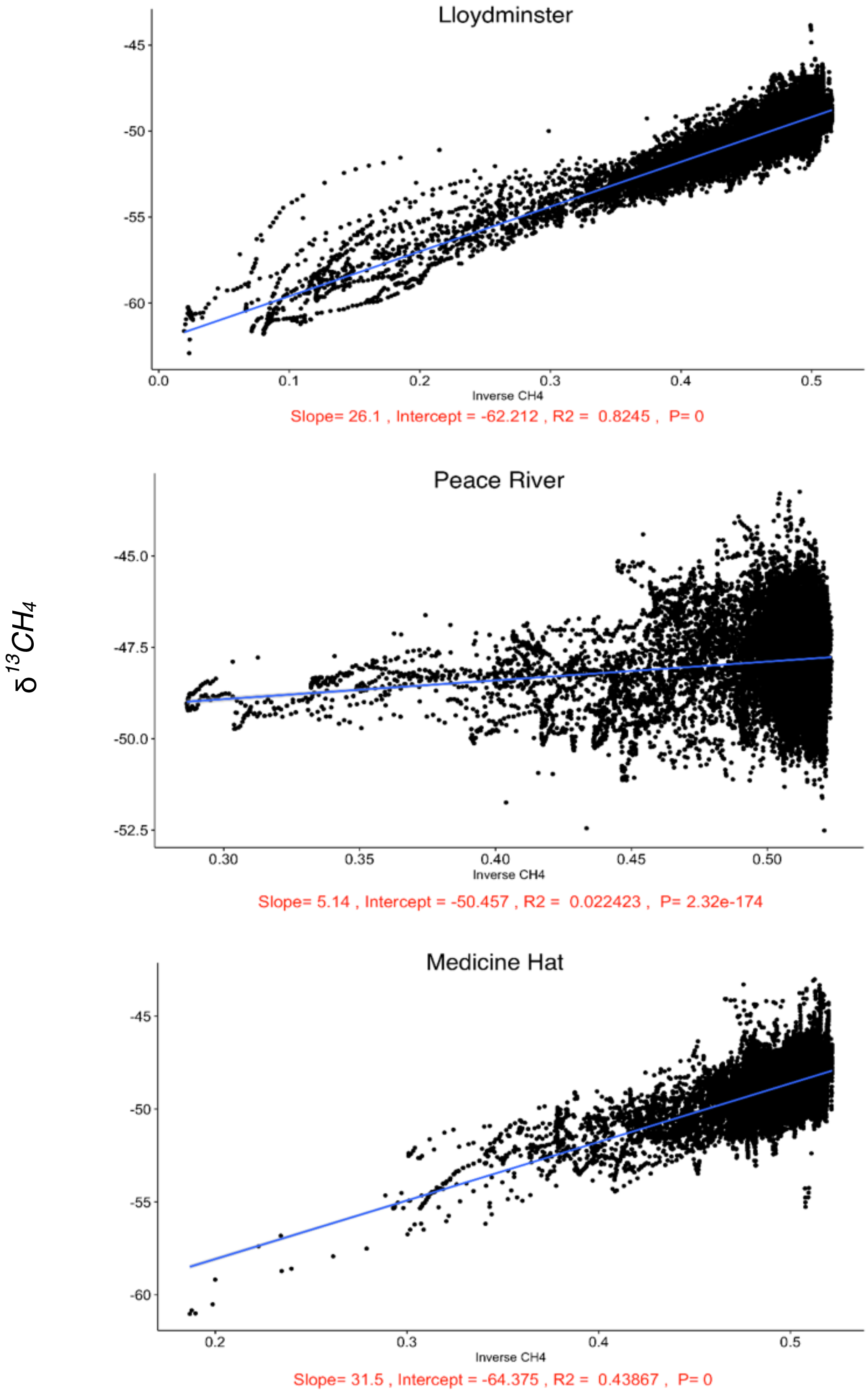


Figure 7. Keeling plots of each development, showing isotopic methane measurements in relation to inverse methane.

Overall, values we measured in air anomalies were representative of known produced fluid ratios, showing how one can recover these ratios through air sampling of fugitive and vented emissions near infrastructure. In fact, the geochemistries were more consistent at these sites than in many others we have measured, suggesting that oil and gas methane is the dominant local methane source in each case. The fact that our ratios generally follow those of produced fluids for these developments, and because natural or agricultural sources have very different fingerprints, gives us high confidence that plumes were measured were sourced from oil and gas activities.

If we dug deeper, our datasets would also contain information on localized geochemical variations within each development. Such variations would generally be associated with specialized processes, operators, or reservoir variation. But, we did not analyze these data in a detailed local context, as the purpose of the study was to create developmentally-averaged geochemical fingerprints that would allow for identification of plumes with few false positives.

Figure 8 below shows kernel density plots from three campaigns, comparing the deviation in excess CO_2 to CH_4 from natural background levels. Each density plot contains an aggregate of excess concentration data from all 15 surveys within a campaign.

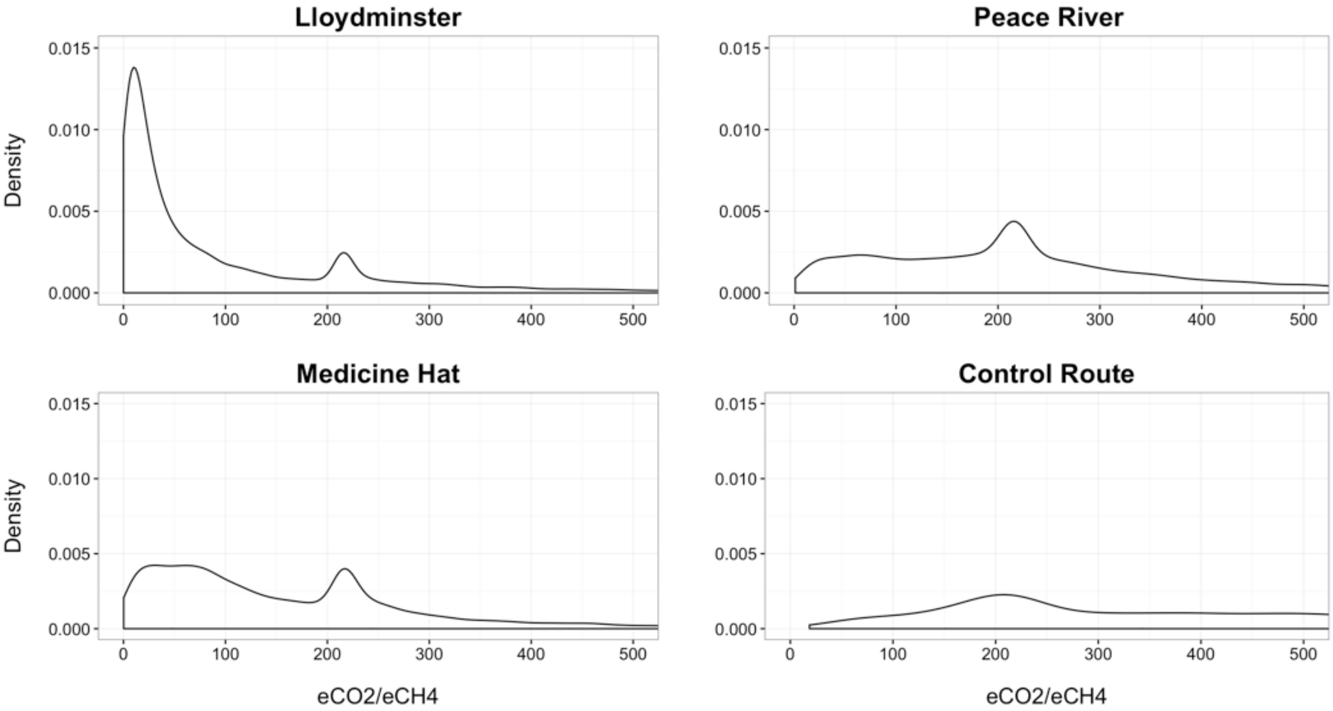


Figure 8. eCO_2:eCH_4 Kernel Density plots of excess concentration ratios. Natural ambient background is ~215. Populations lying to the left represent methane-enriched air parcels / plumes.

The excess gas ratio is an indicator of CO_2/CH_4 ratio of the vent or fugitive sources, but also methane severity. Each plot contains a peak in eCO_2:eCH_4 signatures around 215, which represents the natural, ambient background. The peak to the left of each plot implies a population of eCO_2:eCH_4 signatures that are numerically smaller than the natural background. This indicates a density of methane enriched anomalies, originating from localized oil and gas development. For instance, peaks <60 indicate an enriched CH_4 signature roughly 3.5 times that of the natural atmosphere. The excess eCO_2:eCH_4 ratio specific to each campaign, presented in the methodology section, was inferred from this peak. Lloydminster surveys show the greatest density of depressed ratios, indicating that CH_4 enrichment is predominant in this development over its comparators. We did not survey a control route as part of the work in Alberta, but as an example we have included a kernel density plot from a control survey conducted in Weyburn, SK during a fall 2016 mobile survey campaign in a region relatively free of infrastructure. Methane-enriched peaks are visible to the left of the natural ratio on all routes except for the Control, where no anomalous plumes from energy development were detected. In general, the gas ratio fingerprint detection approach provides high confidence in detection, and very few false positives.

b) *Ambient background*

Ambient background gas (ABG) concentrations vary as a function of time, biological, geographical, and atmospheric influences. It is critical to understand changes in ABG concentrations, so that natural variability is not falsely mistaken as industrial emissions. Average ambient methane values for Lloydminster, Peace River, and Medicine Hat were 2.41 ppm (n=185 236), 2.03 ppm (n=146 537), and 1.97 ppm (n=147 447) respectively, with all regions being more enriched than the current global mean of 1.85 ppm (NOAA, 2017). The regional effects of oil and gas development, or other methane intensive industries including agriculture/livestock (not an appreciable source locally), are reflected in the atmospheric means of each campaign. The ambient background remained very stable in Peace River ($\sigma = 0.13$) and Medicine Hat ($\sigma = 0.10$), yet less so in Lloydminster ($\sigma = 1.77$). Background methane varies significantly by region. For context, a similar mobile surveying study conducted by Atherton et al. (2017) in the Montney Shale Gas Basin recorded a mean methane value of 1.90 ($\sigma = 0.084$) (n= 444 585), and a mobile measurement campaign through dense developments in the Barnett Shale, led by Rich et al. (2014), recorded background methane at 11.9 ppm.

As seen by the range in background methane concentrations, calculating the running minimum interval and eliminating background variation prior to resolving industrial related plumes is an important step of our methodology, because it allows for this natural variation. Further to that, if we better understand the norms, we can opportunistically schedule field work around times of low variance when our ability to detect is enhanced.

Concentration duration analyses illustrate how raw methane concentrations are sustained over differing time intervals (Figure 9). After single surveys from each campaign were combined, running averages of the methane time series was computed for 1-min, 15-min, and 60-min intervals, resulting in a time series of the averaged values. The highest value on the averaged time series represents the maximum sustained average value for the development. The highest value from a 60-minute averaging interval reflects the most severe regional scale anomaly observed, which was 62 ppm, 3.7 ppm, and 5.5 ppm in Lloydminster, Peace River, and Medicine Hat respectively. In Figure 8, the 'all' column is the arithmetic average methane concentration over the full 15 surveys. This process helps capture local and regional averages. Such plots are a useful indicator of plume persistence and severity across geographies. A strong peak at the left of the bar chart suggests that one or more disproportionately large emitters may exist, around which values are highly elevated relative to around other infrastructure. The horizontal line represents the global atmospheric methane background concentration of 1.85 ppm.

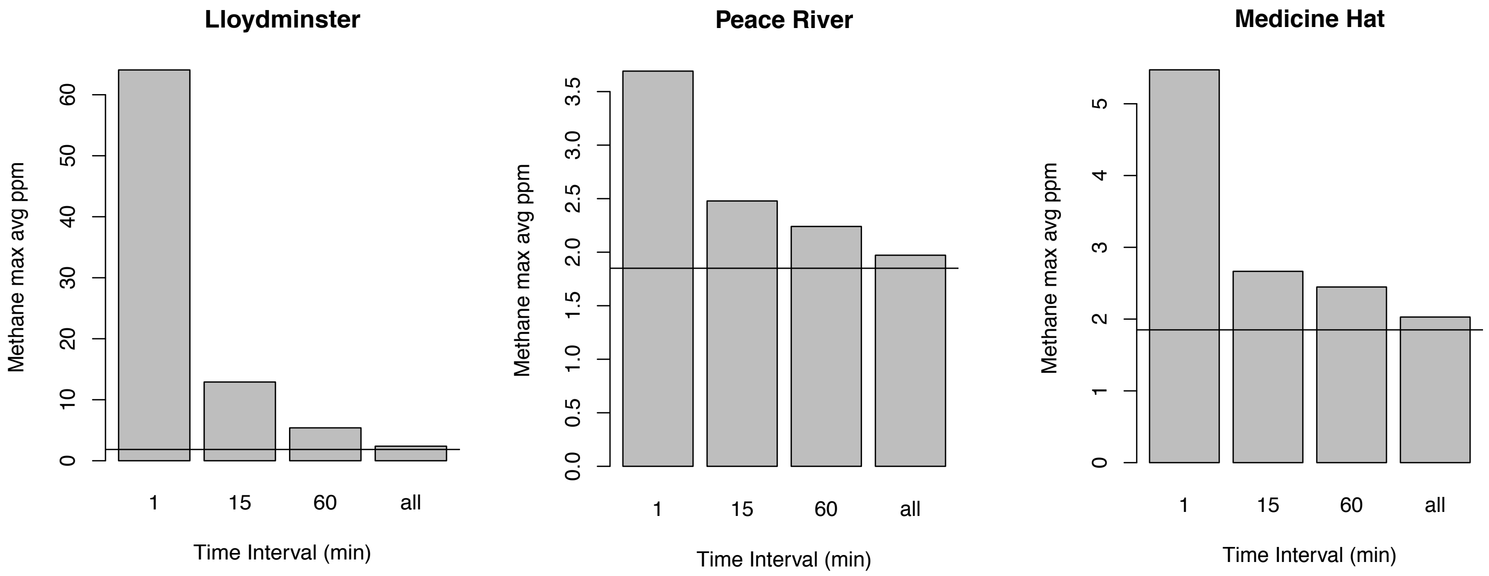


Figure 9. Methane plume concentration vs duration

As we are mobile during the surveys, at speeds of 60 km/h to 80 km/hr, the aforementioned moving averages also reflect concentrations over space. A 1-minute moving average might reflect a spatial domain of some hectares (local scale). A 1-hour moving average reflects average concentrations across many square kilometers (regional scale). Again, Lloydminster is the anomaly amongst the three campaigns, having by far the highest methane concentration over all timescales.

We know that local atmospheric CH_4 varies both spatially and temporally, but the influence of variables such as elevation, temperature, and time are unknown. A GAM analysis was run on ambient methane resets, meaning all natural or thermogenic plumes were filtered out in advance (Table 5). This deconvolution allows us to observe climatic and spatial influences on the background gas specifically. After running a series of Generalized Additive Models, it is apparent that time is the primary driving force for ambient methane variability during all three campaigns. This indicates that seasonal variability played a role in background concentrations. Temperature had the second largest influence. Elevation and longitude/latitude coordinates had the least influence, as determined by their individual percent of deviance explained. All were significant predictors, individually, and together. As shown in Table 5, the combined GAM score generally explained a very high fraction (>86%) of the deviance, which means that background variance was not random.

Table 5. Generalized additive model outputs. The F-statistical parameter is presented here to show the relative importance of each variable.

Lloydminster	% Deviance Explained	F	P-Value
Elevation	14.80%	49.87	<2e-16
Temperature	39.30%	313.6	<2e-16
Windspeed	23.10%	221.3	<2e-16
Time	77.00%	4248	<2e-16
Lat/long coordinates	12.20%	856.9	<2e-16
Combined	**91.90%**		
Peace River	% Deviance Explained	F	P-Value
Elevation	47.20%	95.69	<2e-16
Temperature	51.00%	181.1	<2e-16
Windspeed	45.60%	52.56	<2e-16
Time	84.70%	3254	<2e-16
Lat/long coordinates	43.00%	3681	<2e-16
Combined	**86.20%**		
Medicine Hat	% Deviance Explained	F	P-Value
Elevation	16.20%	34.1	<2e-16
Temperature	44.50%	500.9	<2e-16
Windspeed	28.80%	227.2	<2e-16
Time	84.70%	3254	<2e-16
Lat/long coordinates	14.00%	786.5	<2e-16
Combined	**97.00%**		

c) *Emission detection and attribution – patterns and comparisons across developments*

In total we enumerated many thousands of plumes, sampling downwind of infrastructure on nearly 10,000 occasions. Using geospatial back-trajectory analysis, we estimated emissions frequencies for various classes of infrastructure, as these statistics can be used to nuance (or confirm) the assumptions used in emission factor models. After applying the criteria described in section e) of the Methodology section, all known pieces of oil and gas infrastructure within the radius of on-road collection (200m-400m, depending on campaign) were tagged as either an emissions source - or not. We considered only pieces of infrastructure that we had sampled at least in duplicate within the triplicated campaigns, and excluded all pieces of infrastructure that were sampled only a single time. For these pieces of infrastructure sampled at least in duplicate, there average detection distances of emitting and sampled infrastructure are summarized below in Table 6. We also present minimum detection limits in Table 6 for this analysis, which we calculated according to prevailing atmospheric conditions at the time of campaigns. While infrastructure was farthest away from the road in the Peace River campaigns, it was the Lloydminster campaigns that had the coarsest MDL owing to less favourable wind conditions.

Table 6. Detection distance and associated and minimum detection limit per campaign

	Average Distance (m)	**Minimum Detection Limit (m^3/day)**
Lloydminster	124.9	10.34 - 25.86
Peace River	239.8	6.463 - 12.93
Medicine Hat	130.8	1.034 - 2.586

Before presenting development-specific emission frequency statistics, readers should remember that road-based campaigns generate remotely-sensed estimates that are not equivalent to inspections or on-pad measurements. We are typically very confident in emissions detection (regardless of size or severity), but back-trajectory analysis incorporates some uncertainty. Even when directions are perfectly on-point, we cannot readily identify shadow plumes from infrastructure in the farther distance. We are also unable to discern emissions that originate from pipelines or other pervasive forms of infrastructure not considered in this study, which may cause wells or facilities to be inadvertently flagged. Finally, parsing individual emissions from closely-grouped infrastructure is difficult, and frequency statistics may be moderately inflated where multi-well pads are common, because a plume detected at road may cause several co-located wells to be flagged. We manage this uncertainty by being conservative in approach, for example by requiring pieces of infrastructure to be flagged multiple times (independent measurements, usually on different days) before classifying them as emitters.

In total, 439 wells and facilities within the Lloydminster heavy oil region, 130 within Peace River oil sands, and 232 around the Medicine Hat shallow gas field that were tagged as potential emission sources of methane. Table 7 presents a fractional breakdown of wells by status, and their contribution to total emissions by region. Table 8 presents a similar fractional breakdown, yet by facility type. Infrastructure was tagged as emitting in a binary, 'yes' or 'no' fashion, which omits details on severity so that both super emitters and infrastructure emitting near the minimum detection limit contribute equally to the overall emitter totals. The final column on Tables 7 and 8 (average methane above background (or excess methane)), at the point of detection, is an indicator of severity. These tables also indicate emission persistence. Any piece of infrastructure emitting over 50% of the times it was surveyed was counted as emitting. Persistent emitters, labeled in the table as continuous emitters, are those that are emitting for 100% of survey passes. Discrepancy between these two columns in Tables 7 and 8 reflect the episodic nature of emissions.

For simplicity, suspended, active, and abandoned wells of all categories have been combined under a singular heading. Suspended wells include: suspended crude bitumen, suspended gas, suspended oil, suspended shale gas, suspended water disposal, suspended water source, suspended water injector, and suspended cyclical crude bitumen. Abandoned wells include: abandoned and whipstocked, abandoned crude bitumen, abandoned crude bitumen zone, abandoned cyclic oil, abandoned gas, abandoned observation, abandoned oil, abandoned water disposal, abandoned re-entered oil, abandoned coalbed methane, abandoned farm gas, abandoned zone, oil abandoned zone, and abandoned gas zone. Active wells include: flowing gas, flowing oil, flowing coalbed methane, pumping crude bitumen, and pumping oil.

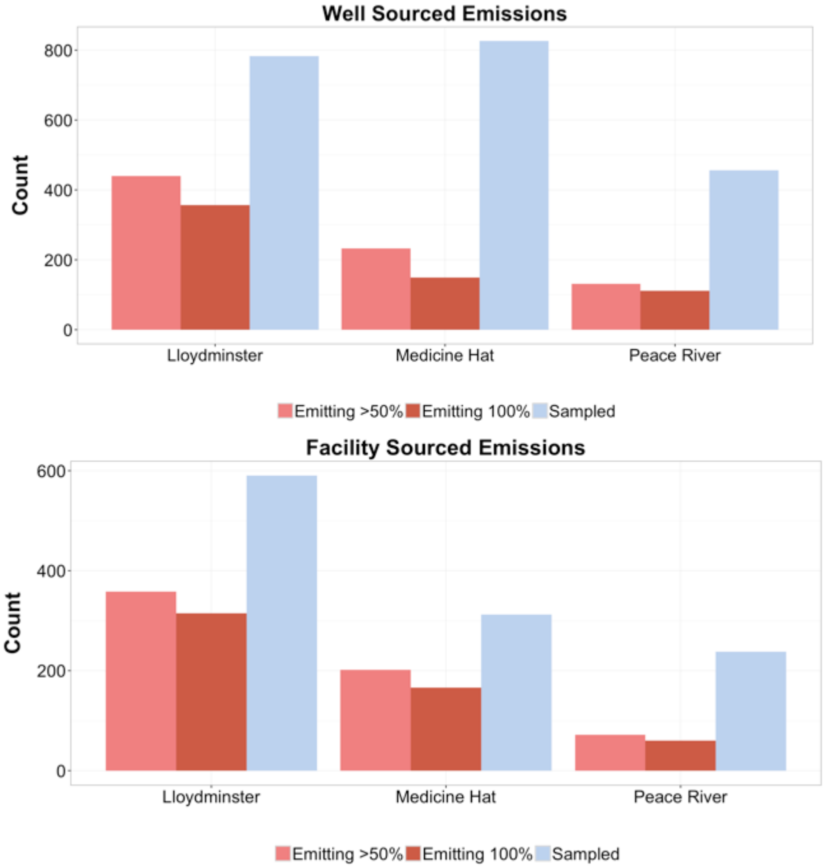


Figure 10. A comparison of wells and facilities tagged as emitters, relative to the overall amount sampled per campaign. Continuous (or persistent) emitters flagged on each and every pass are labeled as 'Emitting 100%'.

Tables 7 and 8 show that in all campaigns we flagged a certain number of suspended wells as emitters. However, readers should note that active wells in all cases were emitting at a higher methane concentration than suspended wells. In Medicine Hat's case, suspended wells were emitting at a higher frequency, although active wells were emitting at a more significant severity. In some cases, emissions from the flagged suspended wells may originate from Gas Migration, or potentially also from old associated pipelines etc.

Table 7. Breakdown of surveyed vs emitting wells for each campaign. Only well classes that were sampled over 7 times have been included, explaining why totals are smaller than Table 2.

Lloydminster

Well Type	Sampled	% Emitting	% Continously Emitting	Avg. CH_4 above background (ppm), & standard deviation (σ)
Suspended*	286	56.99	45.10	0.788, **σ**1.79
Abandoned*	264	45.83	35.23	0.533 **σ**1.40
Active*	192	64.58	56.77	0.844 **σ** 1.78
Standing	25	80.00	68.00	2.63 **σ** 5.00
Total	**767**	**55.80**	**45.37**	

Peace River

Well Type	Sampled	% Emitting	% Continously Emitting	Avg. CH_4 above background (ppm), & standard deviation (σ)
Active*	168	38.69	33.93	0.246 **σ** 0.310
Abandoned*	105	9.52	5.71	0.154 **σ** 0.205
Suspended*	45	35.56	24.44	0.173 **σ** 0.222
Water Injector	38	36.84	36.84	0.399 **σ** 0.297
Cyclical Crude Bitumen	28	0.00	0.00	0
Standing	24	41.67	29.17	0.247 **σ** 0.343
Drain	20	50.00	50.00	0.082 **σ** 0.059
Total	**428**	**29.21**	**24.53**	

Medicine Hat

Well Type	Sampled	% Emitting	% Continously Emitting	Avg. CH_4 above background (ppm), & standard deviation (σ)
Active*	601	26.29	15.97	0.061 **σ** 0.186
Abandoned*	100	29.00	19.00	0.055 **σ** 0.075
Commingled	51	29.41	23.53	0.048 **σ** 0.070
Suspended*	49	40.82	22.45	0.046 **σ** 0.092
Standing	11	27.27	27.27	0.093 **σ** 0.114
Total	**812**	**27.71**	**17.36**	

Table 8. Breakdown of surveyed vs emitting facilities for each campaign. Only facility classes that were sampled over 7 times have been included, explaining why totals are smaller than Table 2.

Lloydminster

Faciltiy Type	Sampled	% Emitting	% Continously Emitting	Avg. CH4 above background (ppm), & standard deviation (σ)
Battery	554	61.01	53.25	0.882 **σ** 2.19
Meter and/or Regulator Station	9	33.33	33.33	0.145 **σ** 0.295
Gas Gathering System	8	75.00	75.00	1.00 **σ** 2.25
Injection Plant	7	42.86	42.86	1.25 **σ** 2.39
Total	**578**	**60.55**	**53.11**	

Peace River

Faciltiy Type	Sampled	% Emitting	% Continously Emitting	Avg. CH4 above background (ppm), & standard deviation (σ)
Battery	194	31.44	25.77	0.154 **σ** 0.195
Meter and/or Regulator Station	19	21.05	15.79	0.071 **σ** 0.064
Injection Plant	8	37.50	37.50	0.120 **σ** 0.179
Total	**221**	**30.77**	**25.34**	

Medicine Hat

Faciltiy Type	Sampled	% Emitting	% Continously Emitting	Avg. CH4 above background (ppm), & standard deviation (σ)
Battery	241	67.22	56.02	0.251 **σ** 0.321
Meter and/or Regulator Station	25	52.00	52.00	0.081 **σ** 0.089
Compressor Station	25	60.00	40.00	0.162 **σ** 0.239
Gas Gathering System	13	53.85	38.46	0.177 **σ** 0.257
Total	**304**	**64.80**	**53.62**	

In Lloydminster, suspended, abandoned, and active wells accounted for 95% of the 783 wells that were sampled downwind. Of these, active wells (124 total) contributed the most to the overall emitting infrastructure count (439). Active wells were emitting with the highest severity. Lloydminster emissions were the most episodic. A surprisingly high proportion of suspended and abandoned wells were flagged as emitters. It is possible that they are emitting, or that proximal infrastructure is emitting and we can't discern source so all infrastructure is flagged. Grouped infrastructure was a problem for the geospatial attribution in Lloydminster more than at other sites, and ideally we would like to carry out future ground campaigns on-pad at Lloydminster to address this issue and refine our estimates. As illustrated in Figure 11 below, wells and facilities of numerous classes contributed to the total emissions in Lloydminster, where 56.07% of wells and 60.71% of facilities were identified as emission sources.

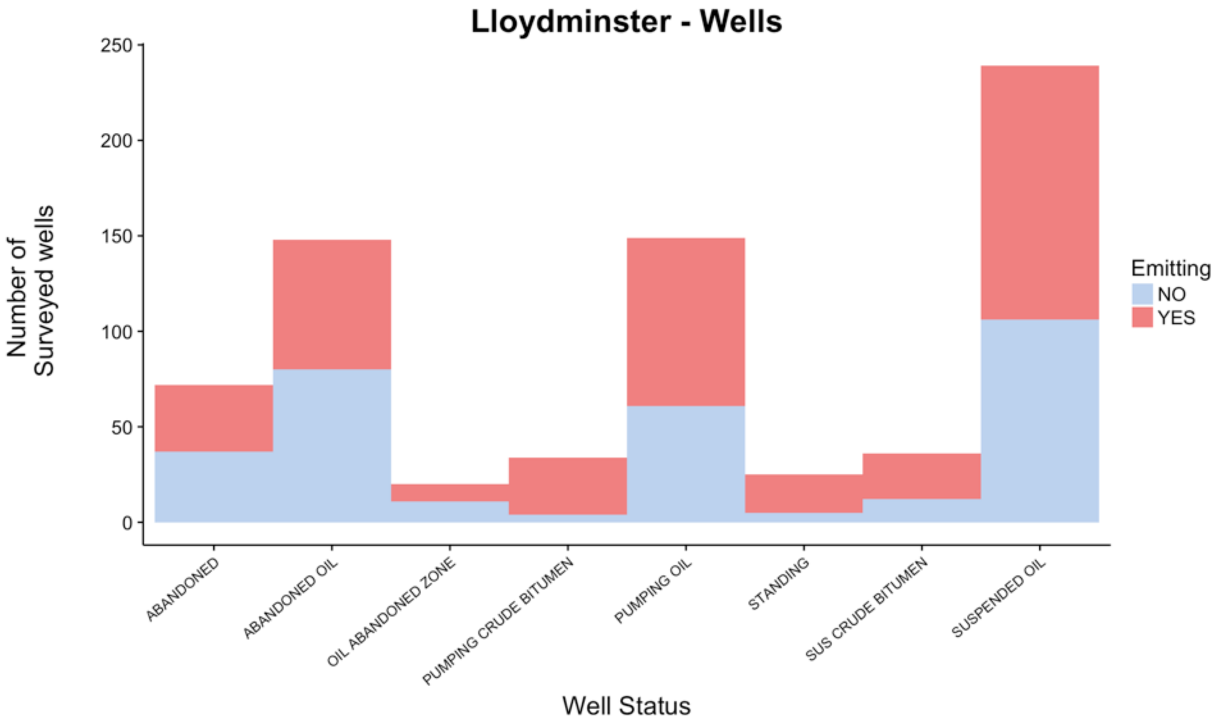


Figure 11. Emitting and surveyed well totals for Lloydminster, AB, broken down via status. Classes of wells which were sampled under 10 times have been omitted.

Some proportion of CHOPS-related methane emissions may originate from wellhead (casing) venting or tank venting. These wellhead vents are a significant source of emissions in Alberta, according to the current Federal National Inventory Report on Greenhouse Gas emissions. They tend to be intermittent, which poses one of the basic challenges of methane mitigation from CHOPS developments. In Alberta, proposed legislation aims to reduce venting from CHOPS sites. CHOPS facilities in the Lloydminster area do not typically include pipeline gathering systems or infrastructure to capture the vented gas. The only solution to venting gas at such sites currently is to conserve the gases, consume the gases, or convert the gases to CO_2. Emissions from newer sites can be controlled by a vapor recovery unit, yet such infrastructure is not prevalent in Lloydminster, resulting in more substantial emissions from tanks. A breakdown of well and facility classes by emissions persistence is illustrated in Figure 12 of the Appendix.

Figure 13 (below) shows that active wells in Peace River made up the majority of sampled wells in the region (168), and contributed the most to overall well emissions (38.7%). Due to road constraints and the layout of the field, the least amount of infrastructure was sampled in Peace River, over 300 pieces less than the other two regions. Well and facility emissions were both low, and similar, when compared to other campaigns. Unlike Lloydminster, very few abandoned wells were interpreted to be emitting.

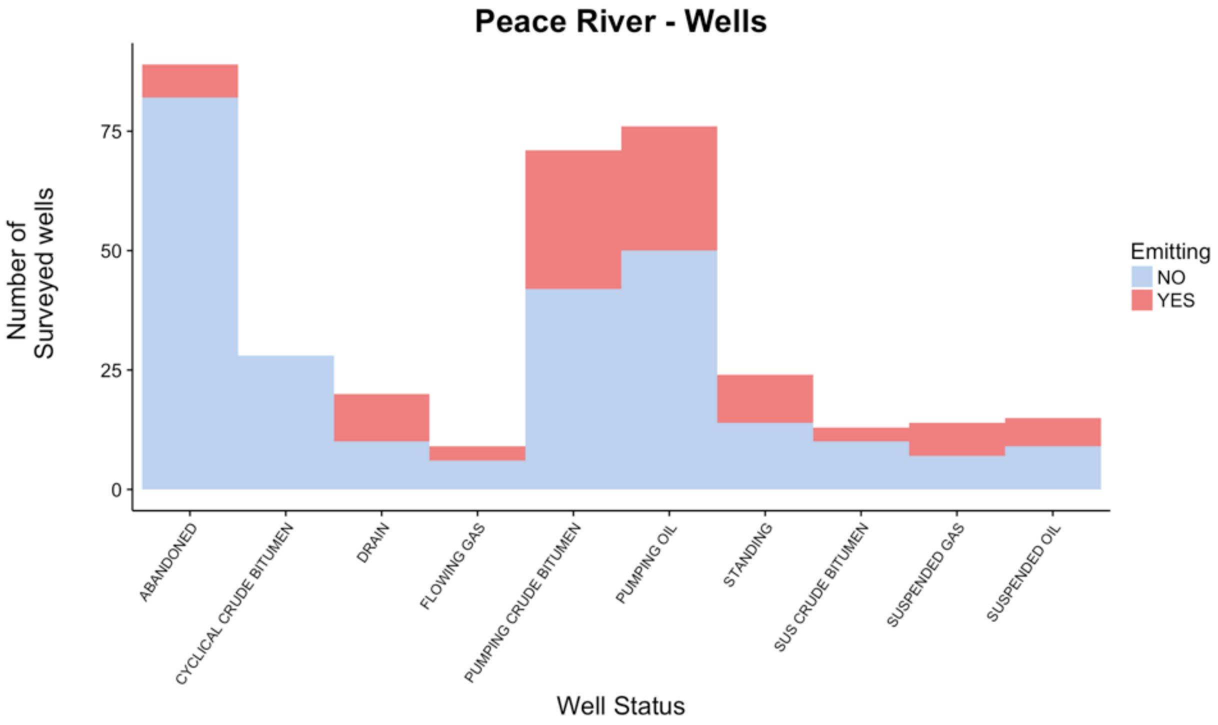


Figure 13. Emitting and surveyed well totals for Peace River, AB, broken down via status. Classes of wells which were sampled under 10 times have been omitted.

Figure 14 (in Appendix) breaks down the 130 well emitters and 71 facility emitters by status or type, and persistence. Regulatory action taken by AER within the past three years in Peace River may be partly responsible for the low emissions count within the region, as Bulletin 2014-17's mandate is to eliminate venting and minimize flaring in the area. Peace River experienced the lowest combined well and facility emission incidents of all campaigns. Despite emission management by industry, Peace River also recorded the highest H_2S of all campaigns, which is not surprising due to the sulfurous nature of the deposits. Alberta's ambient air quality objectives for H_2S state that concentrations must not exceed a one hour average of 10 ppb, or 24-hour average of 3 ppb (Alberta Government, Ambient Air Monitoring Performance Specification Standards, 2015). Although values in Table 3 surpass such limits, we cannot classify this as an accurate exceedance. Mobile surveying only captures a point in time snap-shot. A series of stationary ambient measurements over a defined time interval would be needed to make an accurate statement. However, our results do indicate a possibility of exceedances in the area, and further stationary monitoring is recommended to ensure compliance with ambient air quality guidelines.

Illustrated in Figures 15 below, active wells and battery facilities were the most common class of infrastructure surveyed in Medicine Hat, with 73% of all surveyed wells classified as active. A further analysis, involving persistence, is shown by Figure 16 in the Appendix. Favorable wind conditions and a dense development allowed us to survey 826 unique wells and 311 facilities throughout 15 surveys. Unlike Peace River, where emitting frequencies for wells and facilities were nearly equal, Medicine Hat showed a large difference between the rate of emitting wells (28.09%) and emitting facilities (64.63%). In the Medicine Hat and adjacent regions, many facilities do not use pneumatic pumps or controls, due to production specifications and facility design. Here, wells generally have a pipe-in/pipe out configuration with no surface facilities such as separators. As a result, there are limited emissions from pneumatic devices (Asualt, 2016).

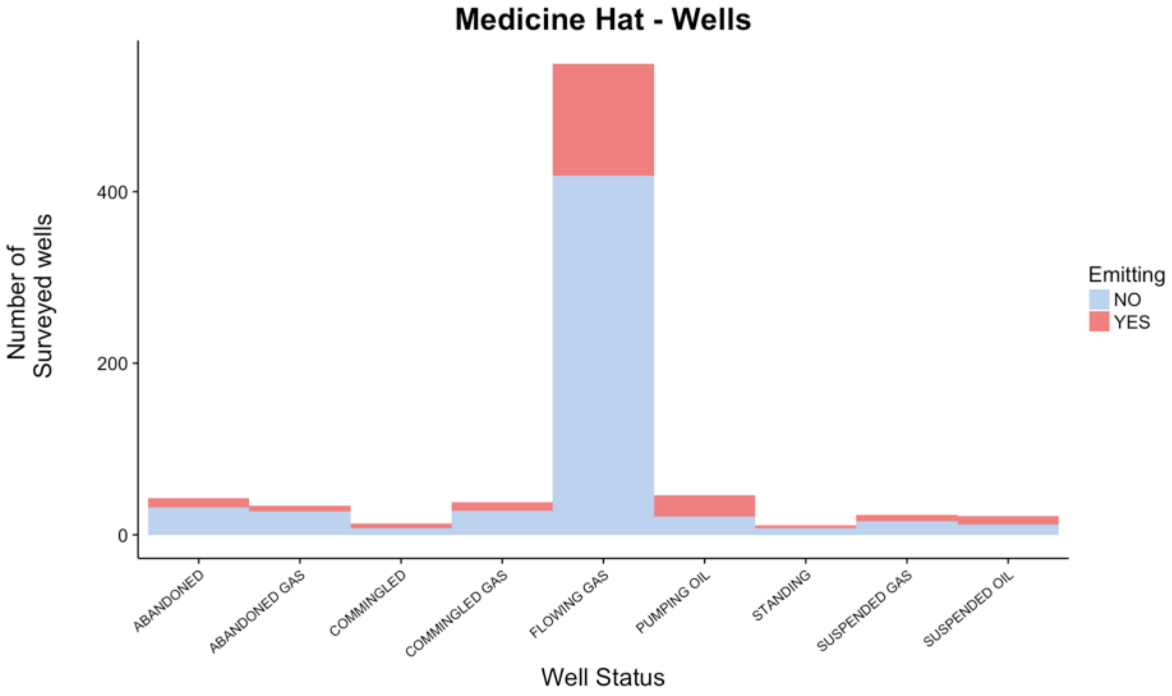


Figure 15. Emitting and surveyed well totals for Medicine Hat, AB, broken down via status. Classes of wells which were sampled under 10 times have been omitted.

There were no statistically significant trends between emissions persistence and operator size (Figure 17). Although there is a general trend amongst all campaigns that the percent of emitting wells surveyed decreases with operator size, the relationship is not statistically significant.

Several additional Figures are included in the Appendix, including emissions density heat maps for the developments that were sampled. Readers who are interested in additional data visualizations should leaf through the Appendix.

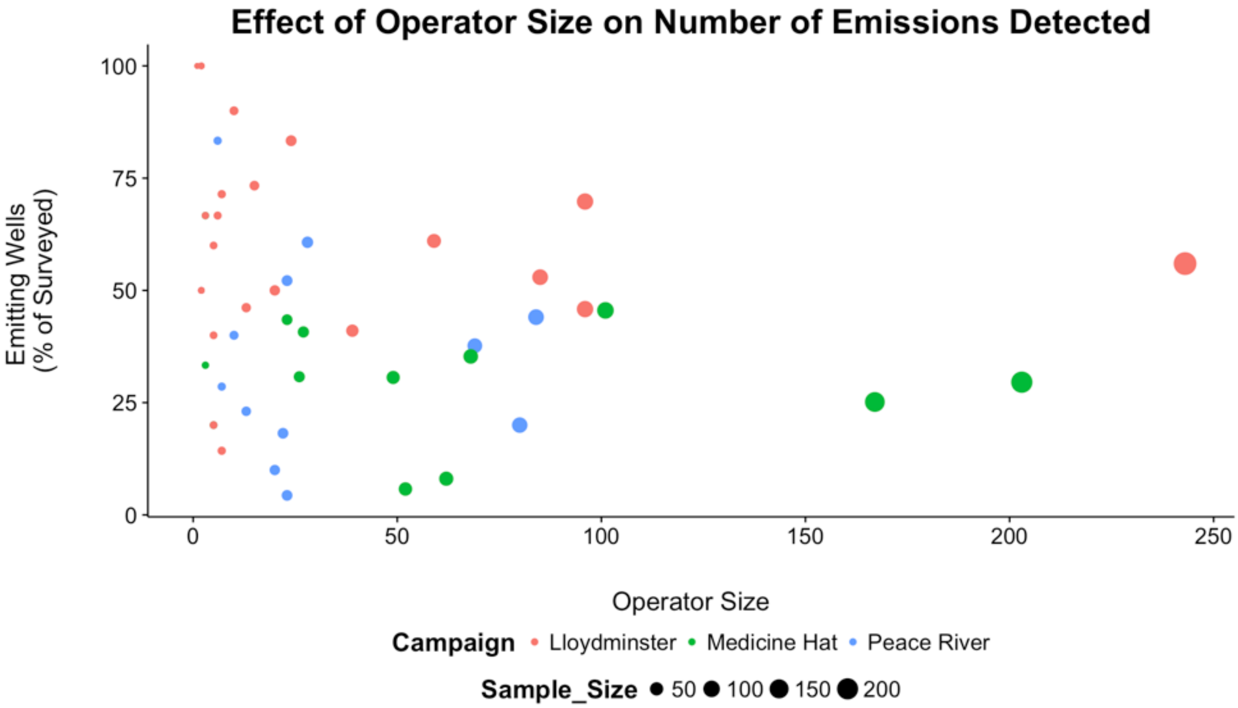


Figure 17. Effect of operator size on detected emissions. The size of the dots represents number of samples, or occurrence (n). There was no statistical relationship between operator size and emissions in any of the developments.

We generally prefer to do these surveys on-pad with the permission of an industry partner, because proximity helps reduce or eliminate most of these uncertainties. However, roadside campaigns are a good first-order approach, which also help to map concentrations and geochemistries/competing sources. The geochemical approach provides high certainty that plume hits are generated by energy sector activities, giving excellent screening data for further investigation at points of interest.

Our emission frequency estimates are somewhat lower (more conservative) than the Greenpath 2016 Alberta Fugitive and Vented Emissions Inventory Study (Anhalt, 2016) that used FLIR-type inspections. This difference is to be expected, as very small vents or fugitives that can detected onsite may well fall underneath our road-based minimum detection limit. Where the studies differ significantly is in the numbers. This study involved ~10,000 infrastructure passes in total, whereas the Greenpath study involved 676 inspections. The Greenpath study is a significant FLIR effort given that industry estimates for FLIR imaging allow for 2.7 hours per wellpad (ICF International 2014) or more. Road-based ExACT (or on-pad ExACT) screening is simply more efficient and allows for more coverage – though information is less detailed. But when a FLIR inspection takes 2.7 hours, and when the average on-pad ExACT truck survey takes 4.8 minutes

(100 pads per 8-hr day, at MDLs of 1-5 m^3/d), it makes sense to screen first by truck, then send FLIR operators only to where they're needed. The techniques are complimentary to one another.

Conclusions

Alberta's roughly 180,000 pieces of oil and gas infrastructure present numerous pathways and opportunities for methane-rich gas to escape to the atmosphere. This study was the first of its kind in Alberta, based on breadth and measurement density. Three-week campaigns conducted during fall 2016 collected several million geo-located data points. As determined from the report, emissions differ on a regional scale, by development, and thus need to be managed at an equivalent level. We cannot extrapolate these results across the broader Alberta upstream oil and gas inventory.

We identified several gas signatures (eCO_2:eCH_4, eCH_4.:eC_2H_6, and eCH_4:eH_2S) as being useful ExACT indicator ratios of plume presence and severity, source origin (i.e. biogenic vs thermogenic), and hydrogen sulfide presence, respectively. The isotopic signature of methane was also found to be a useful marker of energy sector emissions, except at Peace River. Quantifying the composition of ambient background and industrial plumes is an important first step for applying ExACT further within Alberta developments. Knowledge gained during this project will guide us during future monitoring campaigns.

This project has shown that some developments are more emission-prone then others, with emissions and air anomalies that are much more severe. Lloydminster, AB is an anomaly amongst Canadian developments, which is likely due to the high volume of tank batteries and associated venting. Infrastructure of all classes have shown to emit to some degree, including abandoned wells and facilities.

Future Work

Methane cannot be managed without the accurate collection of widespread, defensible measurements. An operation and its methane inventory is subject to continuous change over time. As governments work with operators to enforce more stringent regulations, emissions quantification data will be essential to track progress. This study has provided a foundation for further applicability of ExACT in Alberta.

The study will also continue. We have secured an NSERC Collaborative Research and Development (CRD) grant with the Petroleum Alliance of Canada (PTAC), enabling a one year extension of this research project. During this coming year, we will calculate volumetric emission rates, and inventory estimate calculations for existing data. We will also conduct more surveys. We propose to visit Red Deer area, a site in the Deep Basin, and to make a return visit to Lloydminster for more detailed follow-up work. In our return visit to Lloydminster, we will ideally pre-arrange well-site permissions with an operator or government group such as AER, or Alberta Energy. As further mobile monitoring surveys are completed in Alberta, a resulting database of atmospheric emissions will build depth and gain value over time. In the follow-up project, we will also push our understanding further by new research initiatives. This includes a ‘fit with FLIR’ component, where we will determine an optimized pass-off threshold between large-scale detection (mobile surveys) and short-scale detection (FLIR). The upcoming CRD project will collect supplementary emissions data for the benefit of government and industry. Additionally, it will increase our understanding of the advantages and limitations of our ExACT technique, as we develop it into a practical and assessable monitoring tool for the oil and gas industry.

Though we continue to do pioneering studies such as this, in new developments or territories, ExACT is now also available commercially to operators through Altus Group / Altus Geomatics.

Recommendations (Best Practice)

This project offers potential technological, operational, and policy solutions for emissions management. ExACT surveys are useful as a conformance tool, a screening tool, a detection tool, and a localization tool.

For conformance, many of the current industry inventory emission estimates are based on emission factor models. Up-scaling of these measurements propagates uncertainties or erroneous assumptions. Widespread direct measurements (100-400 well pads per day) can help test conformance of the inventory models measured from a small sub-population of infrastructure in good condition. Mobile measurements help mitigate inventory uncertainties, and allow an operator or regulator to demonstrate that emissions do conform to model estimates.

As a screening tool, ExACT holds significant efficiency advantages over FLIR. It can move much faster, and an entire development can be captured within a short timeframe. But ExACT also works extremely well with FLIR. Since FLIR requires a comparatively long time on site, it makes sense to send FLIR operators only to the well pads or facilities that are known to be emitting, and where a source must be established. Both techniques are part of a sensible emissions measurement approach.

As a detection tool, ExACT is particularly useful for detecting super-emitters. It can detect emissions >10 times farther away than a FLIR camera, with good geochemical certainty of source. Past US studies agree that a small amount of infrastructure is often responsible for a large proportion of emissions (10% of facilities are responsible for 60% of emissions, Rella *et al*, 2016). Super-emitters are rarely captured, which commonly leads to inventories that are underestimated (Brandt, 2014). There is a potential for significant methane reduction by targeting only a few heavy emitters, but they must first be identified, which can be difficult due to their rarity. ExACT is currently the closest thing to a remote sensing technique that can quickly map large areas at coarse resolution, and still record super-emitters because of sensitivity. Although the purpose of this report was to present regional scale patterns, we would recommend that further studies conduct more close-up monitoring where infrastructure is found to be emitting heavily. As equipment failure is a plausible cause of heavy emissions, targeting these sites for checkups could enhance operational safety.

As a localization tool, an ExACT crew can often arrive at a remotely-detected plume within 30-60 minutes. In some cases, where geochemistries are distinct between co-located operators as a function of differing process or reservoir, localization can be even faster. There are reports that, in some Alberta developments where public odor complaints were common, it took years to firmly establish source. Such uncertainty significantly erodes public confidence in both operators and regulators. Mobile tools like ExACT are designed for, and should be used for, problems of this nature.

ExACT is best used by operators – on-pad, and in proximity to infrastructure in large developments. This results in extremely low uncertainties, and distinct sources of interest like surface casing vent flows can sometimes be resolved geochemically. Regulators may also benefit from ExACT. While roadside campaigns always result in some uncertainty as to source, in some cases the actual source may not matter. For example, a regulator may be more interested in plumes and plume volumes, than in exactly where the plumes were coming from – which they might regard as an operator's issue.

Application

This study contributes to the body of vented and fugitive emissions knowledge, not only in Canada, but in North America more broadly. Large-scale emission snapshots and datasets have been generated for the benefit of multiple stakeholders, including government, academics, industry, and First Nations Communities. Results are a publicly available resource for people concerned about climate impacts of increased oil and gas production.

Proper understanding and application of this data has the potential to enhance environmental performance of oil and gas extraction activities across Alberta. Project outcomes could inform the development of smart policies, regulations, and best practices for the sustainable development and monitoring of Alberta's hydrocarbon resources, whilst assisting industry with cost reduction, ease of operations, and social license. Independently verified and updated emission factors inform the government about oil and gas emissions that are not captured by current monitoring practices. This data serves as a regional baseline, from which reduction policy progress can be built. Regulators may consider applying this study's methods to update improved fugitive and vented emissions monitoring, as well as reporting regulations or technology standards.

In the short term, project outcomes include:

- Enhance oil and gas industry environmental performance indicators;
- Use the significant quantities of data to construct "norms" of variation;
- Engage operators in the development of new, tailored monitoring technologies;
- Deliver widespread information on emission norms within the province.

Long term outcomes of this work include:

- A means by which Alberta operators and regulators can better understand gas emissions, report on gas emissions, address landowner complaints, and use this knowledge and technology to mitigate emissions;
- A means by which operators can clearly communicate with their regulator about air quality and monitoring issues;
- Potential to discriminate between operators who are emitting and those who are not, even within a dense development area;
- Enhancing the knowledge base of the provincial regulators;
- Intellectual Property (IP) that has the potential to provide economic benefits to Canadians.

Projection of Tangible Project Outcomes

If left unmonitored, fugitive emissions often go unnoticed. Such emissions represent lost product, have the potential to be toxic, and contribute to greenhouse warming. ExACT enables the industry to efficiently identify problematic infrastructure. This will minimize losses, preventing more serious problems from developing, and improving public image/social license. There are more wells in Canada than regulators can monitor with existing technology. ExACT fills this technological gap, allowing regulators to inform and enforce policy. Financial, environmental, and health/safety outcomes of this project are discussed below.

a) *Financial Value*

Emissions data enables industry to make quick, educated repair and reduction decisions, which could provide an economic advantage. As an effective method of detecting super-emitters, operators are able to identify and mitigate the most obvious emission sources on their field, ensuring regulatory compliance. Vehicle-based ExACT surveys would allow the oil and gas sector to develop better inventories at a lower cost.

Mobile surveying can help optimize fugitive and vented emissions monitoring programs. Fugitive and vented emissions are normally detected by FLIR imaging cameras. This technique is not appropriate for benchmarking emissions across thousands of wellpads. With a well understood combination approach, it is possible to maximize effectiveness, decrease costs, and augment data flow for operators.

In compliance markets, oil and gas operators must run Leak Detection and Repair (LDAR) programs that normally cost several hundred thousand dollars per year for a typical large site. Thermal optical imaging cameras are the industry standard for detection, although they are not the regulatory requirement in any country. While convenient, these $100,000 cameras lack the sensitivity of the off-the shelf analyzers used with ExACT surveys, and are primarily useful in up-close circumstances. While a FLIR operator can screen about 16 wells per day (ICF International, 2014), the range and mobility of the ExACT technique makes it possible to investigate several hundred in the same timeframe. It is unlikely that FLIR cameras will ever be displaced from the market, due to their very high utility in up-close situations. However, if the average infrastructure leak rate within the industry is roughly 20% (determined from previous large-scale monitoring projects), then FLIR camera use could be reduced or better used. This is because a FLIR operator should only attempt to find the source of a leak when up-close (impossible in many cases). ExACT is more cost-effective for screening.

The Environment and Climate Change Canada (ECCC) division of the federal government has released its proposed regulatory approach to reduce methane emissions from the oil and gas sector by 40 to 45 percent from 2012 levels by 2025. Upstream oil and gas facilities, except single well-heads, would be required to implement LDAR programs as of January 1, 2020. Regular inspections would be required three times per year, and corrective action would be required if leaks are discovered. The tools for inspection are not prescriptive, so innovative techniques such as mobile monitoring will be in the best interest of industry due to their cost and time saving capabilities. Truck-based screening tools could improve the economics of LDAR by reducing FLIR visits to non-emitting well pads or facilities.

b) *Environmental Net-Benefit*

Researching the severity of CH_4, CO_2, H_2S, and C_2H_6 released from oil and gas activity can help establish whether emissions are within regulatory thresholds, whilst indicating areas of opportunity for methane emission abatement. In this project, we defined appropriate geochemical targets, instrument suites, and frequencies of measurement, that can allow us to visit these developments at any time in response to emission issues. The overarching environmental net-benefit of this project, and mobile monitoring in general, is the potential for meaningful and transparent emissions (primarily methane) reduction.

c) *Health and Safety Improvements*

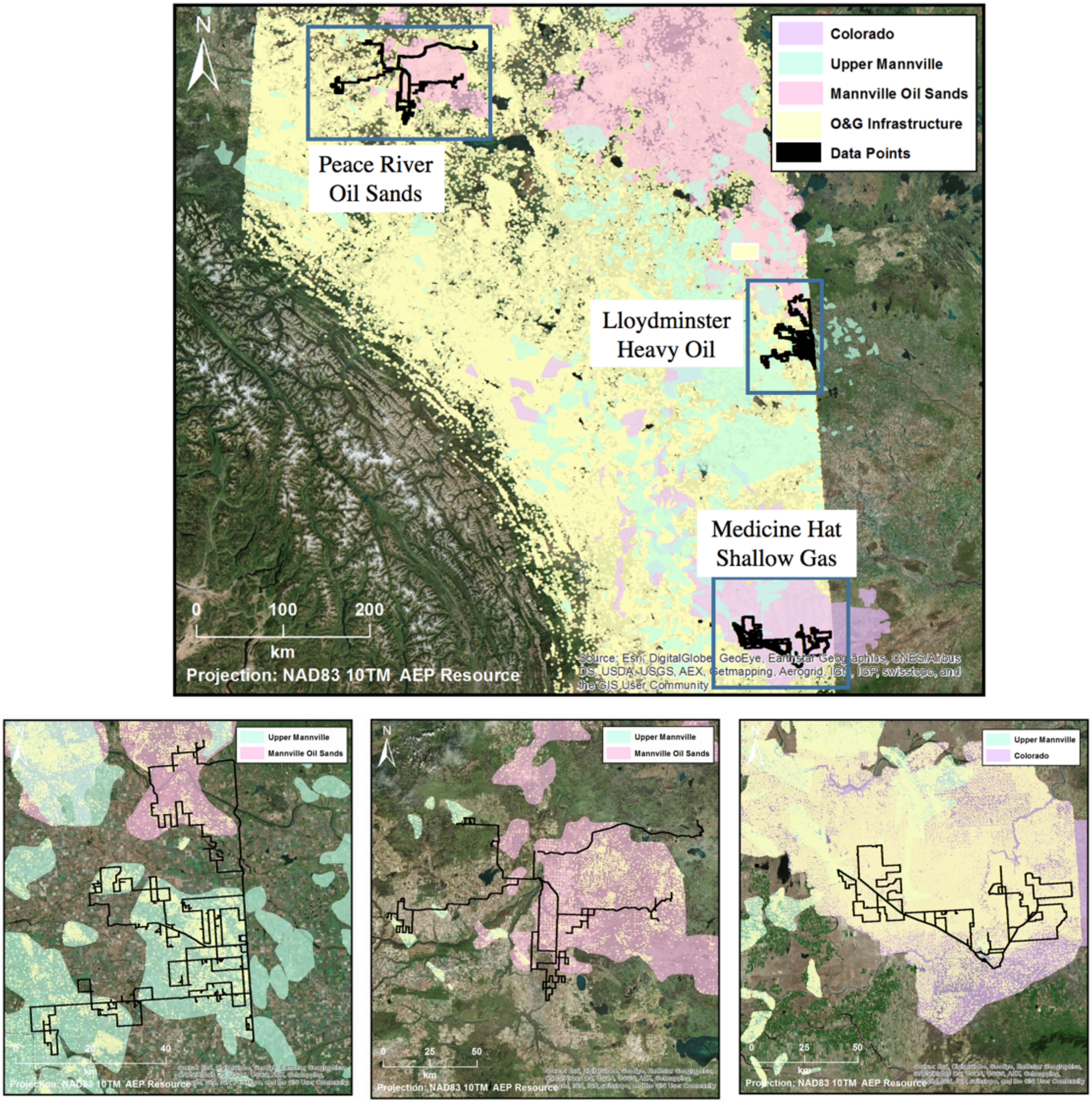
H_2S emissions are the prevalent reason for odor complaints on sour fields. ExACT's analyzer suite records H_2S (ppb concentration) at 1 Hz. The identification and attribution of this gas to associated infrastructure will assist in odor, (and hence complaint) management, allowing operators to efficiently respond to complaints. Due to the toxicity of this gas, H_2S management has both health and safety implications.

The presence of severe fugitive emissions in an energy development is an indicator of an operational error. A house exploded in the US recently, due to an unplugged flow line. Mobile surveys are an effective way to screen entire developments for hazards. Past research shows that sites with historic odor and/or H_2S issues are often tighter, indicating that regulators and industry *can* solve emission related problems. Some operators within this study already have very low emission indices, setting a benchmark for what is reasonably achievable.

Acknowledgements

We are very grateful for the support of the Petroleum Technology Alliance of Canada, whose Upstream Petroleum Research Fund (AUPRF) has funded this project.

Appendix



Lloydminster, AB *Peace River, AB* *Medicine Hat, AB*

Figure 1. AUPRF field campaign sites, showing the predominant geological formations within the region. Yellow symbols represent oil and gas infrastructure that lies within the specified formations. Survey routes are depicted in black.

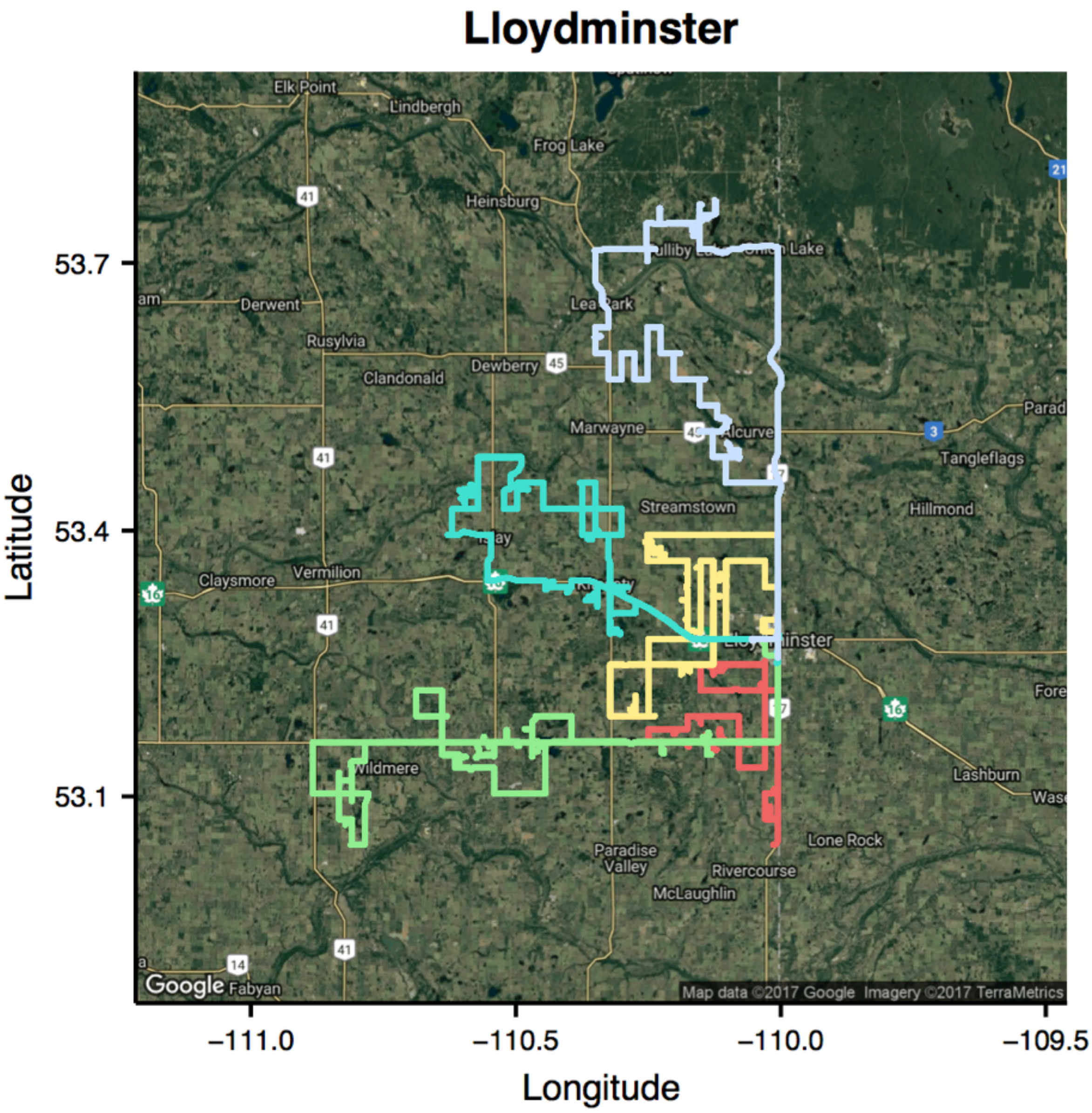


Figure 2. Lloydminster, AB survey routes. All five routes were repeated three times, totaling 15 surveys per campaign.

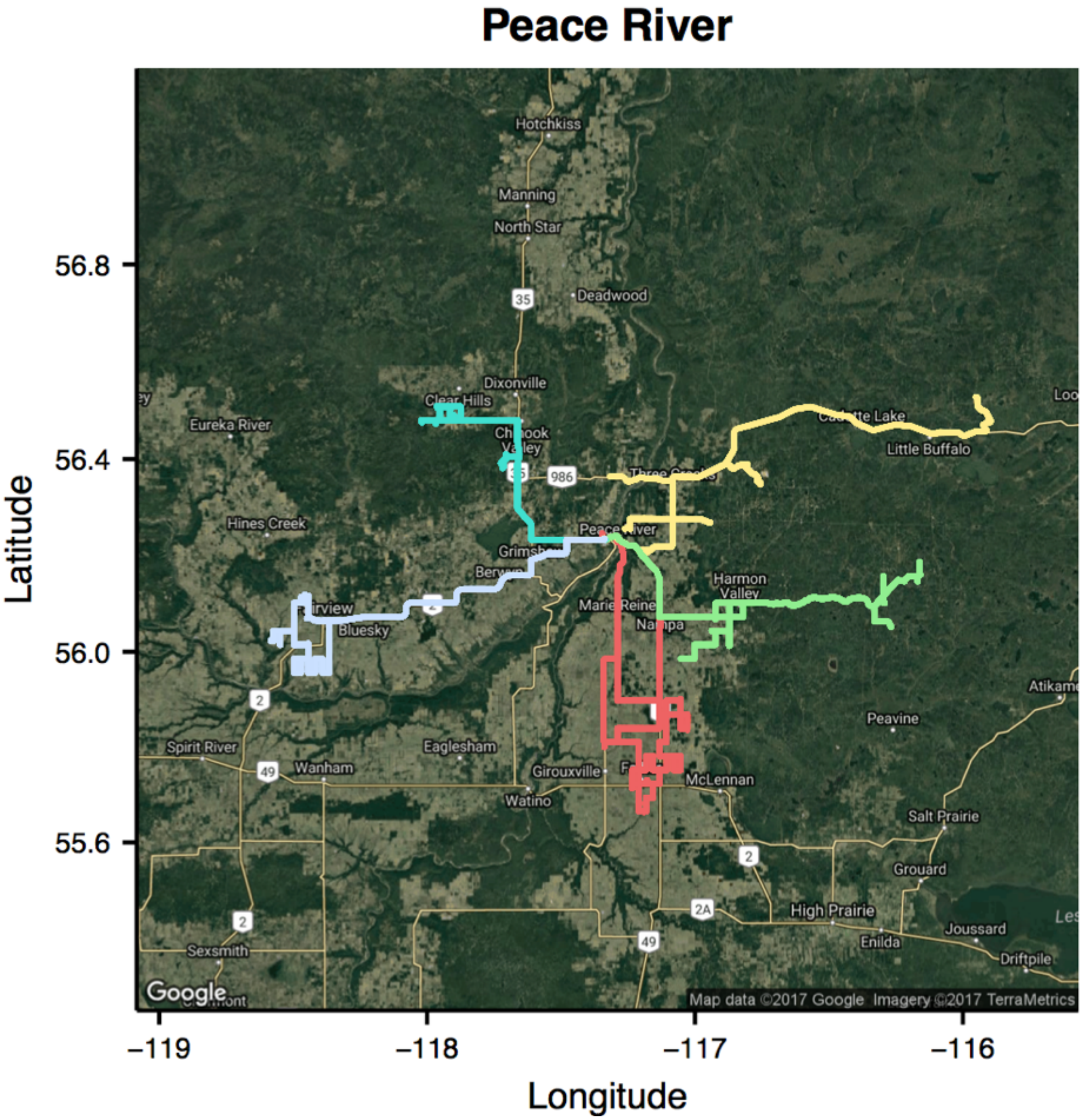


Figure 3. Peace River, AB survey routes. All five routes were repeated three times, totaling 15 surveys per campaign.

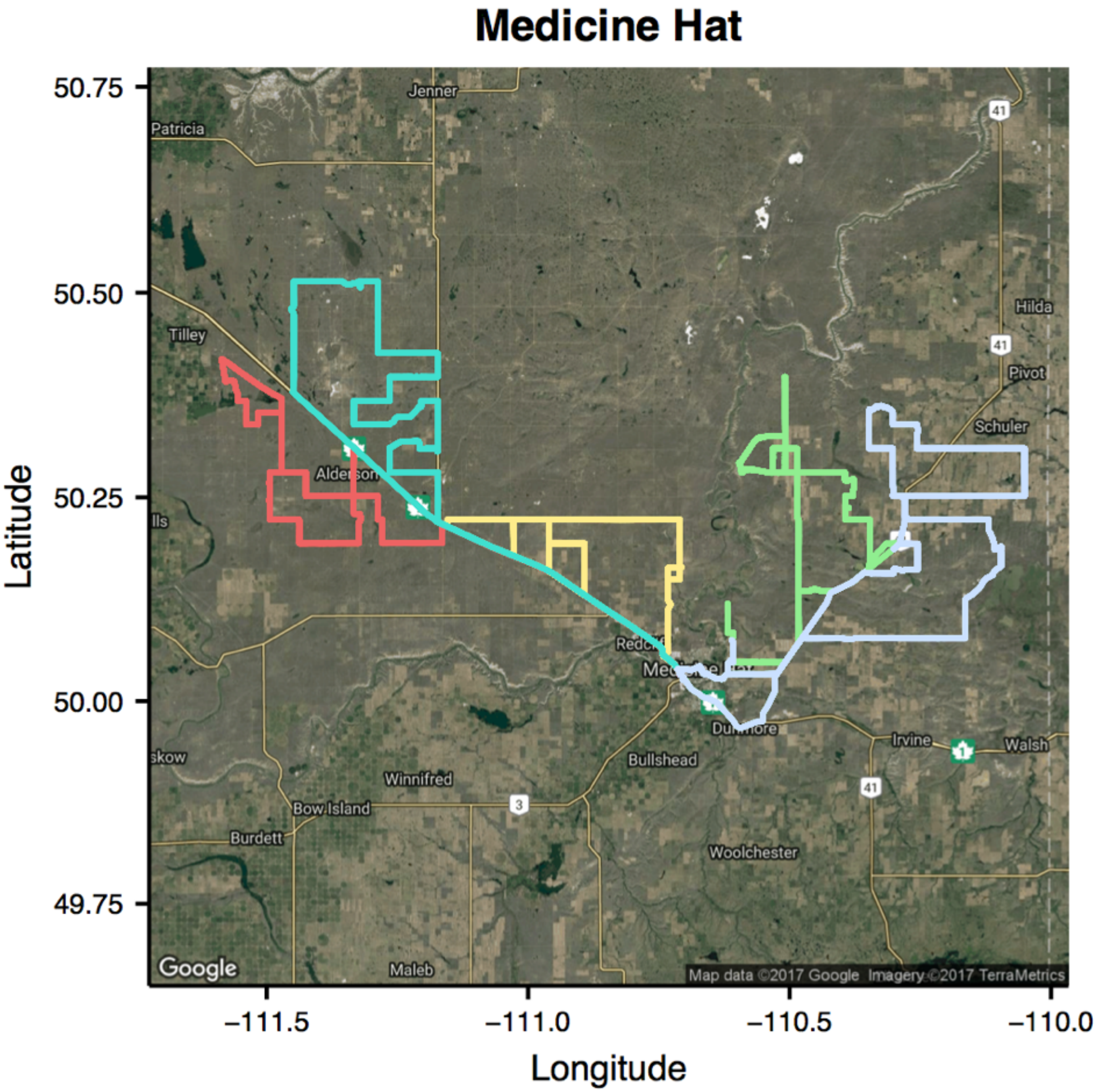


Figure 4. Medicine Hat, AB survey routes. All five routes were repeated three times, totaling 15 surveys per campaign.

Lloydminster

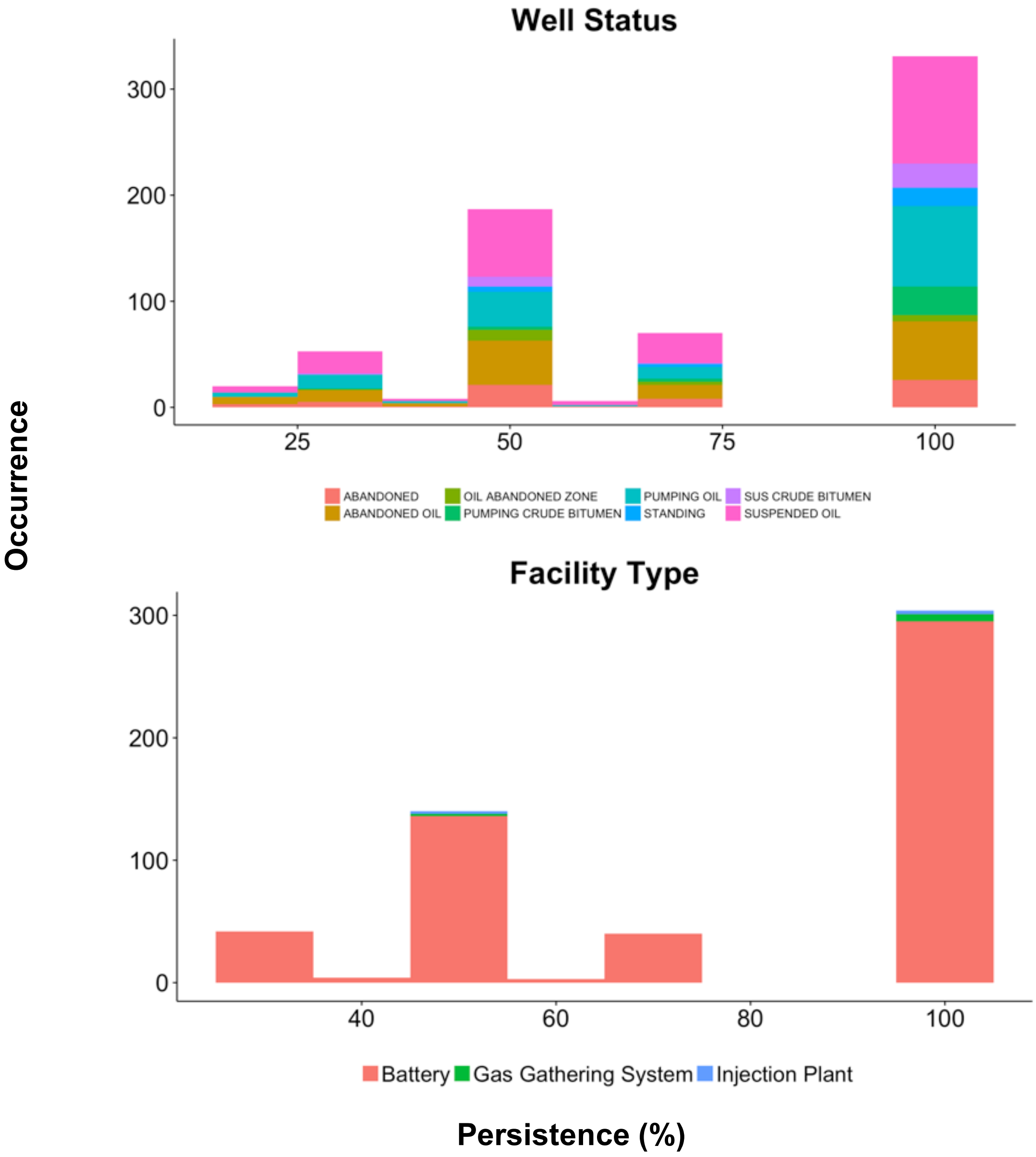


Figure 12. Occurrence (number) vs emission persistence (%) for wells and facilities in Lloydminster, AB. Persistence refers to the repeated tagging of the infrastructure according to criteria on each of the passes, when our truck was downwind and could have potentially detected an emission from the infrastructure in question. Although we only counted emitting infrastructure with over 50% persistence in our totals, infrastructure emitting less than that amount are often indicative of one-time events, or episodic emitters.

Classes of wells which were sampled under 10 times, and under 7 times for facilities, have been omitted.

Peace River

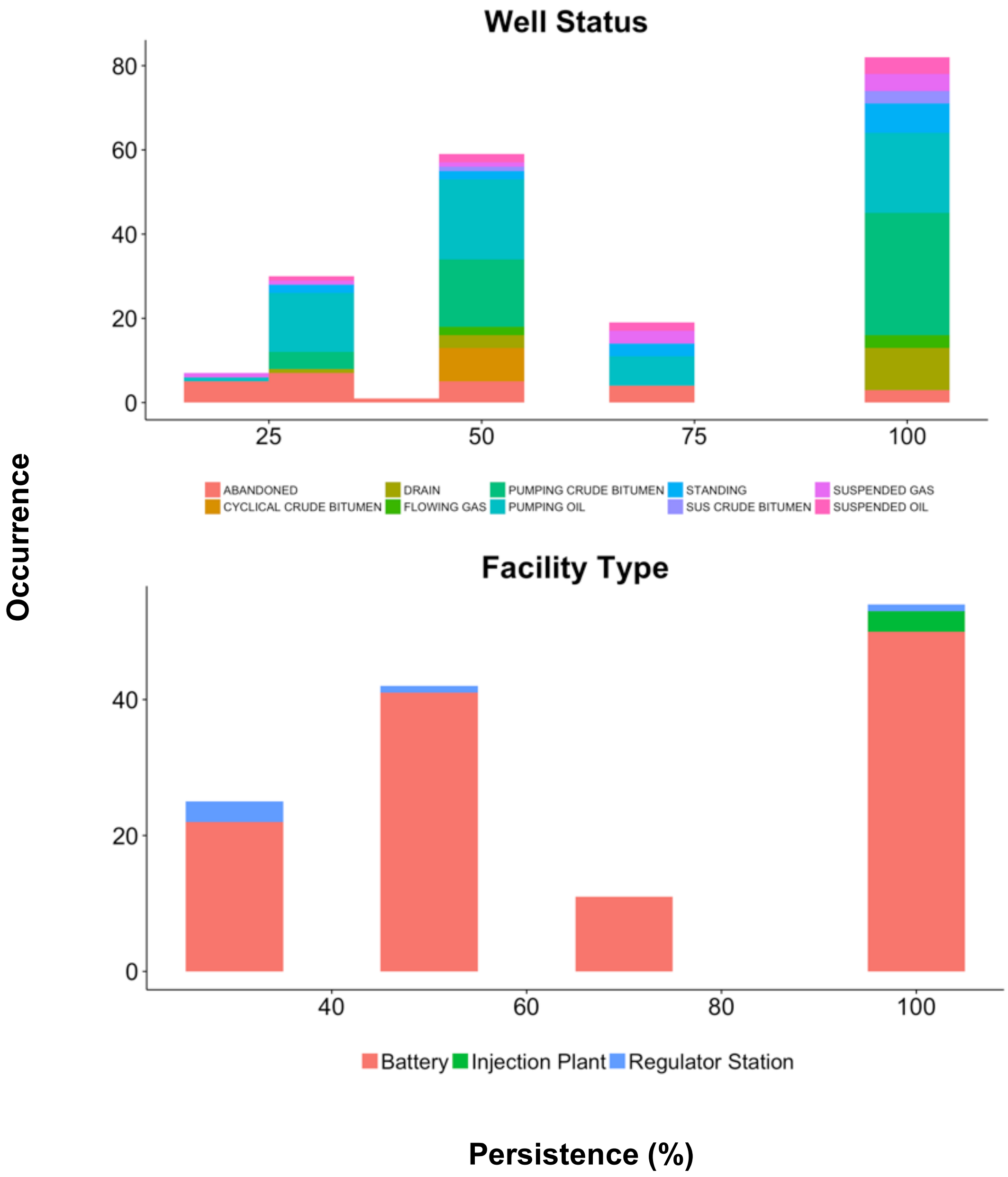


Figure 14. Occurrence (number) vs emission persistence (%) for wells and facilities in Peace River, AB. Persistence refers to the repeated tagging of the infrastructure according to criteria on each of the passes, when our truck was downwind and could have potentially detected an emission from the infrastructure in question. Although we only counted emitting infrastructure with over 50% persistence in our totals, infrastructure emitting less than that amount are often indicative of one-time events, or episodic emitters.

Classes of wells which were sampled under 10 times, and under 7 times for facilities, have been omitted.

Medicine Hat

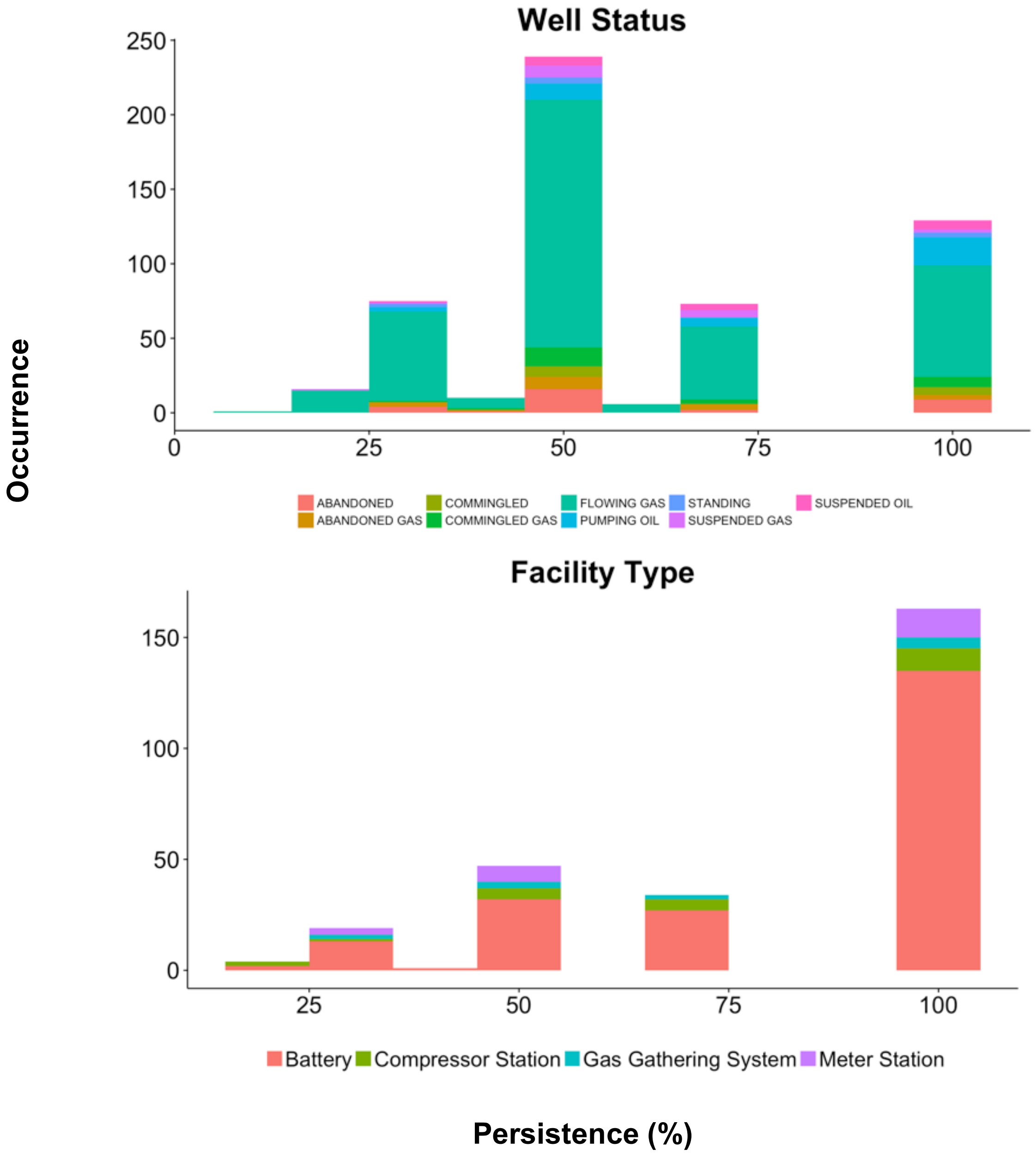


Figure 16. Occurrence (number) vs emission persistence (%) for wells and facilities in Medicine Hat, AB. Persistence refers to the repeated tagging of the infrastructure according to criteria on each of the passes, when our truck was downwind and could have potentially detected an emission from the infrastructure in question. Although we only counted emitting infrastructure with over 50% persistence in our totals, infrastructure emitting less than that amount are often indicative of one-time events, or episodic emitters.

Classes of wells which were sampled under 10 times, and under 7 times for facilities, have been omitted.

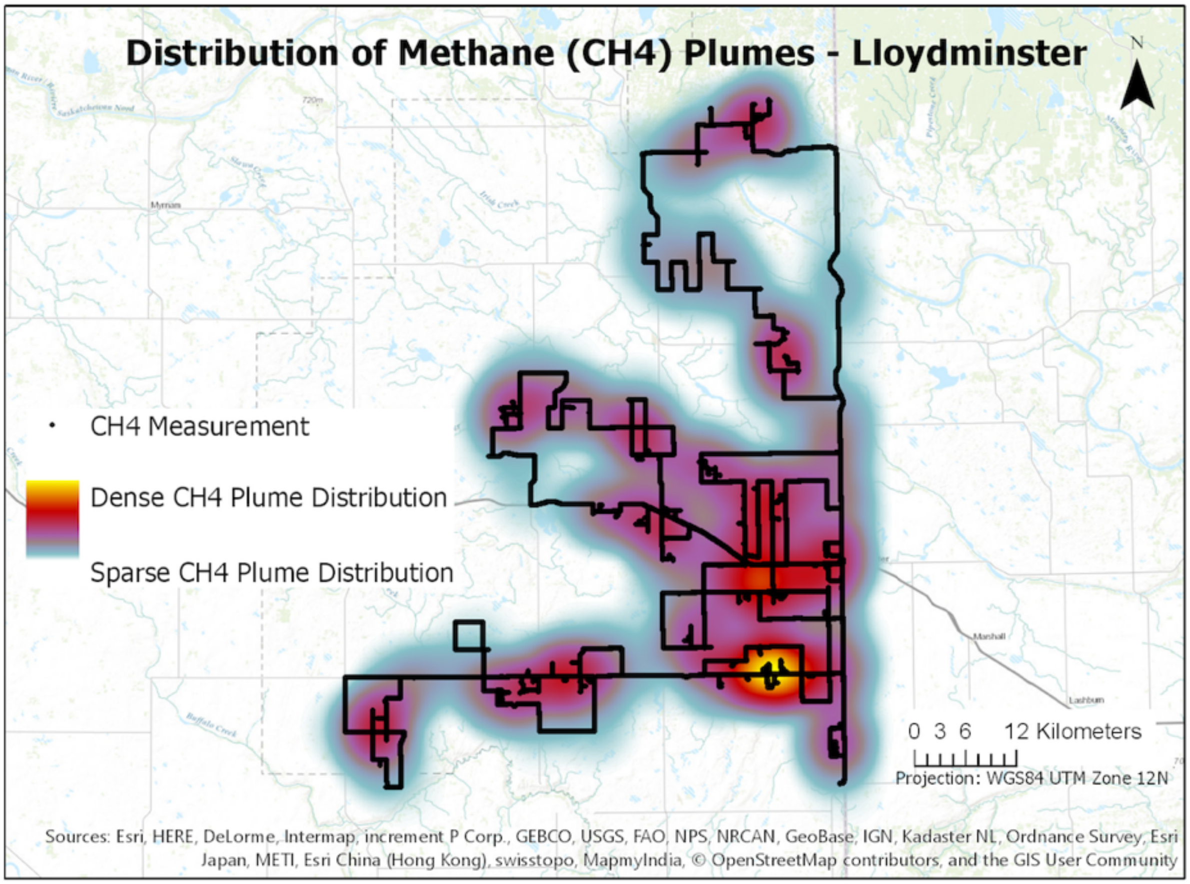


Figure 18. Distribution and density of methane plumes in Lloydminster, AB.

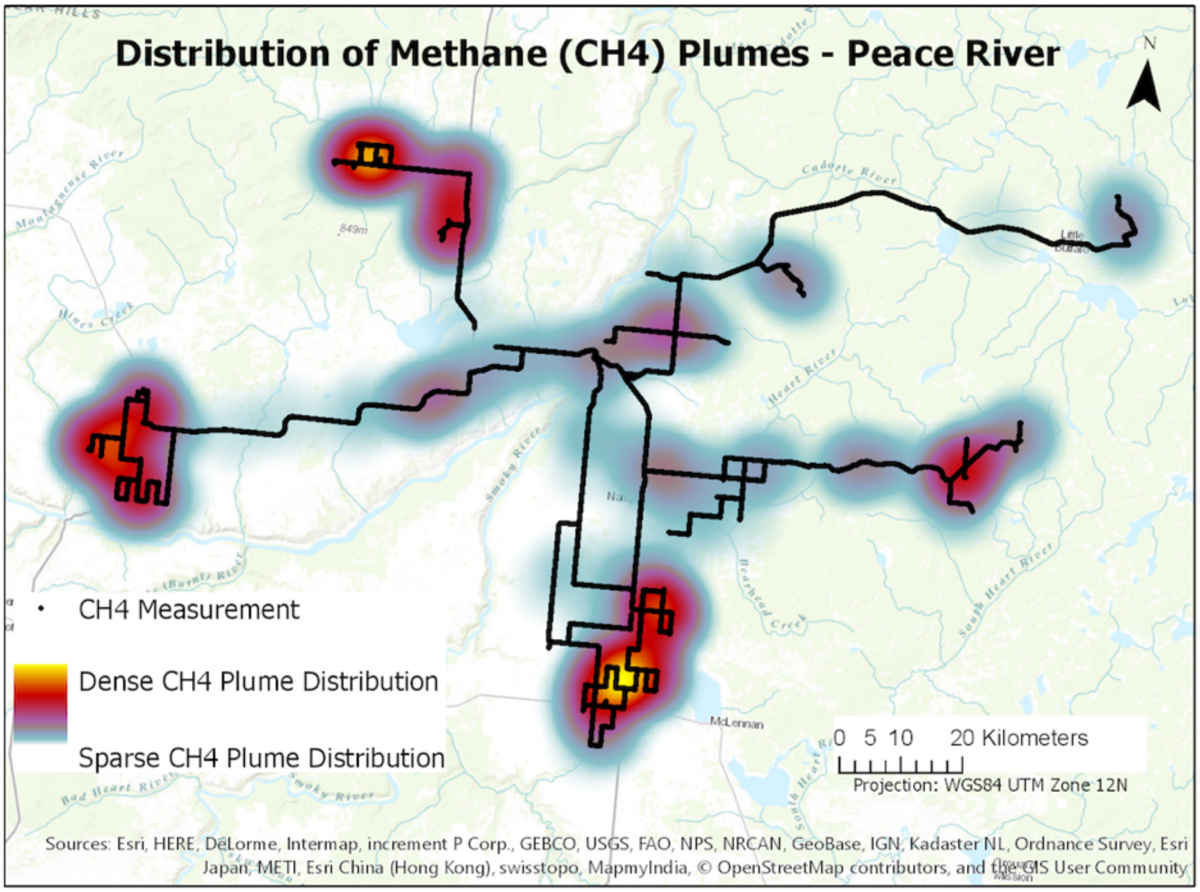


Figure 19. Distribution and density of methane plumes in Peace River, AB.

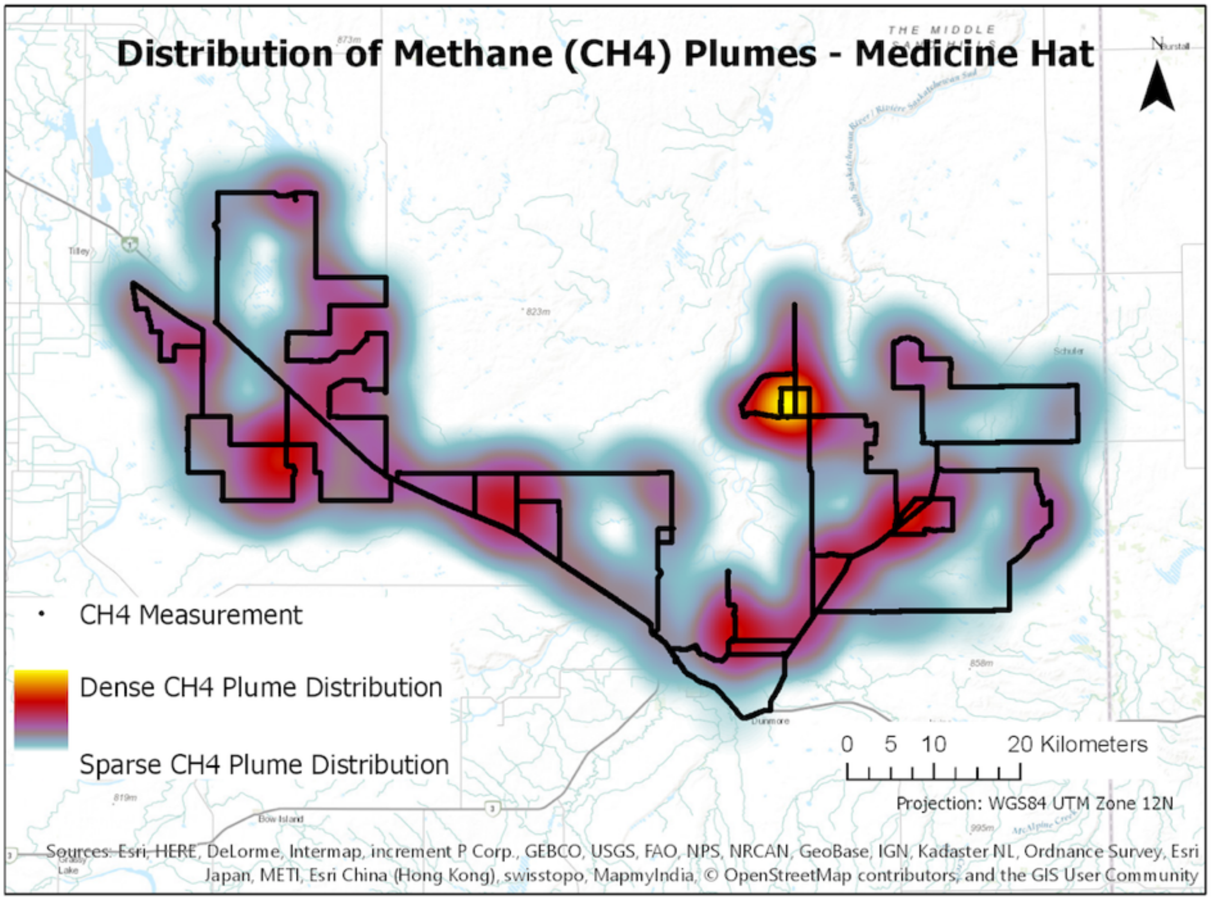


Figure 20. Distribution and density of methane plumes in Medicine Hat, AB.

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