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Article

Quantification of Methane Emissions from Cold Heavy Oil Production with Sand Extraction in Alberta and Saskatchewan, Canada

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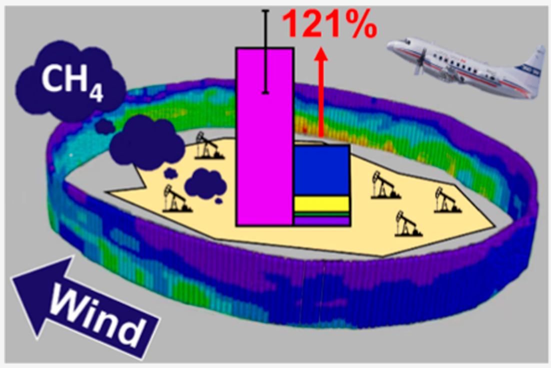

ABSTRACT: Cold heavy oil production with sand (CHOPS) is an extraction process for heavy oil in Canada, with the potential to lead to higher CH_4 venting than conventional oil sites, that have not been adequately characterized. In order to quantify CH_4 emissions from CHOPS activities, a focused aerial measurement campaign was conducted in the Canadian provinces of Alberta and Saskatchewan in June 2018. Total CH_4 emissions from each of 10 clusters of CHOPS wells (containing 22−167 well sites per cluster) were derived using a mass balance computation algorithm that uses in situ wind data measurement on board aircraft. Results show that there is no statistically significant difference in CH_4 emissions from CHOPS wells between the two provinces. Cluster-aggregated emission factors (EF) were determined using correspondingly aggregated production volumes. The average CH_4 EF was 70.4 ± 36.9 kg/m^3 produced oil for the Alberta wells and 55.1 ± 13.7 kg/m^3 produced oil for the Saskatchewan wells. Using these EF and heavy oil production volumes reported to provincial regulators, the annual CH_4 emissions from CHOPS were estimated to be 121% larger than CHOPS emissions extracted from Canada's National Inventory Report (NIR) for Saskatchewan. The EF were found to be positively correlated with the percentage of nonpiped production volumes in each cluster, indicating higher emissions for nonpiped wells while suggesting an avenue for methane emission reductions. A comparison with recent measurements indicates relatively limited effectiveness of regulations for Saskatchewan compared to those in Alberta. The results of this study indicate the substantial contribution of CHOPS operations to the underreporting observed in the NIR and provide measurement-based EF that can be used to develop improved emissions inventories for this sector and mitigate CH_4 emissions from CHOPS operations.

KEYWORDS: *methane emission, venting, CHOPS, aircraft measurements, emission factor*

1. INTRODUCTION

Global oil and gas (O&G) production has been increasing in recent years in response to increased economic activity around the world. With such increasing production, there arises the potential for increases in greenhouse gas (GHG) emissions. O&G extraction, processing, transmission, storage, and distribution can result in unintentional leakage or intentional venting of natural gas to the atmosphere, for which methane (CH_4) is the primary component. Methane is a powerful GHG that is responsible for roughly 30% of global warming since preindustrial times.[1] The increases in GHG concentrations arising from releases of natural gas into the atmosphere can reduce the climate benefits of replacing coal with natural gas for energy production if the total natural gas loss rate were to exceed 3.2%.[2] In Canada, oil and gas facilities are the largest industrial CH_4 emitters, accounting for 40% of total industrial CH_4 emissions.[3] As a result, the Canadian government committed to reduce CH_4 emissions from oil and gas activities 40−45% below 2012 levels by 2025 and published federal regulations to achieve this reduction in 2018.[4] Further commitments to reduce CH_4 emissions by at least 75% by 2030 have been announced. The provinces of Alberta and Saskatchewan, which collectively accounted for 93% of Canada's oil production[5] and 66% of gas production[6] in 2021, published their own provincial regulations[7,8] and equivalency agreements were established for both provinces.[9,10] The equivalency agreements pledged reduction of

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methane emissions (in CO_2e) through the implementation of limits on venting of gas from upstream oil and gas facilities and restrictions on fugitive emissions. According to the Alberta Energy Regulator Directive 60 regulations, any emissions from a cold heavy oil production with sand (CHOPS) site totaling more than 500 m^3/d need to be combusted or conserved at single well sites or multiwell batteries. Saskatchewan Ministry of Economy has legislation that a facility venting and/or flaring greater than 900 m^3/d of gas must either conserve or flare all gas.[11] Evaluating the effectiveness of these regulations would require oil and gas CH_4 emission data prior to and after their implementation.

Accurate data on CH_4 emissions from the oil and gas industry are a key component of government climate policy initiatives, and to this end, it is critical to obtain atmospheric measurement-based emissions data to validate and improve the activity-based, inventory estimates presented in Canada's National Inventory Report (NIR). This is especially important as many recent studies have shown that inventory estimates are biased low in comparison to atmospheric measurements. In recent years, several studies utilizing a variety of methods have been conducted to examine CH_4 emissions from oil and gas facilities. Of particular interest are airplane-mounted technologies, typically including airborne in situ measurements[12−17] and aircraft-based remote sensing techniques,[18−23] which are increasingly used in large-scale field campaigns with success.

CHOPS is a nonthermal process widely used for producing heavy oil in the Lloydminster region, with operations straddling the Alberta−Saskatchewan border in Canada[24] as well as operations in other heavy oil producing deposits globally.[25−27] CHOPS is defined as primary heavy oil production that involves the deliberate initiation of sand influx into a perforated oil well, and the continued production of substantial quantities of sand along with the oil, perhaps for many years. Approximately 460,000 b/d of Canada's total oil production arises from CHOPS, which represents 22% of Canada's total oil. CHOPS facilities in the Lloydminster area do not typically include gas gathering infrastructure, and more commonly gases are used onsite as fuel, eliminated via flaring, or vented directly to the atmosphere.[11,28,29] Venting of casing gas to atmosphere or through storage tanks from CHOPS operations is more common than conventional operations,[30] making CHOPS prone to emitting more CH_4 than conventional oil sites. A CHOPS facility typically consists of a well equipped gas engine which drives a hydraulic power unit which in turn drives a progressive cavity pump. Oil produced from the well flows from the wellhead to a heated, insulated tank. Oil is periodically removed from the tank and transported by truck to a plant for processing. Tank heat is required to maintain the appropriate viscosity of the oil for tank unloading, and the tanks are often intended to vent to the atmosphere such that the tank temperature affects the amount of gas being vented.[11] Emissions from the wellhead are also present in the form of casing gas. As with most other well types, casing pressure must be relieved to avoid restricting oil production and to avoid pushing the liquid column down to the point where gas enters the pump and leads to cavitation and motor failure.[31] Thus, the potential sources of CH_4 emissions from a CHOPS facility includes the release of casing gas from an annular vent, engine shed vents, failing pneumatics, flashing losses, breathing losses from storage tanks, truck loading emissions as well as fugitive leakage including leaking connectors and valves.[18,19,31] Emissions can also arise from abandoned or suspended CHOPS wells. Casing gas can be utilized as fuel for the engine, and studies have reported that a large portion of total site emissions in Lloydminster was from sheds containing fuel gas engines.[19,28,31]

The documented underestimation of CH_4 emissions from oil and gas operations in general, along with the potential for significant release of CH_4 from CHOPS activities, has spurred recent interest in quantifying their emissions. Using aircraft measurements of CH_4 from the Alberta side of the CHOPS region near Lloydminster, Johnson et al.[32] estimated that the emission rate is 5 times greater than that using an activity-based inventory approach. Festa-Bianchet et al.[31] measured CH_4 venting from 962 single-well CHOPS facilities in Saskatchewan using airborne LiDAR and their analysis showed that measured CH_4 emissions were nearly four times greater than emissions derived using industry-reported vent volumes. Seymour et al. conducted two aerial mass balance measurements over a CHOPS-dominant region near Lloydminster, Saskatchewan, and found that measured emission rates were ~2.8 times higher than Saskatchewan's current inventory.[33] Conrad et al. presented a measurement-based, source-resolved CH_4 inventory and found that total CHOPS-related emissions from tanks, wellheads, and engine sheds in Alberta are markedly lower than parallel measurements in Saskatchewan.[18] Roscioli et al.[24] conducted ground-based measurements from five CHOPS wells in Alberta and found that CH_4 emissions measured from these Alberta sites showed large discrepancies between the measured and reported rates, with emissions being mainly underreported. Another ground-based study by O'Connell[34] in the Alberta CHOPS region investigated a total of 434 CHOPS wells and estimated that 40.2% of them emitted above the venting threshold in which emissions mitigation under federal regulations would be required. A truck-based survey characterized CH_4 emissions in two major CHOPS developments in 2016 and 2018, and found that the measured CH_4 emission rates in Peace River were significantly lower than in Lloydminster for both years and had fallen from 2016 to 2018 due to the implemented mitigation strategy in the Peace River region targeting olfactory compounds.[28] Nevertheless, significantly more CH_4 being emitted than reported at CHOPS sites may actually improve the economics of mitigation.[30,33] Studies have demonstrated that cost-effective opportunities exist to reduce venting volumes at CHOPS sites in Alberta and Saskatchewan,[35,36] for example, by aggregating vented CH_4 volumes from more than one site to a single utilization site for conservation.[11,37] While studies have improved the emission information available for the CHOPS regions in Alberta and Saskatchewan, no measurement-based emission data are available for the comparison of CHOPS operations in both provinces for the same period of time. Given the large geographical extent of CHOPS regions, additional measurement-based emissions estimates remain important, especially as a means of evaluating the consistency of different atmospheric emissions measurement approaches for this sector and for assessing emissions variability over multiple years. Further data on CH_4 emissions from CHOPS facilities at a regional level, particularly EFs, would be valuable for evaluating their contributions to provincial sectoral total emissions and to the CH_4 emissions in the national inventory. Such measurement-based results could support the development of relevant and effective mitigation strategies.

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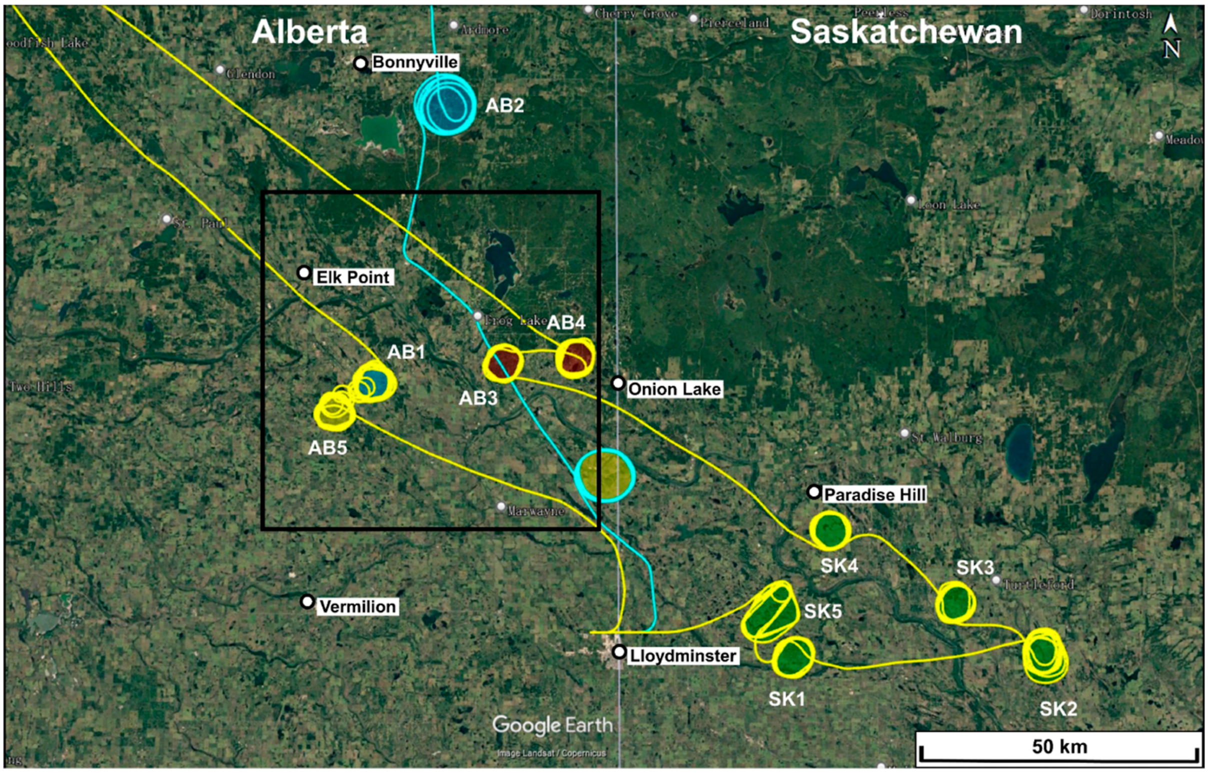

Figure 1. Flight tracks over multiple clusters of CHOPS wells. The flights on 13 June and 30 June are shown as the yellow and blue lines, respectively. Clusters in Alberta or Saskatchewan are sequentially labeled. The black box represents the investigated region in the Johnson et al. study.[32] Map data: Google, Image Landsat/Copernicus.

In this study, we report aircraft-based measurements of CH_4 emissions from the CHOPS regions in the provinces of Alberta and Saskatchewan near Lloydminster collected in the summer of 2018. The Top-down Emission Rate Retrieval Algorithm (TERRA), a mass balance method previously validated against real-time continuous emission monitoring data,[38] was applied to aircraft measurement data to derive CH_4 emission rates from clusters of CHOPS wells. The results were compared with production data from the studied CHOPS facilities extracted from the public Petrinex database,[39,40] to obtain cluster-aggregated EFs. The Petrinex reporting system provides produced oil and natural gas volumes, as well as gas volumes flared, vented, or used as on-site "fuel" reported by the industry. Here, we applied the CHOPS wells EFs to the heavy oil production in Saskatchewan to estimate CH_4 emissions from heavy oil production, assuming that these EFs are representative of heavy oil production and compared the results to the CH_4 emissions from inventory estimates. The present emission data for 2018, prior to the federal and provincial CH_4 emissions regulations, together with the recently published data for the same industry after the implementation of the regulations serve as a useful evaluation tool for the emissions reduction progress.

2. METHODS

As part of a broader air pollution measurement campaign for the Alberta Oil Sands Region,[41,42] three flights were made over the CHOPS region of Alberta and Saskatchewan to measure CH_4 emissions from the CHOPS operations (Figure 1). The CHOPS measurement flights were conducted in June 2018, using a suite of instruments on board the National Research Council of Canada's Convair-580 research aircraft. For these flights, emissions from eleven clusters of CHOPS operations, containing between 22 and 167 CHOPS sites each (both active and shut-in sites are included), were measured to determine their aggregated CH_4 emissions. Based on the turning radius of the aircraft, these clusters were preselected using the age of the wells to provide a representative sample of well ages for CHOPS wells in the Lloydminster area, as new wells often have higher oil production volumes. The CHOPS well clusters are sequentially labeled for those in Alberta (AB1, AB2, AB3, AB4, and AB5) and Saskatchewan (SK1, SK2, SK3, SK4, and SK5). The detailed information of each cluster is listed in Table S1. For each cluster of CHOPS wells, the aircraft was flown in a pattern that circumscribes a virtual cylinder of approximately 3.5 km radius that encloses the cluster, with flight tracks at 4−5 altitude levels that intercepted the emitted CH_4 plumes on the downwind side of the virtual cylinder. Each virtual cylinder flight duration lasted between 20 and 30 min.

Measurements of CH_4 were made using a cavity ring-down spectrometer (CRDS, Picarro G2401-M) at a 0.5 Hz frequency. The instrument was calibrated once per flight. A limited number of discrete canisters were collected in the CH_4 plumes on the downwind side during two flights around two clusters of wells (SK5 and AB1) followed by laboratory analyses for volatile organic compounds.[43] The canister samples were analyzed for 154 VOCs, including C2−C12 *n*-alkanes, branched alkanes, cycloalkanes, alkenes, aromatics, and halogenated hydrocarbons, postflight in the National Air Pollution Survey (NAPS) analytical laboratory as per the NAPS analysis protocols. Meteorological parameters needed to derive the emission rates included temperature (T) measured with a Rosemount 858 probe, dew-point temperature (T_d) measured with an Edgetech hygrometer, and pressure (P)

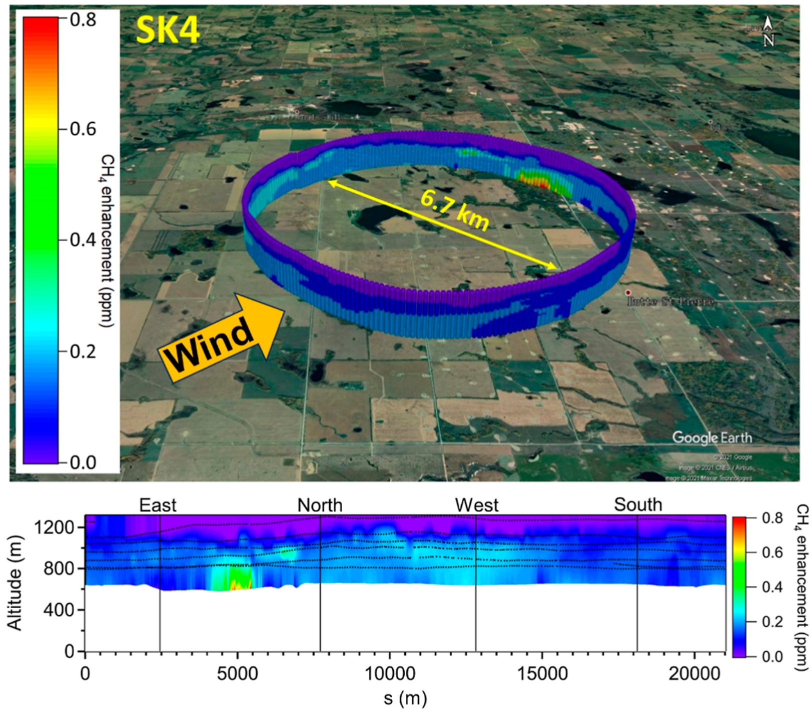

Figure 2. CH_4 mixing ratios above the local background for the virtual flight cylinder surrounding SK4 (upper panel) and unwrapped screen of CH_4 mixing ratios for the SK4 flight (bottom panel) on 13 June. CH_4 mixing ratios below the lowest flight path were estimated using a combination of linear or exponential extrapolation to the ground by finding the best fit for the concentration vertical profile using data above the lowest flight track. Map data: Google, CNES/Airbus, Maxar Technologies.

measured with a DigiQuartz sensor. In situ wind measurement on board aircraft are essential for accurate flux calculations. In this study, the three-dimensional wind speeds (U_x, U_y, U_z) were derived from the measurements using a Rosemount 858 probe, GPS, and Honeywell inertial measurement unit on board aircraft. The latitude, longitude and ellipsoid height altitude of the aircraft were determined using a GPS receiver.

CH_4 emission rates for each cluster of CHOPS wells surveyed were determined using TERRA,[29] which computes integrated mass fluxes through the virtual cylindrical walls from the aircraft measurements (see Supporting Information). TERRA has been used successfully and extensively for emission rate determination of CO_2,[44] CH_4,[17] volatile organic compounds,[43] oxidized sulfur and nitrogen,[45] black carbon,[46] and secondary organic aerosol.[47] As will be further rationalized in Section 3.1, CH_4 emissions from these clusters are assumed to primarily arise from oil and gas operations, thus neglecting nonoil and gas sources. Gordon et al.[38] demonstrated that using TERRA to derive the total emissions of CH_4 from a facility in the Athabasca Oil Sands Region has an uncertainty of 25−27%. Baray et al.[17] described an overall uncertainty of less than 30% when quantifying CH_4 emissions from Athabasca Oil Sands Region using TERRA. For four out of the eleven clusters that were flown over, upwind CH_4 fluxes that entered the virtual cylinders exited the cylinder from the top rather than the downwind wall of the cylinder, thus calling for additional corrections for estimating the top track air mixing ratios used in computing the vertical advective fluxes. The top track mixing ratios for these cylinders were estimated alternatively based on averaging the data collected during the flight path across the top after completing the cylinder and while en route to the next cylinder, rather than using the data measured on the top track of the cylinder. The corrections were successfully made for three cylinders where additional cylinder top flight data were available, but could not be made for one cylinder in Alberta due to insufficient cylinder top data. Thus, emission rates for ten out of eleven clusters were successfully obtained. This correction resulted in larger uncertainties than those reported by Gordon et al.[38] and Baray et al.[17] as the number of the additional flight data across the top was limited resulting in a larger standard deviation when deriving the average value of the top mixing ratio. Consequently, the uncertainty was estimated as 53−411% for the cylinders with the cylindrical top correction and 7−28% for those not requiring correction. Different sources of uncertainties were propagated to obtain the final overall uncertainties. Assessments of uncertainties for emission rates and further details of the ten clusters are listed in Table S2. In this work, the determination of the background value depended on the upwind measurement of CH_4 for each cylinder. The lowest 10% of CH_4 mixing ratios for each flight was extracted and linearly interpolated to obtain a time series of the CH_4 background values, so that each CH_4 data point had a corresponding background value. The background value of CH_4 was subtracted prior to the TERRA application.

CH_4 emissions attributed to CHOPS operations are not presented explicitly in Canada's National Inventory Report (NIR) where they are a subset of provincial totals of emissions from conventional heavy oil production in Alberta and Saskatchewan. For this work, CHOPS emissions from the NIR are identified from the facility subtype (subtype 331, 341, 342, 343 for Alberta and 313, 325, 326, 327 for Saskatchewan). Emissions from other non-CHOPS heavy oil types under these subtypes are neglected since they account for less than 10% of the total number of wells. Inventory estimates of annual CH_4 emissions arising from oil and gas operations located within each flight boundary (cluster-level) and CH_4 emissions from

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Table 1. Cluster-Aggregated CH_4 Emission Rates (E_M) and emission factors (EF_C) for the CHOPS Wells in Alberta and Saskatchewan[a]

labeled clusters	no. of CHOPS sites	no. of active CHOPS sites	aggregated emission rates (kg/h)	aggregated oil production rates (m^3/h)	emission factors (kg/m^3 oil)	provincial average CHOPS emission factor (kg/m^3 oil)
AB1	36	26	691 ± 83	25.9	26.7 ± 3.2	
AB2	22	16	267 ± 75	2.31	115.3 ± 32.3	
AB3	23	17	1128 ± 248	10.3	109.6 ± 24.2	AB: 70.4 ± 36.9
AB4	25	11	322 ± 1322	2.05	156.6 ± 643.6	
AB5	73	58	1023 ± 72	8.19	124.8 ± 8.7	
SK 1	94	48	852 ± 102	7.12	119.7 ± 14.4	
SK 2	69	28	871 ± 104	13.8	63.2 ± 7.6	
SK 3	28	16	203 ± 107	3.85	52.6 ± 27.9	SK: 55.1 ± 13.7
SK 4	84	33	233 ± 51	12.1	19.3 ± 4.2	
SK 5	167	50	137 ± 205	4.82	28.4 ± 42.6	

[a]The number of sites in each cluster are listed based on the HIS reporting system.[50]

CHOPS operations in Alberta and Saskatchewan (provincial-level) were derived following the same methodologies used in the NIR. While the same methodologies were used for the provincial- and cluster-level estimates, the provincial values include only the emissions originating directly from CHOPS wells and facilities while the cluster-level estimates include emissions from all oil and gas operations within the flight boundary, including any non-CHOPS facilities. The bottom-up inventory estimates include emissions from active oil and gas production facilities derived using well and facility populations and operator-reported volumetric activity data, including reported volumes of gas vented, flared, and used as fuel. Estimates for abandoned and inactive wells are included for each cluster, in addition to other ancillary (nonproduction) oil and gas activities that result in CH_4 emissions (well drilling/servicing/testing, waste disposal, accidents and equipment failures, and petroleum liquids transportation). For specific details on the application of inventory methodologies to produce the bottom-up CH_4 emissions presented in this study, please refer to Supporting Information Section S6.

3. RESULTS AND DISCUSSION

3.1. Emission Rates and Emission Factors. The CH_4 emission rates (E_{CH_4}) for the different clusters of CHOPS wells were obtained by applying TERRA to the aircraft measurements. Figure 2 shows a virtual flight cylinder surrounding a cluster of 84 active and shut-in CHOPS sites referred to as SK4. The CH_4 mixing ratios were interpolated and mapped on the wall of the virtual cylinder to an altitude of 1320 meter ASL based on the height of CH_4 plume. Winds originated from the southwest direction at 245 ± 30° during the flight, resulting in a plume visible on the downwind side of the cylinder wall, with a maximum CH_4 mixing ratio of 0.79 ppmv above the background value. The unwrapped, interpolated CH_4 screen of the flight cylinder for SK4 is also shown in Figure 2, which shows the CH_4 plume on the downwind northeast side of the cylindrical wall. CH_4 mixing ratios below the lowest flight path were estimated using a combination of linear or exponential extrapolation to the ground by finding the best fit for the concentration vertical profile using data above the lowest flight track as described previously.[38] Figure 2 indicates that a significant portion of the main plume (in concentration units; ppm) is below the minimum flight altitude. However, the extrapolated plume below the lowest flight track accounted for less than 10% of the flux through the entire screen, which indicates that the errors due to the downward extrapolation were minor. Using TERRA, the CH_4 emission rate from this cluster of CHOPS wells was 233 ± 51 kg h^{-1}. The CH_4 emission rates for all ten clusters of CHOPS facilities estimated using TERRA are listed in Table 1. The average CH_4 emission rate for all measured clusters (across both provinces) is 572 ± 237 kg/h, and is 686 ± 360 kg/h for Alberta and 459 ± 114 kg/h for Saskatchewan. CHOPS emissions have been observed to vary in time,[24,31] which possibly contributes to the uncertainty in the derived CH_4 emission rates from different clusters.

A common way to identify CH_4 emission sources from oil and gas production is to associate CH_4 with ethane (C_2H_6). In the present study, analyses of the five available discrete canisters sampled during the flight over the SK5 cluster show a good correlation of C_2H_6 with the averaged CH_4 over the C_2H_6 sampling period (Figure 3), indicating that the emission

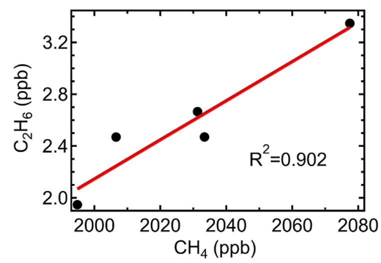

Figure 3. A correlation of C_2H_6 and CH_4 mixing ratios measured during the flight over the SK5 cluster. CH_4 mixing ratios were averaged over the C_2H_6 sample time periods.

sources of CH_4 were primarily from oil and gas production.[48] Typically, conventional and hydraulically fractured wells produce significant amounts of higher molecular weight hydrocarbons.[24] In this study, however, hydrocarbons larger than ethane, including propane, benzene, and toluene, were not detectable. Indeed, the federal inventory suggests CHOPS-region produced gas comprises over 90% CH_4.[49] Similar results were also reported by Roscioli et al.[24] In addition, the C_2H_6 to CH_4 ratio of 0.015 ± 0.009 in this study is lower than the ratio from conventional oil and gas wells, which could be as high as 0.124. The C_2H_6 to CH_4 ratio can also be used to estimate the emission rates of C_2H_6 by multiplying by the CH_4 emission rates (Table S3).

To develop a representative EF from the measurements, one method would be to simply divide each cluster-total emission by the number of wells in the cluster to calculate an average

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emission per well. However, this approach would not take into account various factors affecting emissions at the wells, in particular the production volume which is likely to affect the emission and may be a better predictor of emissions. The well-level production rates (P_{well}) in June 2018 reported in Petrinex[39,40] are summed into monthly cluster-total production rates ($P_{cluster}$), and then scaled down to hourly cluster-total production rates (P_{hour}). An overall average emission factor ($\overline{EF_c}$) is determined by dividing the sum of emissions, $\sum E_{CH_4}$, from the wells in all clusters by the sum of production, $\sum P_{hour}$, of the wells in all clusters. Using this approach, the average emission factor ($\overline{EF_c}$) is calculated to be 63.4 ± 26.2 kg/m^3 oil produced for all the facilities across both provinces. The average CH_4 emission factor is 70.4 ± 36.9 kg/m^3 produced oil for Alberta ($\overline{EF_{AB}}$) and 55.1 ± 13.7 kg/m^3 produced oil for Saskatchewan ($\overline{EF_{SK}}$) (Table 1).

The cluster aggregated emission factors EF_C varied by a factor of 8, ranging from 19.3 to 156.6 kg/m^3 oil produced (Table 1). As will be demonstrated below, such a large variation appears to be related to the oil storage and transportation mode where there are two main modes—piped versus nonpiped. The nonpiped well heads are connected to individual storage tanks and oil produced is stored in the tanks until it is transferred onto tanker trucks, while piped well heads are connected to off-site tank batteries through a network of pipelines with no individual tanks on-site. The nonpiped sites are determined based on the facility type reported in the IHS system.[50] For each cluster of wells surveyed during the study, the percentage of nonpiped oil production volume ($P_{non\text{-}piped}$) of the total oil production volumes is defined as below

$$R = \frac{P_{non\text{-}piped}}{P_{non\text{-}piped} + P_{piped}} \times 100\% \quad (1)$$

It was found that for all the investigated clusters, the percentage of nonpiped oil production volume of the total oil production volumes was positively correlated with cluster-aggregated emission factors (R = 0.64) (Figure 4). Clusters with a larger percentage of nonpiped oil production exhibited generally higher cluster-aggregated CH_4 emission factors. For the nonpiped wells connected to storage tanks, fugitive emissions can occur in addition to those at the wellheads and the engine sheds. For the nonpiped wells, CH_4 and other volatile compounds contained in the head space of the storage tanks are vented to the atmosphere through hatches or pressure relief valves during tank breathing, resulting in uncontrolled venting. In addition, they can also experience evaporative loss to the atmosphere when trucks unload the liquid from the tanks and when the wells are vented to unload liquids accumulated in the wellbore causing flashing losses.[51] In contrast, piped wells that transfer oil to a central processing facility are more likely to employ measures to mitigate emissions or conserve the gas. Clearly, due to the extra loading/unloading handling of oil for the nonpiped production, the emissions are not as well controlled. Within each cluster, there are many site-specific factors that could contribute to the cluster-aggregated emission factors, in addition to the CH_4 emissions resulting from the oil storage and transportation mode. These factors include the type of activity, the age of the infrastructure, management practices, as well as site-specific operating conditions (e.g., avoidable equipment maintenance issues), and likely explain some of the scatter within each cluster in Figure 4.

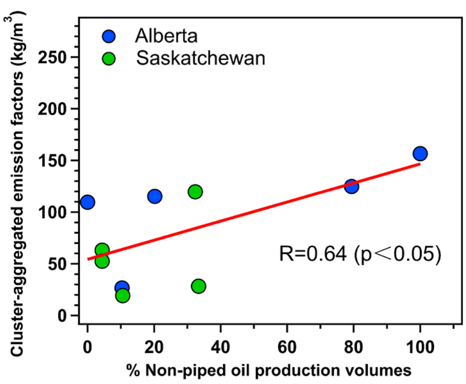

Figure 4. Relationship between cluster-aggregated CH_4 emission factors and the ratio of nonpiped oil production volume to total oil production volume within each cluster.

3.2. Comparison to Recent Measurements: Effectiveness of Oil Gas Methane Regulations with Other CHOPS Emissions Measurements. The study by Johnson et al.[32] estimated CH_4 emissions from the Alberta CHOPS region based on airborne measurements. With the reported centroid in the Johnson et al. study, their investigated region is mapped and shown in the black box in Figure 1. The investigated region (60 × 60 km) in the Johnson et al. study overlaps with four clusters of CHOPS wells in the present study, which are labeled AB1, AB3, AB4, and AB5. In the present study, the average CH_4 emission factor for these four clusters of wells is 60.9 ± 33.2 kg/m^3. To compare with the Johnson et al. study,[32] we extracted the production volume data in their measured region and calculated a corresponding CH_4 emission factor of 55.5 ± 13.4 kg/m^3 using the emission rates for the 60 × 60 km investigated region reported in the Johnson et al. study (Figure 1). Though both studies arrived at similar emission factors, considerable differences exist between the two methodologies, one of which is the size of the controlled box volume. The area that was covered in Johnson et al. (3600 km^2) is significantly larger than that in our study (38 km^2). For a significantly larger box volume with a considerably longer flight time, the conditions (e.g., meteorology, emissions) measured during the Johnson et al. study were more likely to have deviated from the steady state assumptions for mass-balance computations. Temporal and spatial variations in meteorological conditions and/or source emission rate can also lead to storage-and-release events, in which transient storage of emitted CH_4 mass within the box volume and its later release can contribute to over- or under-estimations of emission rates based on mass-balance techniques.[52] Despite these potential issues, the results from the present study and Johnson et al. are in good agreement with each other, suggesting that the relatively few wells covered in the present study may be representative of the bigger area.

In recent years, a series of aerial surveys utilizing Bridger Photonics' airborne Gas Mapping LiDAR have been conducted across CHOPS sites in both Alberta and Saskatchewan and derived site-level CH_4 emission rates.[18,19,31] Among these studies, Festa-Bianchet et al.[31] targeted 962 single-well CHOPS facilities in Saskatchewan, reporting a population-average CH_4 emission rate of 12.5 kg/h/site (12.0−13.1 kg/h/site). At the same time, Conrad et al.

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investigated all types of upstream oil and gas facilities within Alberta[18] and Saskatchewan.[19] Site-level CH_4 emission rates for CHOPS operations from these studies were recalculated based on the results from CHOPS activity subtypes (subtype 331, 341, 342, 343 for Alberta and 313, 325, 326, 327 for Saskatchewan in Petrinex). The results of these studies are shown in Figure 5. To compare with these results, the

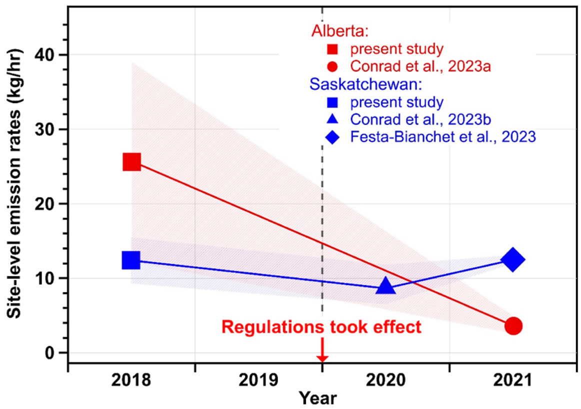

Figure 5. Trends in CHOPS site-level emission rates from 2018 to 2021 based on comparison with other previous CHOPS emission studies. CH_4 Regulations took effect on January 1, 2020 for both provinces. The shaded are as represent the uncertainty bounds reported from present study and those cited.

population-average CH_4 emission rate is derived in this study based on the number of active CHOPS sites in each cluster as listed in Table 1, where active sites are determined by nonzero oil or gas production volumes in the IHS reporting system.[50] The IHS system includes the location information that was used to identify sites falling within the flight boundaries. Additionally, each facility is categorized through a type description, with those labeled as "heavy" being taken as CHOPS facilities. Facilities with zero production or reported activity were also included in the IHS database, enabling the identification of both active and nonactive facilities. Although the area covered by the ten clusters is similar, there are more CHOPS sites in Saskatchewan (442) compared to Alberta (179), as indicated in Table 1. This discrepancy arises because CHOPS sites on the Saskatchewan side of these investigated clusters are single-well facilities, while those on the Alberta side are multiwell facilities consisting of 1−12 wells. The CH_4 emission rate for active sites in the clusters was determined assuming that inactive sites represent only 4.4% of total emissions.[31] By normalizing the cluster-total active CH_4 emission rate by the cluster-total number of active sites, the average CH_4 emission rate per site is derived at 25.6 ± 13.4 kg/h for Alberta and 12.4 ± 3.1 kg/h for Saskatchewan (Figure 5).

While the aerial surveys using airborne LiDAR were conducted after the introduction of new regulations at the beginning of 2020, the present study predates these regulations. Hence, leveraging all available data through the various years facilitates a trend analysis of CH_4 emission since 2018, and offers a baseline for understanding CH_4 emissions after the regulatory changes. In line with the federal regulations, Alberta and Saskatchewan enacted CH_4 reduction regulations for their respective upstream oil and gas sectors, with each going into effect on January 1, 2020. Notably, the Alberta regulations are currently more stringent than those in Saskatchewan. The government of Saskatchewan has published Directive PNG036[53] that imposes restrictions on oil wells and oil facilities, limiting venting to no more than 900 m^3/d. Sites with higher gas volumes must either conserve or flare all gas. In comparison, starting in 2020, Directive 060[54] in Alberta required that any emissions from a CHOPS site totaling more than 500 m^3/d must be combusted or conserved at single well sites or multiwell batteries.

As shown in Figure 5, the site-level emission rates for CHOPS facilities in Alberta have decreased from 2018 to 2021,[18] indicating regulatory impacts in mitigating CHOPS emissions in Alberta. However, despite regulatory efforts, results from the aerial surveys conducted in 2018, 2020,[19] and 2021[31] showed no significant difference in emission rates in Saskatchewan. While Saskatchewan has declared to have met its 2025 reduction target based on inventory estimates,[55] uncertain baselines, underreported emissions, decreased production, and lack of measurement data preclude a definitive conclusion regarding the efficacy of recent regulations.[19,33] Of particular concern is the potential for significant, often underestimated CH_4 emissions from CHOPS operations in Saskatchewan,[31,33] which may not have received adequate attention during the implementations of CH_4 reduction regulations. Consequently, more accurate reporting by industry, thorough verification processes and additional independent studies would be beneficial for improving trend analysis and ensuring the effectiveness of CH_4 regulations governing Saskatchewan's CHOPS operations.

3.3. Comparison with Bottom-Up, Inventory-Based Emissions. The aircraft-measured CH_4 emission rates for each cluster of wells were upscaled to annual emissions using the production volumes in June (P_{June}) and annual production volumes (P_{Annual}) within each cluster. Annual CH_4 emissions (E_{annual}) for individual clusters are derived and shown in Figure 6a, together with the bottom-up, inventory-based CH_4 emissions from oil and gas operations within the same clusters derived using NIR methodologies (see Supporting Information). The official NIR includes both operator-reported emissions data and estimates of unreported emissions. The operator-reported data aggregates monthly volumetric emission rates reported through the Petrinex data management system.[39,40] These data include produced oil and natural gas volumes, as well as gas volumes flared, vented, or used as on-site "fuel", reported in whole gas units with a 100 m^3 resolution, while the unreported emissions and fugitive emissions are derived based on average counts per facility and emission factors from Clearstone or engineering estimates and models. The aircraft-measured annual CH_4 emission rates are 111−1076% higher than the inventory-based CH_4 emissions for eight clusters, with the exception of cluster SK5 where the measured CH_4 emissions are lower than the inventory-based emissions by 68% and SK4 where the measured and inventory estimates are almost the same. Notably, the difference between the aircraft-measured and inventory-based CH_4 emission is larger in Alberta (171−1076%) than in Saskatchewan (5.7−143%).

Based on the emission factors determined in this study and the provincial heavy oil production volumes reported by industry[39,40] (see Supporting Information), emissions of CH_4 from CHOPS are estimated at the provincial level in Saskatchewan. Since the investigated sites in this study (CHOPS near Lloydminster) may not accurately represent all cold heavy oil production in Alberta, this calculation is only

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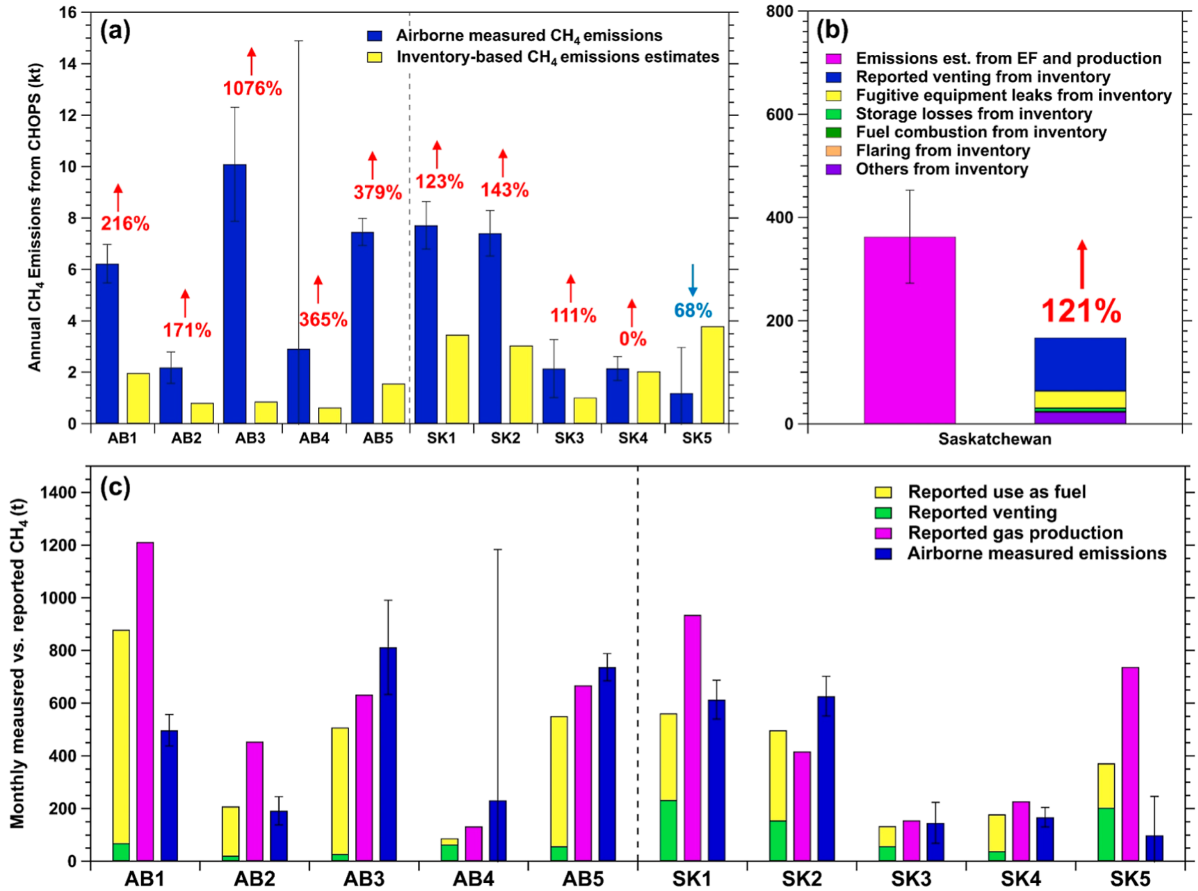

Figure 6. (a) Comparison of airborne-measured CH_4 emissions scaled up to a year with bottom-up, inventory-based CH_4 emissions using Canada's National Inventory Report (NIR) methodologies for each cluster in 2018. (b) Annual CH_4 emissions of CHOPS estimated using the aircraft-derived emission factors and annual heavy oil production reported in Petrinex compared with bottom-up, inventory-based CH_4 emissions from CHOPS wells for Saskatchewan. (c) Airborne measured CH_4 emissions scaled up to a month compared to gas volumes reported in June 2018 to Petrinex by operators.

performed for Saskatchewan. The annual CH_4 emissions from CHOPS are estimated to be 370 ± 92 kt yr^{-1} for Saskatchewan, which had a total heavy oil production volume of 6.73 × 10^6 m^3 for the year 2018. The measured CH_4 emission from CHOPS in this work is 121% higher (or 2.2 times larger) than the total bottom-up inventory estimates from CHOPS wells in Saskatchewan. Such measurement-inventory differences are consistent with other reported CHOPS focused studies in Saskatchewan[19,31,33] using a different aerial technology or nearby long-term regional measurement studies.[56] Utilizing various top-down approaches has yielded consistent findings, demonstrating the robustness of such methodologies in validating bottom-up inventories. This ensures the credibility of employing top-down measurements to support and validate the data obtained from bottom-up, inventory-based estimates. Notably, the measurement-inventory discrepancy is larger in the CHOPS region than in the entire province of Saskatchewan observed in previous studies.[19,33] This further indicates the substantial contribution of CHOPS operations to the underreporting observed in the ECCC's inventory, suggesting the presence of more cost-effective mitigation opportunities within CHOPS operations. There is evidence that CH_4 emission intensities for heavy oil production are higher than for the production of other types of oil,[57] due to significant volumes of venting occurring without proper reporting and/or venting below reporting thresholds that may not be required to be included in volumetric reporting to provincial regulators. These emissions would be captured by the top-down measurements, whereas inaccurate reporting of volumetric data to provincial regulators would lead to underestimations in the inventory.

Figure 6c shows the airborne measured CH_4 emissions for each cluster scaled up to a month compared with gas input volumes (gas production) and the gas output volumes (venting and fuel use) in June 2018 reported to Petrinex by operators. The reported gas volumes were converted to CH_4 mass employing the average CH_4 fractions used in the inventory, where the fraction used is 92% for CHOPS facilities in Alberta and 88% for the Lloydminster area in Saskatchewan. By adding up the ten clusters, the total airborne measured CH_4 emissions are 4.5 times larger than the total reported venting and approximately equal to the total reported gas production for most of the clusters. Such a lack of mass conservation indicates that either a part of the gas being reported used as fuel is lost to the atmosphere,[31] or that reported venting volumes in Petrinex are not accurately estimated. One potential explanation for this discrepancy is operators' use of gas to oil ratio (GOR) when reporting estimated vented gas volumes at CHOPS sites. CHOPS wells are not required to meter their gas production unless it exceeds 2000 m^3/day, such that most of the sites use GOR-based estimation methods.[58] The operators determine the GOR by measuring the ratio of gas to oil and then estimate

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the gas production based on the GOR and the measured oil production. GOR is derived from a 24 h measurement and updated every six months or as infrequently as every three years depending on estimated produced gas volumes.[30,59] Studies have suggested that uncertainties in GOR are likely contributors to the underestimation of CH_4 emission in CHOPS operations.[28,29,32] The inherent assumption for GOR is that the total gas volume being produced and measured over the 24 h is stable and that the oil production is stable over the periods in which the oil volumes are determined. However, in most CHOPS wells, the daily flow rates of oil and gas can change quite radically over short periods of time making GOR determination problematic. There is currently no industry standard for ensuring GORs reported are actually representative.[36] Alternatively, fugitive CH_4 emissions from suspended or abandoned wells in the clusters unaccounted for in industrial reports were captured by aircraft measurements. Wells with zero production volumes, which likely indicate suspended wells, accounted for up to 51% of the total well count in each cluster (Table 1), whose emissions, while captured in bottom-up inventories, are not as well studied and may be inaccurately characterized. The results here suggest that top-down aircraft measurements can provide an assessment of CH_4 emissions from bottom−up GHG inventories and data reported by oil and gas operators to provincial regulators (i.e., Petrinex).

4. IMPLICATIONS

The measured areas in this study only account for small portions of the CHOPS region and yet cover a wide range of the CHOPS well operations (Figure 1) with clearly distinct operation types and well ages. The selected CHOPS sites include off-site wells with minimal on-site equipment where a single wellhead is connected through a pipeline network to a processing battery, single-well batteries equipped with tanks and separators, and multiwell batteries. Thus, the CH_4 emission factors in this study may reflect those from the overall emissions from CHOPS in both Alberta and Saskatchewan, and hence are useful data for further emission inventory development and preparation. The comparison between Alberta and Saskatchewan suggests that there is no statistically significant difference in CH_4 emissions factors from CHOPS wells between Canada's largest producers of oil and gas.

Overall, the results indicate that the CHOPS region is a considerable source of CH_4 emissions. The differences between inventories and the aircraft measurements discussed here suggest the need for them to be reconciled through additional measurement studies in the CHOPS region, which must include additional wells, across various states of production, and across seasons. While the present study provides emission factors (and emissions) that can be used in future CHOPS inventory development, the uncertainties associated with the current airborne top-down method, other ground-based atmospheric techniques, or inversion modeling approaches indicate that additional intercomparisons between methods are required. In doing so, alignment between atmospheric measurement-based and activity-based emission estimates is more likely to be achieved.

The Canadian government has enacted regulations aiming at reducing CH_4 emissions from the oil and gas sector by 45% below the 2012 levels by 2025. The large emissions from CHOPS present a challenge, but larger emissions typically provide better opportunities for reductions, thereby achieving the overall CH_4 emission reduction goal. The observation here, that nonpiped CHOPS wells are related to higher CH_4 emission factors than piped wells by as much as a factor of 8, is an important result for consideration in future emission mitigation strategies. All production practices being equal, converting nonpiped wells into piped ones may require short-term investments but may achieve significant emission reduction benefits.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c02333.

Information of each cluster, TERRA method, CH_4 emission rates for each cluster, assessment of uncertainties, emission rates of C_2H_6, inventory based CH_4 emissions estimates, and references (PDF)

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Notes
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