Capturing Well Integrity Loss Through Measurements of Methane and Ethane Emissions from Surface Casing Vents and Soils Surrounding Oil and Gas Wells

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Abstract

Oil and gas wells (OGWs) can leak and lead to gas migration (GM) and surface casing vent (SCV) emissions of methane (CH_4), ethane and other contaminants. Studies measuring GM and assessing its variability with well parameters and studies assessing the relationship between SCV and GM emissions through field measurements are limited. Here, we used static chambers and conducted 1241 measurements of soil CH_4 emissions, indicative of GM, near 60 OGWs in Alberta and British Columbia, Canada. We also conducted a field test to check for SCV emissions of 41 of the 60 GM-measured wells and measured SCV flows at 37 wells using digital flowmeters. We found that soil CH_4 emissions varied by well status, produced fluid and sour status, where sour wells are wells with signs of hydrogen sulfide. Overall, we found a GM occurrence rate of 31.6%

with plugged abandoned and unplugged wells having the largest occurrence percentages of 50 and 32.1%, respectively. In Alberta, we found that measurement-based GM and SCV emission occurrence rates are larger than estimates based on provincial reports. Our results showed that GM and SCV emission occurrence can be higher than previously thought, highlighting the need for better regulations with improved measurement methods and policy enforcement.

Keywords

Oil and gas wells, gas migration, surface casing vents, field measurements, methane emissions.

1. Introduction

Oil and gas wells (OGWs) can lose their integrity and cease to contain oil and gas formation fluids within the well due to cement, casing, and above ground wellhead infrastructure failure (El Hachem & Kang, 2023; King & King, 2013; Kiran et al., 2017; Montague et al., 2018). Loss of well integrity leads to gas leakage that can be expressed through surface casing vent (SCV) and gas migration (GM) emissions (Abboud et al., 2020; El Hachem & Kang, 2023; Kiran et al., 2017; Montague et al., 2018; Wisen et al., 2020). SCV emissions occur when leakage migrates along the well casing and is released through the SCV, and GM emissions occur when leakage migrates away from the well casing into surrounding soil and reaches the atmosphere (Abboud et al., 2020). OGWs can emit methane (CH_4), higher order alkanes, volatile organic compounds, and hydrogen sulfide, thereby affecting human health, increasing climate change, contaminating groundwater and reducing air quality (El Hachem & Kang, 2023; Jackson et al., 2020; Masson-Delmotte et al., 2021; Osborn et al., 2011). Therefore, to comprehensively understand OGW integrity loss and its environmental impacts, it is essential to conjunctively study leakage expressed through GM and SCV emissions.

Recent studies highlight the importance of regulations to create measurement datasets that can be used to understand OGW leakage (El Hachem & Kang, 2023); however, regulations in Canada are more focused on SCV testing with limited requirements for GM testing (Seymour et al., 2024). The Canadian government has proposed new CH_4 regulations extending monitoring obligations to OGWs (Environment and Climate Change Canada (ECCC), 2023a, 2023b); however, the new monitoring regulations do not include GM. Although the regulations in Alberta recommend that SCVs are to be repaired in the presence of GM, GM testing after drilling and abandonment is required only for wells in the Lloydminster and Cold Lake heavy oil regions of Alberta (Seymour et al., 2024). In other regions in Alberta, GM testing is required only when stressed vegetation or bubbles in accumulated water near the well have been observed (Alberta Energy Regulator, 2023). Therefore, in the absence of robust GM testing requirements, relying on industry reported data to understand GM is challenging, and comprehensive measurements are needed to accurately assess the extent of GM.

Although GM and SCV emissions are both the result of OGW leakage, studies measuring GM emissions at the soil surface, and studies investigating the relationship between SCV and GM through field measurements are limited. In Canada, studies that investigated GM and its relationship with SCV emissions analyzed publicly available provincial reports that are based on industry submissions. This data is primarily focused on SCV emissions, with GM measurements conducted through in-soil concentration sampling, as recommended by regulators in Directive 087: Well Integrity Management (Alberta Energy Regulator, 2021). Unlike surface soil chambers, in-soil concentration sampling is not sensitive enough to detect small leaks and cannot be used to determine GM emission rates (Argento et al., 2022). Therefore, using in-soil sampling to measure GM is likely leading to an underestimation of GM occurrence. Similarly, this has been observed in a recent study measuring CH_4 emissions from SCVs of abandoned OGWs in Alberta and Saskatchewan using static chambers (Bowman et al., 2023). The authors found that chamber-based SCV emission occurrence rates were 3 to 5.3 times higher than occurrence rates derived from provincial data (Bowman et al., 2023). Therefore, it is important to use measurement methods that can determine GM emission rates, better estimate GM occurrence and understand its relation with SCV emissions.

In Canada's greenhouse gas inventory, soil CH_4 emissions that are the result of GM are assumed to occur at 7.8% of active (producing) heavy oil wells in Lloydminster in Alberta and Saskatchewan (ECCC, 2022). Thus, GM soil CH_4 emissions from other wells in Alberta and Saskatchewan are estimated to be negligible. The inventory estimates are based on GM soil CH_4 emission rate measurements that were conducted almost 30 years ago in Lloydminster, a region that intersects the borders of Alberta and Saskatchewan (Erno & Schmitz, 1996). Due to emissions from OGWs showing high geographic and temporal variability (Brantley et al., 2014; El Hachem & Kang, 2023; Riddick et al., 2020; Williams et al., 2021), single region measurements from 30 years ago are likely not representative of the current GM occurrence rate of that region and other regions across Canada. Although GM emissions may be lower than SCV emissions, GM has a much higher risk to contaminate groundwater resources. Hence, it is important to conduct GM soil CH_4

emission rate measurements from multiple OGW types in multiple oil and gas producing regions to better inform Canada's greenhouse gas inventory and better understand the impact of GM on groundwater.

In this paper, we used surface static chambers, that do not require ground penetration and can measure extremely small flow rates (Livingston & Hutchinson, 1995; Williams et al., 2023), to conduct and analyze 1241 measurements of CH_4 emissions from soils surrounding 60 OGWs in Alberta and British Columbia. We also measured ethane emissions at 539 of the 1241 soil measurements. To understand well parameters affecting soil CH_4 emissions, we studied the variability of soil CH_4 emissions by well status, produced fluid and sour status, where sour wells are wells with signs of hydrogen sulfide (Alberta Energy Regulator, 2023a). We used these results to develop average methane emissions per well category to inform Canada's greenhouse gas inventory on OGW soil CH_4 emissions. Additionally, we conducted SCV tests at 41 of the 60 GM-measured wells and obtained SCV flow measurements from 37 SCVs according to the method outlined in Directive 087: Well Integrity Management (Alberta Energy Regulator, 2021). Our results and analysis can be used to improve regulatory frameworks and environmental guidelines aiming to reduce OGW SCV and GM emissions indicative of well integrity failure.

2. Methods

2.1. Site Selection

We retrieved information for wells in Alberta from the Alberta Energy Regulator ST37 database (Alberta Energy Regulator, 2023). For wells in British Columbia, we retrieved well information from British Colombia Energy Regulator (BCER) (BCER, 2024b). We selected wells for measurements to cover the different well statuses (active, plugged abandoned, unplugged abandoned, other), produced fluids (oil, gas, other), and sour statuses for wells in Alberta (sour, non-sour). We did not use provincial SCV flows and GM reports to select wells for measurements to avoid biasing our estimates towards wells with reported leaks. We consulted with oil and gas operators and OGW emission monitoring service providers to obtain site access for measurement. Therefore, the geographical coverage of our measurements was largely influenced by site access.

2.2. Selected well sites

We measured SCV emissions and soil CH_4 and ethane emissions indicative of GM from OGWs near Brooks and Grande Prairie Alberta, and Dawson Creek, British Columbia (Figure 1). Out of the 60 wells measured, 15 were active (producing), 28 were unplugged abandoned (unplugged non-producing), 10 were plugged abandoned (plugged non-producing) and 7 were classified as "other" (Figure 1). The "other" wells category included wells with undefined or unknown status. We obtained gas migration measurements from 52 wells in Alberta and tested SCVs at 36 wells. According to the Alberta Energy Regulator Vent Flow and Gas Migration Report (Alberta Energy Regulator, 2023b), only one of the wells we visited was reported for having GM, another well was reported for having GM and SCV flows and 19 wells were reported for having SCV flows. Additionally, 20 of the wells we measured in Alberta were listed on Alberta's Sour Gas Well List (Alberta Energy Regulator, 2023a), which documents wells with signs of hydrogen sulfide. In British Columbia, we conducted GM measurements at eight wells and measured the SCVs at five of these wells. Six of the wells we measured in British Columbia were previously reported for having SCV flows in the BCER database (BCER, 2024).

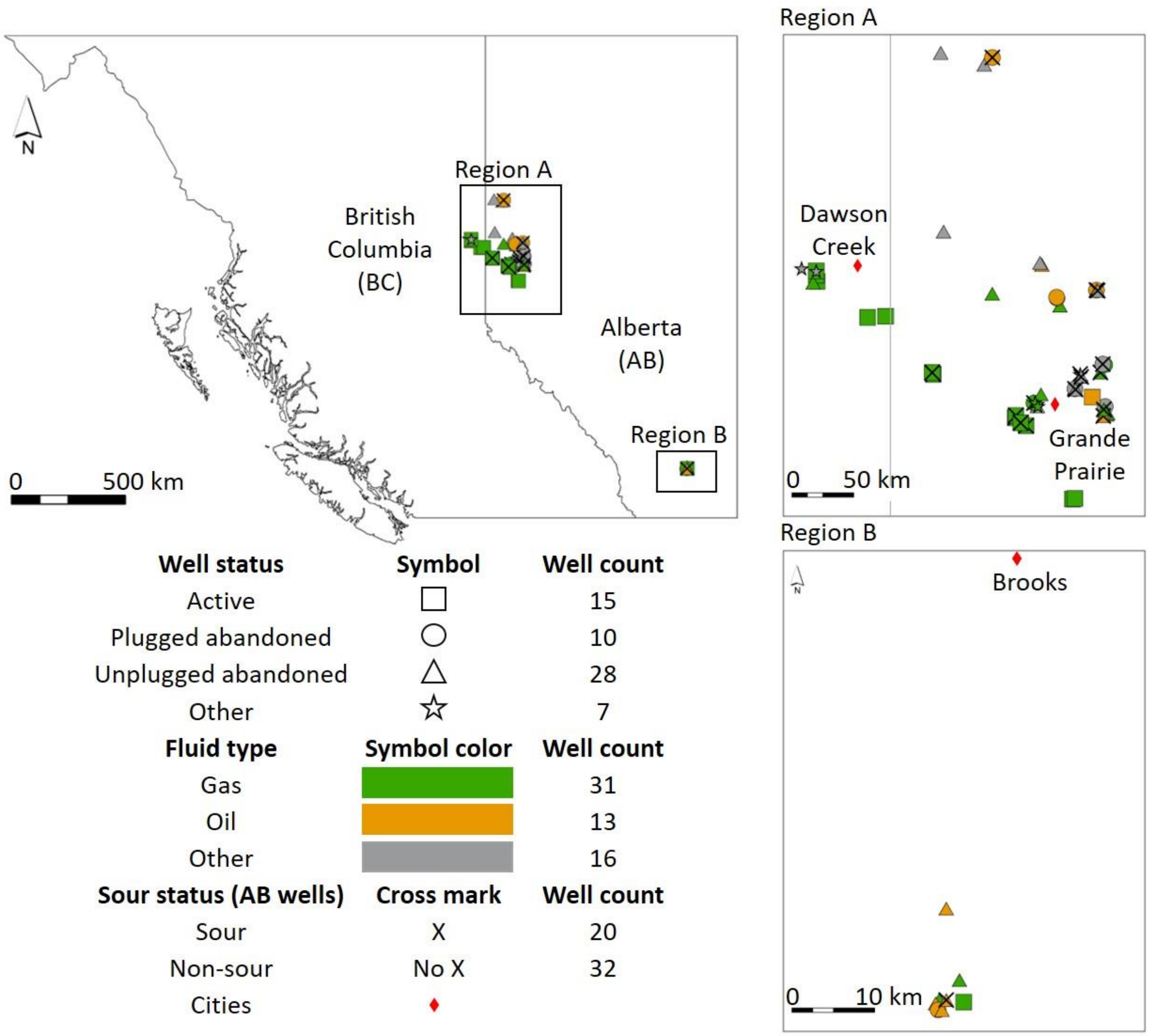

Figure 1. Map showing all the wells where soil CH_4 emission rate measurements were conducted in Alberta and British Columbia. The wells are divided by measurement regions (Region A: Grande Prairie, Alberta and Dawson Creek, British Columbia; Region B: Brooks, Alberta), well status (active, plugged abandoned, unplugged abandoned and other), fluid type (gas, oil and other), sour status (sour, non-sour for wells in Alberta).

2.3. Measurements of Gas Migration Through Methane and Ethane Surface Soil Emissions

We used three static chambers with volumes of 2.66, 2.44 and 7.06 liters and surface area of 0.018, 0.018 and 0.07 m^2 to conduct our measurements. All chambers had a 1 meter long and 0.125 in diameter tubing to allow for chamber venting. We placed the chambers on the soil surface and sealed the outer chamber base to the ground surface using on-site packing material, such as soil and snow. We selected the measurement locations to avoid areas with water accumulation and ensure a flat ground surface. In October 2023, we used an Axetris LDG compact CH_4 and ethane sensor to measure soil methane emissions. Although the sensor can detect ethane concentrations exceeding 15 ppm, this level was not observed in the soil chambers. In August and September 2021 and July 2022 we used a Picarro G2210-i to measure soil CH_4 and ethane emissions. Overall, we collected 1241 point-scale CH_4 and 539 point-scale ethane emission rate measurements. When measuring emission rates, we monitored the gas concentrations for 2 to 10 minutes and fitted a linear model to gas concentration versus time data (Williams et al., 2023). For the 47 wells visited in 2023, we collected soil emission rate measurements north, south, east, and west of the wellheads at 1-, 2-, and 3-meter distance. For the wells visited in 2021 and 2022, we collected measurements up to 7 meters away from the wellheads (Figure 2). We considered measurements within a 7-meter distance from the well as near-well measurements. We also conducted measurements 40 to 138 meters away from the wells and used them as control or baseline measurements, where we assumed the well is not affecting the emissions. We picked 40 meters as distance cutoff for control measurements because previous studies have shown that OGW emissions can be detected up to 40 meters away from the well (Forde et al., 2019).

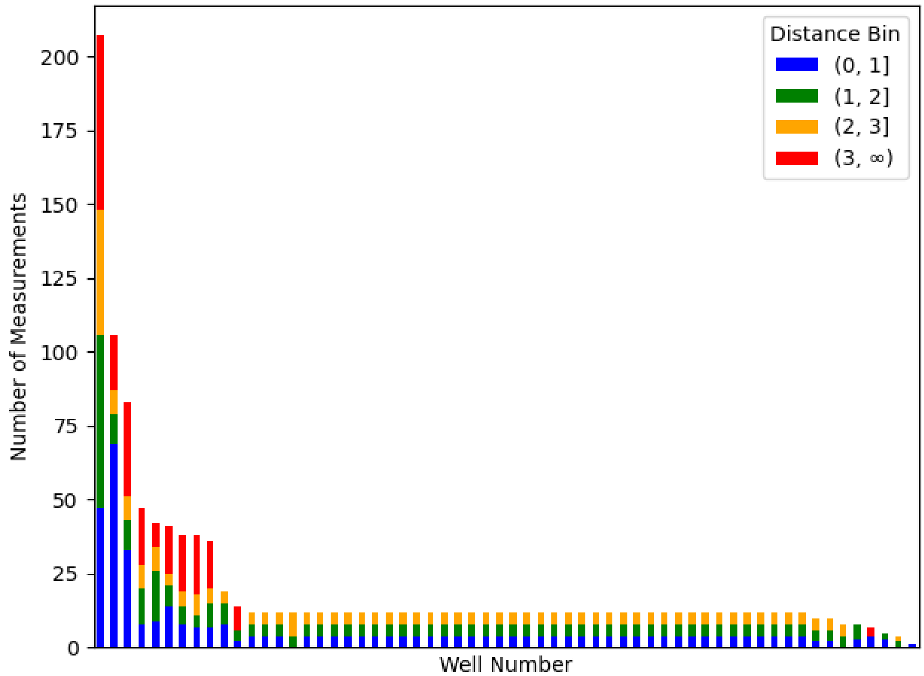

Figure 2. Bar chart showing the number of point-scale measurements taken per well site divided by distance bins (0 to 1 meters, 1 to 2 meters, 2 to 3 meters and larger than 3 meters).

2.4. Classifying wells as potentially having GM and estimating emissions

To investigate which wells were showing signs of GM at the time of our measurements, we compared control soil CH_4 emissions (40 to 138-meter distance) to near-well emissions (less than 7 meters). We initially filtered the control emissions and removed outliers, specifically the -2.0 and 1.7 mg CH_4/m²/hour values, which were larger than the average plus three standard deviations. We then identified wells that had one or more soil CH_4 emission rate measurement exceeding the highest non-outlier control emission rate of 0.14 mg CH_4/m²/hour and considered these wells as potentially having GM.

To estimate CH_4 emissions at the well scale, we assumed that soil emissions are expressed over a circular area around the wellhead with a radius *D*, the distance from the wellhead where more than 85% of cumulative CH_4 emissions occur. We used all soil emission rates at all measured wells to determine the radius, *D*. We then computed average emissions for concentric rings around the wells, with 1-meter increments from 0 to *D*. We multiplied these averages by their respective areas, and summed the emissions of all concentric rings to determine total well soil CH_4 emissions (Lyman et al., 2017).

2.5. Well Parameters Affecting Point-Scale Soil CH_4 Emission Rates and average emissions

To inform emission categorization that can be useful for Canada's greenhouse gas inventory, we studied the variability of point-scale soil CH_4 emission rates based on well status (active, plugged abandoned, unplugged abandoned, other), produced fluid (oil, gas, other), sour status for wells in Alberta (sour, non-sour). To address the limitations of our original sampling protocol, which may not have captured the full variability of soil CH_4 emission rates, we implemented a bootstrapping approach (Egbert & Plonsky, 2020), and created a dataset with a uniform number of point scale measurements per well. First, we resampled the measured point-scale emission rates with replacement 10,000 times, then we resampled that data without replacement to create a synthetic dataset of 1,000 measurements per well. To ensure the analysis is based on wells with comprehensive coverage of distance from the well, we excluded 8 wells lacking measurements within any of the distance ranges: 0 to 1 meter, 1 to 2 meters, or 2 to 3 meters. Using the remaining 52 wells, we conducted Kruskal Wallis ANOVA testing to study how soil CH_4 emission rates vary by well status, produced fluid and sour status for wells in Alberta (Hecke, 2012). Then we used the results of the Kruskall Wallis ANOVA testing to inform categorizing wells based on the well parameters found to affect soil CH_4 emissions. For each well category, we computed the average soil CH_4 emissions, and determined the 95% confidence bounds around the averages using the "bootci" function in Matlab that is appropriate for skewed data, a characteristic of emissions from oil and gas systems (Brandt et al., 2016).

2.6. Measurements of Surface Casing Vent Emissions

We performed SCV emission tests at 41 of the 47 wells visited in 2023. The 6 remaining wells we visited in 2023 were abandoned and buried beneath the ground surface with no SCV. We collected CH_4 and ethane SCV measurements by inserting a tubing linked to an Axetris compact LDG into the SCV. We held the tubing in the SCV for a duration of 10 to 15 seconds while observing the CH_4 and ethane concentration levels. This test yielded a binary value that signifies whether the SCV is emitting or not. We considered the SCV to be emitting if the concentration of CH_4 exceeded 3 ppm or the concentration of ethane exceeded 15 ppm, the lower ethane detection limit of the Axetris LDG compact CH_4 and ethane sensor. We also used a flow meter to measure SCV flows from 37 wells according to Directive 087: Well Integrity Management (Alberta Energy Regulator, 2021). We compared our SCV and soil emissions occurrence results to data presented in SCV flow and gas migration reports for Alberta and British Columbia, to assess the consistency of emission patterns and to identify any regional discrepancies between measurements and provincial databases based on industry reports.

3. Results

3.1. Near-Well Point-Scale Soil Emissions

Our results showed that point-scale soil CH_4 emissions conducted within a 7-meter radius from the 60 measured wells ranged from -138.6 to 1126 mg CH_4/m^2/hour, compared to –0.66 to 0.14 mg CH_4/m^2/hour observed from control measurements conducted at 40 to 138-meter radii from the wells. In terms of ethane emissions, measurements conducted within a 7-meter radius from the wells ranged from -4.92 to 7.93 mg ethane/m^2/hour compared to -0.04 to 0.04 mg ethane/m^2/hour for control measurements. We found that 249 point-scale measurements within a 7-meter radius from 19 wells, 9 of which measured at a temperature below 0°C in October 2023, had CH_4 emission levels indicating GM. At these point-measurements, we observed a strong Spearman correlation (Spearman coefficient = 0.51, p-value = 0.0) between CH_4 and ethane emission rates, indicating that both gases can be measured to detect GM and potentially indicating thew presence of other contaminants. These 249 measurements were collected from soils near 4 active, 5 plugged abandoned, 9 unplugged abandoned, and 1 other. Therefore, 31.66% of all measured wells had emissions indicative of GM. Per well status category, we found that active wells had a GM occurrence rate of 26.6%, whereas plugged abandoned and unplugged abandoned wells had GM occurrence rates of 50 and 32.1%, respectively. Other wells had a GM occurrence rate of 14.3%.

3.2. Well Parameters Affecting Point-Scale Soil CH_4 Emission Rates

Our Kruskal Wallis ANOVA test results indicated that point-scale soil CH_4 emission rates varied by well status (active, plugged abandoned, unplugged abandoned, other), produced fluid (oil, gas, other) and sour status for wells in Alberta (sour, non-sour) (Figure 3). We found that plugged abandoned wells had the highest emission levels, followed by unplugged abandoned, active, and other wells. In terms of produced fluid, we found that oil wells emitted more than gas wells. Surprisingly, although previous studies showed a positive link between hydrogen sulfide and CH_4 emissions (El Hachem & Kang, 2022), and between hydrogen sulfide presence and OGW leakage (Watson & Bachu, 2009), here we found that non-sour wells emitted more soil CH_4 compared to sour wells, which are defined as wells with signs of H_2S (Alberta Energy Regulator, 2023a). Overall, our measurements and analysis indicate that OGW soil CH_4 emissions varied with well parameters, highlighting the need for measurements from wells covering the range of well statuses, produced fluids and sour statuses of the OGW population in target measurement regions.

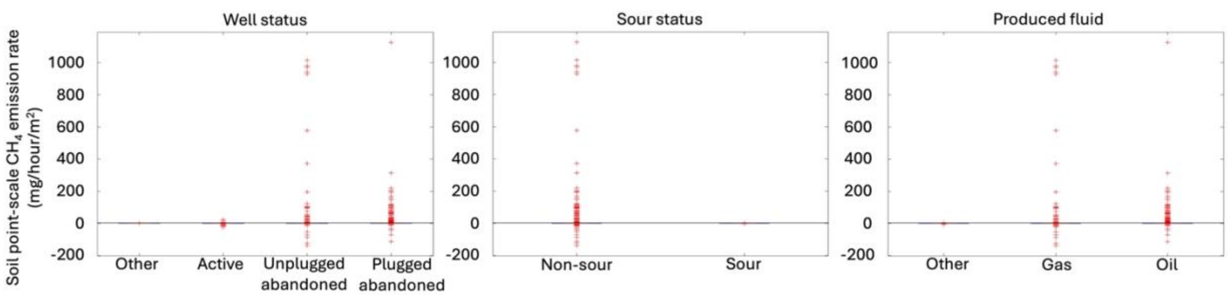

Figure 3. Plot showing the distribution of the resampled point-scale soil CH_4 emission rates categorized by well status, sour status for wells in Alberta and produced fluid.

3.3. CH_4 Emission Estimates on the well scale

We computed cumulative average emissions per distance bin and found that 88% of total cumulative CH_4 emissions occurred within a 3 meters radius from the well (Figure 4). Therefore, we assumed a soil emissions surface expression over a circular area with a 3 meter radius.

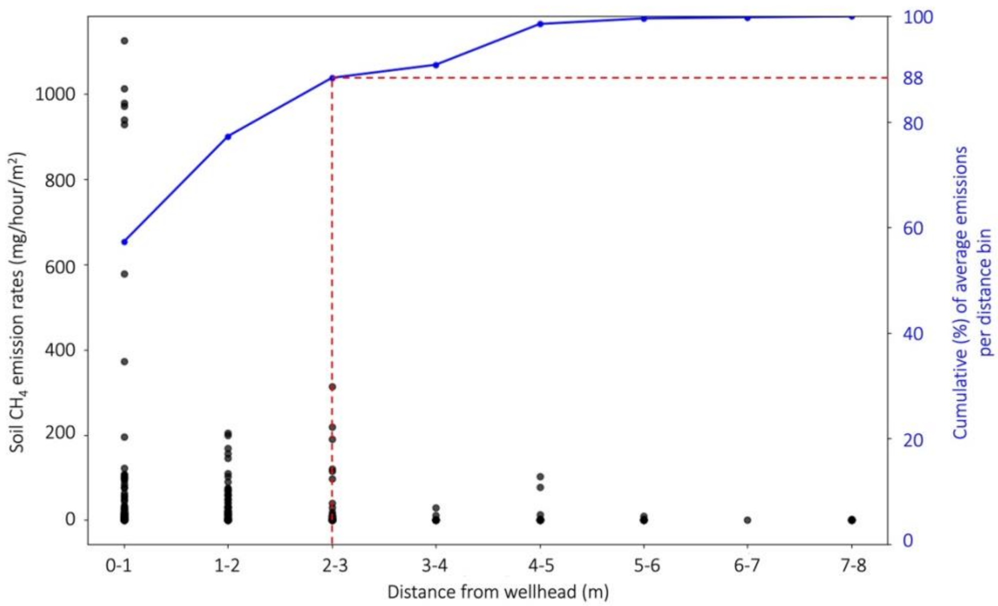

Figure 4. Plot showing in black circles the measured soil CH_4 emission rates (mg/m²/hour) divided by 1 meter distance bins up to 8 meters from the well. In blue, the plot is showing the cumulative (%) distribution of average emissions per distance bin. The red dashed line shows the cumulative % value for the 2–3-meter distance bin.

On the well scale, we found CH_4 emission ranges from -13.1 to 884.7 mg CH_4/hour (Figure 5). Although 19 of the 60 wells (31.66%) we measured were classified as GM wells, only 14 of the 19 wells had positive soil CH_4 emissions on the well scale. This indicates that emissions caused by GM can be highly localized with high emissions in one spot and low or negative emissions in other spots, highlighting the importance of extensive point-scale emission rate measurements to capture GM. Overall, our highest soil CH_4 emitter was one non-sour plugged abandoned oil well emitting at a rate of 884.7 mg CH_4/hour, two non-sour unplugged abandoned oil wells emitting 20.27 and 148.7 mg CH_4/hour, and two non-sour unplugged abandoned gas wells emitting 127.9 and 303 mg CH_4/hour. Our top five emitters dominate the emissions distribution and are responsible for 99.3% of total cumulative soil CH_4 emissions, indicating a highly skewed distribution where a few wells contribute the most emissions.

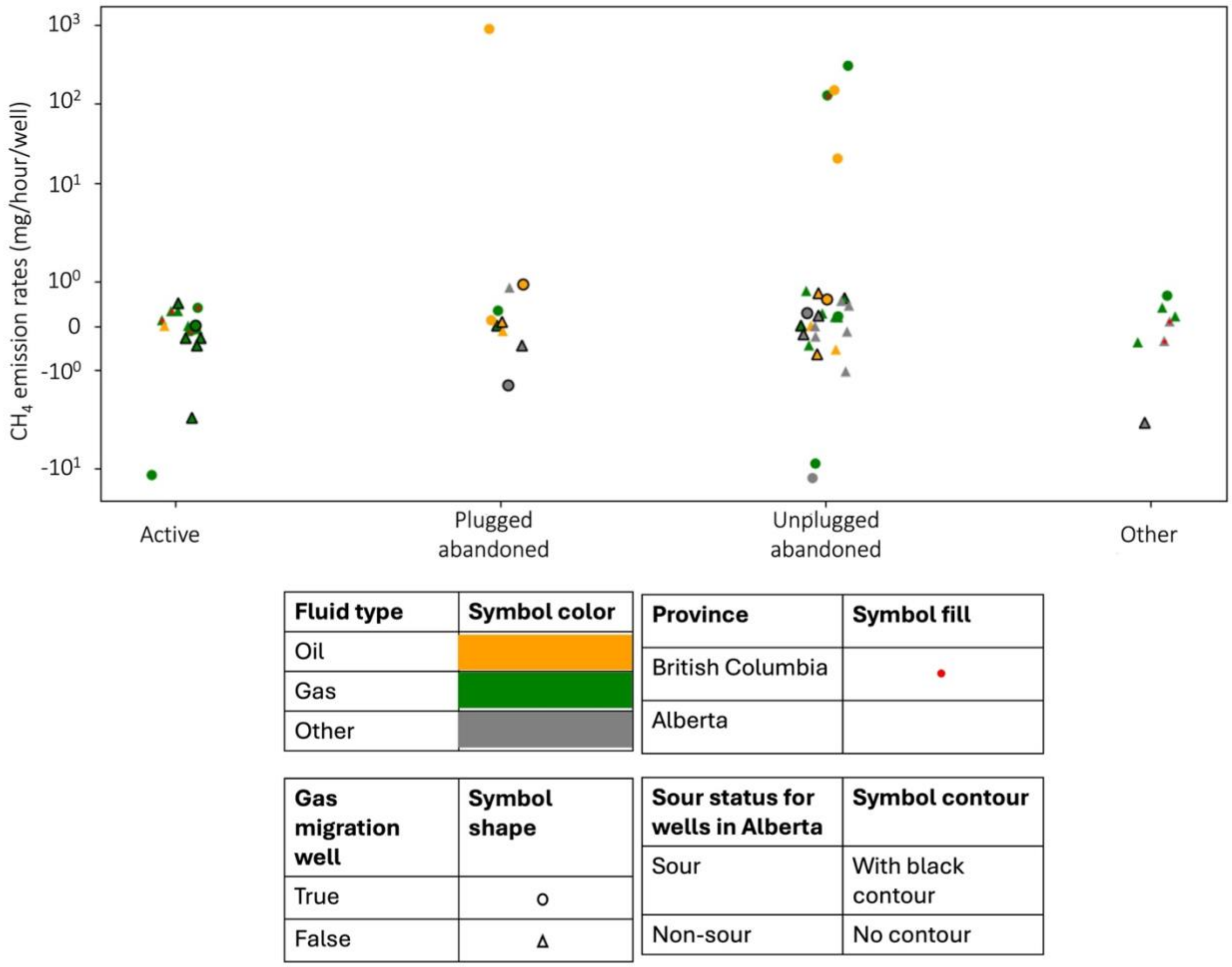

Figure 5. Plot showing the CH_4 emission rate estimates (mg CH_4/hour/well) for all 60 measured wells, categorized by well status (active, plugged abandoned, unplugged abandoned and other), fluid type (gas, oil and other), sour status (sour, non-sour for wells in Alberta), and measurement-based gas migration designation.

3.4. Average soil CH_4 Emissions per well category

Considering all well parameters (well status, produced fluid and sour status) and all measured wells, we found that plugged abandoned non-sour oil wells were, on average, the highest emitters with an average emission rate of 295 mg CH_4/hour/well (Table 1). This was followed by unplugged abandoned non-sour gas and unplugged abandoned non-sour oil wells with average emission rates of 47.07 and 42.11 mg CH_4/hour/well, respectively. All other well categories have negligible average emissions below 1 mg CH_4/hour/well. Considering the well status and fluid type only, we found that plugged abandoned oil wells had the highest average soil CH_4 emission rate of 177.16 mg CH_4/hour/well. This was followed by unplugged abandoned gas wells emitting soil CH_4 at an average rate of 38.6 mg CH_4/hour/well and unplugged abandoned oil wells emitting at an average rate of 24.2 mg CH_4/hour/well (Table 1). Considering the well status parameter only, we found that plugged abandoned wells were the top emitters with an average soil CH_4 emission rate of 88.52 mg CH_4/hour/well followed by unplugged abandoned wells emitting at an average rate of 20.73 mg CH_4/hour/well. For other and active wells, we found negative average emissions of -0.26 and -0.91 mg CH_4/hour/well, this is because we included measurements from all measured other and active wells and GM emissions were not large enough to exceed the soil's CH_4 sink capacity. Overall, we see high variability in average emissions based on the different well parameters considered, highlighting the need for a well parameter focused approach in developing emission factors to inform Canada's greenhouse gas inventory on OGW soil CH_4 emission rates.

Table 1. Soil CH_4 emission factors including the number of wells measured for each well category and upper and lower 95% confidence bound around the emission factors. The table is divided based on the well factors considered in categorizing the data and developing the emission factors. NC stands for Not Considered, NaN stands for not a number.

Well status	Produced fluid	Sour status	Number of wells	Average methane mg/hour	Lower 95% confidence bound	Upper 95% confidence bound
Considering well status, produced fluid and sour status						
Plugged abandoned	**Oil**	**No**	3	294.92	-0.04	884.74
Unplugged abandoned	**Gas**	**No**	9	47.07	-0.62	149.19
Unplugged abandoned	**Oil**	**No**	4	42.11	-0.13	116.61
Plugged abandoned	**Other**	**No**	1	0.87	NaN	NaN
Plugged abandoned	**Oil**	**Yes**	2	0.53	0.11	0.95

Plugged abandoned	**Gas**	**No**	1	0.34	NaN	NaN
Unplugged abandoned	**Gas**	**Yes**	2	0.32	0.02	0.63
Unplugged abandoned	**Oil**	**Yes**	3	0.25	-0.64	0.72
Other	**Gas**	**No**	4	0.24	-0.23	0.55
Unplugged abandoned	**Other**	**Yes**	3	0.13	-0.17	0.29
Plugged abandoned	**Gas**	**Yes**	1	0.02	NaN	NaN
Active	**Oil**	**No**	1	0.00	NaN	NaN
Other	**Other**	**No**	2	-0.12	-0.34	0.10
Active	**Gas**	**Yes**	6	-0.44	-1.48	0.05
Plugged abandoned	**Other**	**Yes**	2	-0.90	-1.35	-0.45
Active	**Gas**	**No**	8	-1.37	-6.01	0.20
Unplugged abandoned	**Other**	**No**	7	-1.93	-7.69	0.08
Other	**Other**	**Yes**	1	-2.54	NaN	NaN
Considering well status and produced fluid						
Plugged abandoned	**Oil**	**NC**	5	177.16	0.14	707.82
Unplugged abandoned	**Gas**	**NC**	11	38.57	-0.36	133.58
Unplugged abandoned	**Oil**	**NC**	7	24.17	0.34	90.68
Other	**Gas**	**NC**	4	0.24	-0.23	0.55
Plugged abandoned	**Gas**	**NC**	2	0.18	0.02	0.34
Active	**Oil**	**NC**	1	0.00	NaN	NaN
Plugged abandoned	**Other**	**NC**	3	-0.31	-1.35	0.87
Other	**Other**	**NC**	3	-0.93	-2.54	-0.05
Active	**Gas**	**NC**	14	-0.98	-4.41	-0.01
Unplugged abandoned	**Other**	**NC**	10	-1.31	-6.50	0.10
Considering well status						
Plugged abandoned	**NC**	**NC**	10	88.52	-0.09	442.21
Unplugged abandoned	**NC**	**NC**	28	20.73	4.48	61.77

Other	**NC**	**NC**	7	-0.26	-1.44	0.24
Active	**NC**	**NC**	15	-0.91	-4.15	-0.01

3.5. Relationship between Surface Casing Vent and Gas Migration Emissions

We measured GM and tested SCVs at 41 wells. We found that 29 of the 41 SCVs (70%) were emitting. Of the 29 wells identified to have leaking SCVs, 7 wells were showing signs of GM. 12 of the 41 tested SCVs did not have SCV emissions with one well showing signs of GM only (Figure 6). Overall, 8 of the 41 wells were showing signs of GM, and 7 of these 8 wells had SCV emissions. Overall, based on our GM and SCV tests at 41 wells, when GM is present SCV emissions are likely to be present too. This indicates that from a surface emissions perspective, in the event of well integrity failure, emissions are more likely to be detected through SCVs compared to GM. However, the lack of surface emissions from soils surrounding OGWs does not necessarily imply the absence of GM. Field experiments have demonstrated that when gas is injected near OGWs to simulate GM conditions, only 30% of the gas is emitted from soils near the well and an equal portion remains in nearby groundwater aquifers (Cahill et al., 2017). Therefore, while surface emissions are a reliable indicator of gas migration (GM), the absence of detectable emissions does not conclusively rule out GM, as significant portions of gas may migrate into subsurface formations rather than reaching the surface.

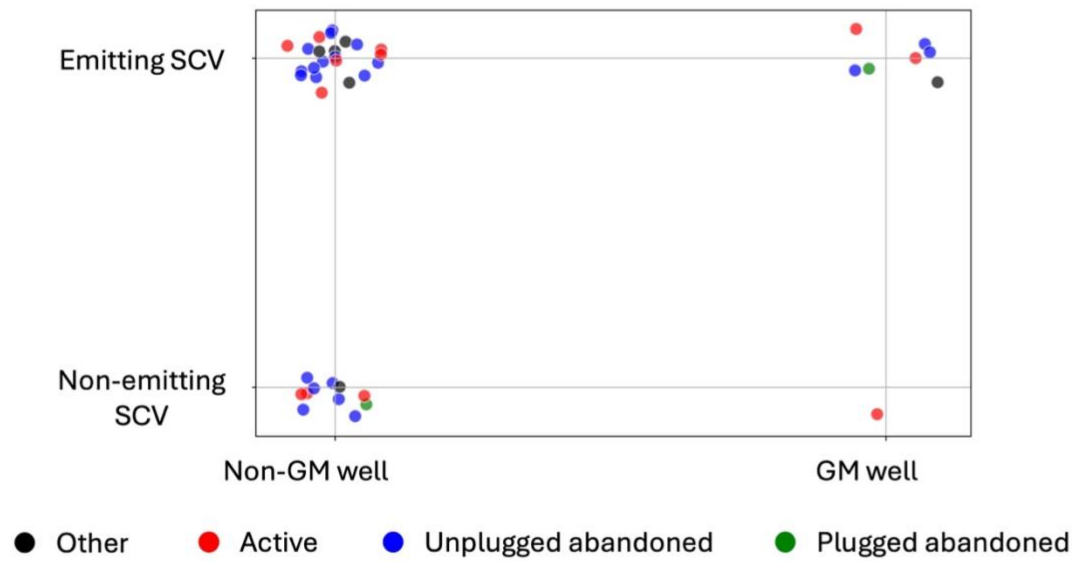

Figure 6. Plot showing four well clusters based on the emission status of the well's SCV and the presence of soil emissions indicative of GM. The wells are divided by well status.

3.6. Comparison of Field tests with Directive 087 method and Provincial SCV and GM Reports

Compared with flow measurements conducted using the method outlined in Directive 087: Well Integrity Management (Alberta Energy Regulator, 2021), we found that 9 wells with SCV field tests indicating leakage had flow rates of 0 m^3/day. This indicates that the flowmeters, recommended to measure SCVs in Directive 087, may not be sensitive enough to detect low magnitude SCV emissions. When looking at provincial SCV flow and GM reports, we found that 6 of the 8 wells we measured in British Columbia were listed on the report. Through our measurements, we identified 3 of these 6 wells exhibiting GM, while 5 of the 6 wells had positive SCV emissions. Note that one of the 6 wells did not have an SCV. Overall, all the measured wells listed on the British Columbia provincial SCV and GM report were determined to be leaking based on our measurements. Therefore, there is agreement between our measurements and the SCV flow and GM report for British Columbia.

In Alberta, one of the wells we visited was reported for having GM, another well was reported for having GM and SCV flows, and 19 wells were reported for having SCV flows on the provincial SCV flow and GM report. Our measurements confirmed that the well reported as having GM only was showing assigns of GM, and the well with GM and SCV flows on the provincial report was showing signs of leakage from the SCV and the well's surrounding soils. For the 19 wells listed as having SCV flows on the provincial report, we found that 8 of these wells had soil emissions indicative of GM and 8 of the 12 tested SCVs had positive emissions. Interestingly, out of 31 wells not listed on Alberta's SCV flow and GM report, we found 6 wells with soil emissions indicative of GM, and 15 of the 23 tested SCVs had positive emissions. Therefore, there is disagreement between our measurements and provincial SCV flow and GM report in Alberta, which could be the result of misreporting or inadequate sensitivity in SCV and GM measurement methods.

4. Discussion

4.1. Revising greenhouse gas inventory estimates: insights from new measurement regions in Canada

Our results can inform Canada's greenhouse gas inventory on soil CH_4 emission rates in areas other than Lloydminster, an area bordering east central Alberta and west central Saskatchewan. Currently, inventory estimates for OGW soil CH_4 emissions are based on previous measurements in Lloydminster, where 7.8% of active heavy oil wells had GM and emitted at an average rate of

3.85 m^3/day (Environment and Climate Change Canada, 2022; Erno & Schmitz, 1996). In our measurement regions, we found GM occurrence rates that were 4 times higher than the 7.8% GM occurrence rate found in Lloydminster (Erno & Schmitz, 1996). However, our highest soil CH_4 emission rate observed at a plugged abandoned non-sour oil well was 119 times lower than the 3.85 m^3/day average soil CH_4 emission rate for wells with GM in Lloydminster (Environment and Climate Change Canada, 2022). Therefore, although we detected a higher occurrence of GM we found lower emissions in Brooks, Grande Prairie and Dawson Creek compared to Lloydminster. The variability between our results and measurements conducted in Lloydminster indicates the importance of measurement samples representative of different well conditions to accurately capture regional emission variability. Additionally, our Kruskal Wallis ANOVA test results indicated that point-scale soil CH_4 emission rates vary by well status, produced fluid and sour status. This highlights the need for a more discretized understanding of GM emissions, where well parameters affecting GM are accounted for, leading to more accurate greenhouse gas inventories and better emissions management strategies.

4.2. The role of localized measurements and advanced detection technologies to test oil and gas wells

Our data and analysis provide critical insights for refining OGW emission management strategies, including the requirements for well integrity testing. Our measurements indicate that 88% of total cumulative soil CH_4 emissions occur within a 3-meter radius of the well. This localized concentration of emissions can guide policymakers in developing targeted measures for GM detection, allowing them to focus resources on the most impactful areas. Additionally, of the 60 wells we assessed, 19 were classified as GM wells, with 5 of the 19 wells having negative soil CH_4 emissions indicating that overall, the soil surrounding the well is a methane sink. This was expected due to the highly localized nature of emissions (Fleming et al., 2021; Lyman et al., 2020), underscoring the need for detailed, point-scale emission rate measurements to accurately detect GM. Additionally, 9 of the 19 GM wells were measured in freezing conditions indicating that GM can be detected not just during the summer. Our use of static chambers, which are more sensitive than the GM detection methods recommended in Directive 087, revealed a higher incidence of GM. Also, a comparison of our data with the provincial GM and SCV flow report for Alberta showed significant discrepancies, further demonstrating the necessity of employing more sensitive detection technologies in regulatory frameworks.

5. Conclusion

Our analysis and results show that OGW soil CH_4 emissions can be highly variable by measurement region, well status, produced fluid and sour status, highlighting the importance of measurements from wells in different regions with different parameters to better understand and account for OGW soil CH_4 emissions. Although our measurements show that soil CH_4 emission rates may not be significant, the occurrence rate of emissions associated with GM was higher than previously thought, and a comparison with provincial reports showed major discrepancies. This means that the current methods recommended by regulators to measure GM may not be sensitive enough to detect low emission rates, which can be a sign of more severe leakage in the subsurface.

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