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Letter

Methane Emissions from Natural Gas Gathering Pipelines in the Permian Basin

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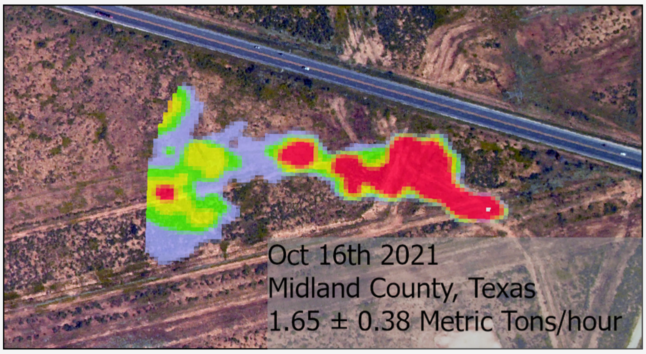

ABSTRACT: The rapid reduction of methane emissions, especially from oil and gas (O&G) operations, is a critical part of slowing global warming. However, few studies have attempted to specifically characterize emissions from natural gas gathering pipelines, which tend to be more difficult to monitor on the ground than other forms of O&G infrastructure. In this study, we use methane emission measurements collected from four recent aerial campaigns in the Permian Basin, the most prolific O&G basin in the United States, to estimate a methane emission factor for gathering lines. From each campaign, we calculate an emission factor between 2.7 (+1.9/−1.8, 95% confidence interval) and 10.0 (+6.4/−6.2) Mg of CH$_4$ year^{-1} km^{-1}, 14−52 times higher than the U.S. Environmental Protection Agency's national estimate for gathering lines and 4−13 times higher than the highest estimate derived from a published ground-based survey of gathering lines. Using Monte Carlo techniques, we demonstrate that aerial data collection allows for a greater sample size than ground-based data collection and therefore more comprehensive identification of emission sources that comprise the heavy tail of methane emissions distributions. Our results suggest that pipeline emissions are underestimated in current inventories and highlight the importance of a large sample size when calculating basinwide pipeline emission factors.

KEYWORDS: *methane, oil and gas, pipelines, leaks, aerial remote sensing*

■ INTRODUCTION

Natural gas production in the United States increased by more than 50% from 2010 to 2020.[1] Although the combustion of natural gas, whose primary component is methane, emits less carbon dioxide than the combustion of oil or coal, recent research has identified large methane emissions from natural gas infrastructure in basins across North America.[2] Rapid mitigation of these emissions from the oil and gas (O&G) sector can significantly curb climate change in a cost-effective manner.[3]

To date, few studies have characterized methane emissions from gathering pipelines, which are part of the gathering system that transports natural gas from well sites to processing plants for treatment, or directly to the transmission system for produced gas already near pipeline composition. Gathering pipelines are most often made of steel, plastic, or cast iron, and inlet pressures of gathering systems typically range from 100 to 2000 kPa (1 to 20 bar),[4−6] making gathering pipeline pressures generally lower than transmission pipeline pressures and higher than distribution pipeline pressures. Gas is moved through the gathering pipeline network by compressor stations, which are components of the gathering system sometimes used to dehydrate gas and which have also been shown to be significant sources of emissions.[7,8] Gathering pipelines generally emit methane in three different ways: (1) from leaking (typically underground) pipelines, (2) from leaking (above-ground) auxiliary equipment, and (3) during intentional venting at auxiliary equipment (e.g., maintenance blowdowns).[5]

Emissions from pipelines tend to be more challenging to measure than emissions from other types of natural gas infrastructure. Pipelines often form complex linear networks, which are more difficult and time-consuming to monitor than large discrete facilities that contain infrastructure elements known to be significant sources of fugitive emissions (e.g., well sites, storage tanks, and compressor stations). Moreover, many gathering pipelines are underground and in difficult-to-access locations, potentially complicating their identification and inspection.

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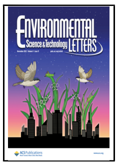

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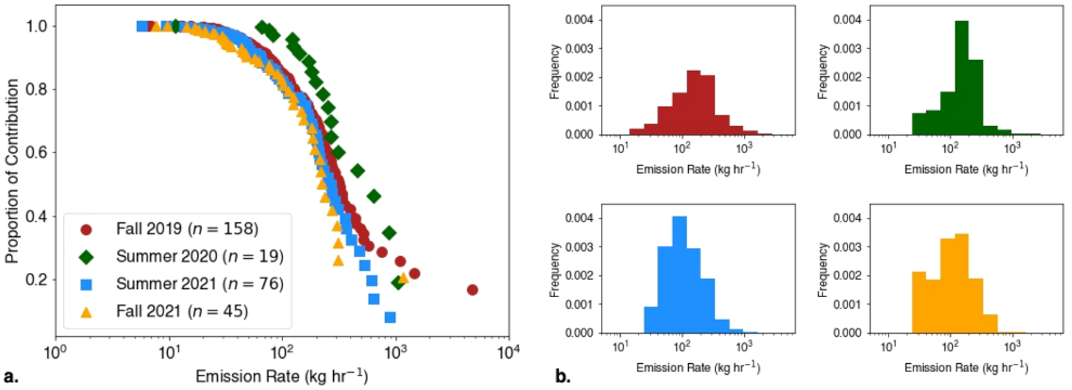

Figure 1. (a) Cumulative contribution of gathering pipeline source emissions to total gathering pipeline emissions, for each of the four aerial campaigns. To accurately estimate each gathering pipeline emission source's persistence-adjusted emission rate, only sources for which $n_o \geq 3$ are included. In each campaign, a small number of high-emitting sources were responsible for a significant portion of total emissions. (b) Distribution of plume emission rates attributed to gathering pipelines. The lower frequency of low-emission-rate plumes indicates the aerial instrument's faltering detection probability.

The greenhouse gas inventory (GHGI) published by the U.S. Environmental Protection Agency (EPA) estimates national methane emissions from gathering pipelines based on operator submissions to the Greenhouse Gas Reporting Program (GHGRP).[9] Additionally, a small number of published studies have used ground-based measurement techniques to estimate methane emissions from gathering pipelines.[5,10,11] These studies each surveyed between 73 and 187 km of gathering pipelines and identified no emission sources measuring higher than 4.0 kg h^{-1}. All three surveys found small leaks from auxiliary equipment, but just one[5] found an explicit pipeline leak.

Recent studies employing developments in aerial remote sensing have identified significant emissions emanating from pipelines in natural gas production regions.[12−14] The primary merit of an aerial-based method lies in the observation that methane emissions follow extreme distributions; specifically, in any given survey, a small number of high-emitting sources tend to be responsible for the majority of aggregate emissions.[15] Because of the positive skew, the mean of most sampled subsets will be lower than the true population mean, and an insufficient sample size will likely miss the high-emitting sources and by extension significantly underestimate aggregate emissions. Aerial methods are suitable for efficiently and cost-effectively collecting large amounts of measurement data (hundreds to thousands of square kilometers of coverage per day, depending on the platform). While the sensitivity of aerial methods is generally lower than that of ground methods and therefore aerial methods fail to detect some small sources, this can be offset by the larger sample size and potential to detect infrequent large sources.

This study aims to integrate such aerial measurements to better constrain the prevalence of large emission sources from gathering pipelines. Specifically, we are interested in deriving a basinwide emission factor (EF) for natural gas gathering lines. Although studies vary in their conventions, we define an EF as a measure of the methane emission rate per unit distance of pipeline. We focus on pipelines in the Permian Basin, a highly productive and rapidly growing O&G basin that spans western Texas and southeastern New Mexico.

■ MATERIALS AND METHODS

In this study, we use emissions measurement data acquired from four aerial campaigns conducted in the Permian Basin (Figure S1). Each of these campaigns (here labeled Fall 2019, Summer 2020, Summer 2021, and Fall 2021) lasted 2−6 weeks and covered major production regions of the Midland and Delaware sub-basins of the Permian. In each survey, an aircraft equipped with the Global Airborne Observatory (GAO) imaging spectrometer,[16] and in the Fall 2019 survey, additionally with the identical Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG), the latter of which has been validated in controlled release experiments,[17] amassed aerial coverage in excess of 8000 km^2. The aircraft followed raster flight patterns to cover all emission sources, including but not limited to pipelines, in a particular area. It should be noted that narrower field-of-view aerial remote sensing deployed in defined flight paths can survey specific pipelines.

For attributing methane emissions to natural gas gathering pipelines, we followed the conventions used in previous aerial-based studies of methane emissions from O&G infrastructure.[12,13] In brief, after an automated attribution process based on radial distances between plume location and infrastructure element GIS data, we manually inspected each emission source (defined as a collection of plumes located within a 150 m radius, the approximate length of a well pad) using imagery collected from the aircraft or satellites. We then assigned each source to a particular type of infrastructure based on GIS data containing upstream and midstream infrastructure, including pipelines.[18] We conducted a second round of manual attribution to discriminate between emission sources emanating from gathering pipelines and those from transmission pipelines, but the occasional co-location of these lines made such discrimination unfeasible in ∼5% of cases (section S1 of the Supporting Information).

To estimate the linear distance of gathering pipelines in each survey region, data for pipelines were acquired in April 2022 from the Enverus Drillinginfo and Enverus Prism platforms (section S2).[18,19] We restrict the data set of pipelines to those categorized as gathering, operational, and carrying a commodity type of natural gas, as these are the pipelines that can emit nontrivial amounts of methane. Realistically, oil pipelines cannot emit sizable volumes of methane because any

Table 1. Emission Factors for the Four Aerial Campaigns and Previous Estimates[a]

campaign	survey subset	area (km^2)	gathering pipeline distance (km)	no. of gathering pipeline emission sources	gathering pipeline emissions ($kg\ h^{-1}$)	emission factor ($Mg\ year^{-1}\ km^{-1}$)
Permian Basin Fall 2019	full	62000	79000 ± 8800	331	90000 ± 55000	10.0 (+6.4/−6.2)
	$n_o \geq 3$	15000	28000 ± 2900	158	28000 ± 18000	8.9 (+6.1/−5.9)
	$n_o \geq 3$; $n_d > 1$	15000	28000 ± 2900	45	14000 ± 8800	4.5 ± 2.9
Permian Basin Summer 2020	full	8400	17000 ± 410	56	13000 ± 6900	6.8 (+3.7/−3.6)
	$n_o \geq 3$	4500	8200 ± 290	19	5500 ± 2900	5.8 (+3.2/−3.0)
	$n_o \geq 3$; $n_d > 1$	4500	8200 ± 290	8	1500 ± 800	1.6 (+0.9/−0.8)
Permian Basin Summer 2021	full	8400	18000 ± 400	80	12000 ± 7300	5.9 ± 3.5
	$n_o \geq 3$	6600	16000 ± 390	76	11000 ± 6700	6.2 (+3.7/−3.8)
	$n_o \geq 3$; $n_d > 1$	6600	16000 ± 390	44	8600 ± 5500	4.8 (+3.2/−3.1)
Permian Basin Fall 2021	full	8800	19000 ± 400	50	5900 ± 4100	2.7 (+1.9/−1.8)
	$n_o \geq 3$	7500	16000 ± 450	45	5600 ± 3700	3.1 (+2.0/−2.1)
	$n_o \geq 3$; $n_d > 1$	7500	16000 ± 450	25	4900 ± 3200	2.7 ± 1.8
EPA GHGI 2020[9]			710000		16000	1.9×10^{-1}
Fayetteville Shale 2017[5]			4700		400	7.5×10^{-1}
Utica Shale 2019[10]			73		4.1×10^{-2}	4.9×10^{-3}
San Juan Basin 2019[11]			190		3.2×10^{-1}	1.5×10^{-2}

[a] In the "survey subset" column, "full" includes all data from the aerial survey, "$n_o \geq 3$" includes just the regions with three or more overflights, and "$n_o \geq 3$; $n_d > 1$" includes just the regions with three or more overflights and just the pipeline emission sources with more than one detection. The EPA estimate for 2020 is sourced from the 2022 GHGI. For the Fayetteville Shale campaign, we calculate the emission factor on the basis of the emissions estimated for the entire region, not just the survey region. Uncertainties, provided for the aerial campaigns only, represent 95% confidence intervals. Section S4 describes uncertainty quantification methods.

entering liquids must first be stabilized so as to not contain more gas than permitted.

To estimate aggregate emissions from gathering pipelines in each survey, we include all individual emission sources that were attributed as gathering pipelines. Including all measured sources produces an unbiased estimate of aggregate measurable emissions within the flight region; however, sources with low n_o values (defined as the number of days the source was flown over) have a positive persistence (defined as n_d/n_o, where n_d is the number of days during which non-zero emissions were detected from the source) bias, meaning that their individual persistence-adjusted emission rate[13] estimates are also potentially positively biased (section S3). We thus consider two sensitivity tests to assess the variability in total emissions quantification. First, we restrict the analysis to sources for which $n_o \geq 3$, a threshold sufficiently high to reasonably estimate an individual source's persistence.[13] For the same reason, throughout this study, we limit our calculations involving individual pipeline sources (e.g., emission rates and persistence) to those for which $n_o \geq 3$. Second, we further restrict the analysis to sources that were detected to be emitting on more than one day's flyover ($n_o \geq 3$; $n_d > 1$). This segregates sources that might be the result of blowdowns, maintenance operations, or otherwise short-term emissions and focuses quantification only on emission sources that are highly persistent and more likely fugitive.

RESULTS AND DISCUSSION

We find that pipeline emission sources in the four aerial surveys exhibit the well-documented behavior that a few large sources contribute to a large amount of aggregate emissions.[15,20] As an illustration, the largest gathering pipeline emission source identified in the Fall 2019 campaign was observed to be emitting 4689 [±2297, 95% confidence interval (CI)] kg of CH_4 h^{-1}, roughly the same rate as the smallest 91 sources (of 158 total, using $n_o \geq 3$) combined from the same campaign. Across the four surveys, a small percentage, between 12.0% and 21.1%, of the highest-emitting sources (again, for which $n_o \geq 3$) account for >50% of total emissions (see Figure 1a). However, this is less extremely distributed than is expected according to the emission size distributions found in previous studies of other O&G components.[15]

Table 1 contains the aggregated pipeline and emission data, and the resulting EF, for each of the four aerial campaigns. Using all measured sources, our EF estimates for natural gas gathering pipelines range from 2.7 (+1.9/−1.8) Mg $year^{-1}$ km^{-1} for Fall 2021 to 10.0 (+6.4/−6.2) Mg $year^{-1}$ km^{-1} for Fall 2019. As part of the Environmental Defense Fund's Permian Methane Analysis Project,[21] operators were provided coordinates and emission rates for all sources in the Summer 2021 data set. This information was shared before the Fall 2021 campaign, which could help explain the decrease in EF.

Figure 1b illustrates the distribution of emissions from plumes attributed to gathering pipelines. Because the peak bin in each plume emission rate histogram is located in the range of 70−200 kg h^{-1}, the detection probability appears to falter at a level significantly higher than the 10−20 kg h^{-1} minimum detection limit estimated through controlled release tests.[17] This increased minimum detection limit may be exacerbated by below-surface processes that can cause emissions to surface far from the pipeline and interfere with the sensitivity of above-ground methane measurement devices.[22] Therefore, aerial measurements of gathering pipelines, which are often located underground, may have functionally higher detection limits. Also, controlled release testing provides, in some ways, ideal conditions for detection and segregation of plumes from the background, so it may provide "best case" conditions that are difficult to obtain in real-world large-scale applications. This renders our EF estimates moderately conservative; the impact is likely moderate because of high-emitting pipeline sources' dominance of total pipeline emissions (section S5).

Due to the occasional co-location of gathering and transmission pipelines, there were several emission sources (29 of 559) that we could not identify as being associated with either gathering or transmission. To produce a conservative estimate for a gathering pipeline EF, we excluded all of these ambiguous emission sources from our calculations; however, it is a reasonable assumption that at least some of these emission sources are in fact from gathering pipelines. By using estimates of activity factors (defined as the mean number of sources per kilometer) of gathering and transmission pipelines, we infer that the gathering pipeline EFs from the four surveys could increase by $\leq$0.4 Mg year^{-1} km^{-1} (section S1).

EPA in its GHGI estimates national gathering pipeline methane emissions and mileage based on operator submissions to the GHGRP, which are subject to certain reporting requirements and EPA verification.[9,23] The EPA figures produce a total gathering pipeline EF of 0.19 Mg year^{-1} km^{-1} for the year 2020.[9] Therefore, the EF estimate derived from each of the four aerial surveys is more than an order of magnitude higher than the EPA's published value. Although the results of this study are specific to the Permian Basin in 2019−2021 and aerial surveys in other basins should be conducted before calculating a national EF, we note that nationally extrapolating the lowest EF computed from the full aerial campaigns (2.7 Mg year^{-1} km^{-1}) would increase the GHGI estimate of total natural gas system methane emissions by 27%.

Past ground-based surveys of gathering pipelines have also collected measurements whose resulting aggregated estimates are significantly lower than the estimates presented in this paper. The first of these surveys, which covered 96 km of gathering pipeline in the Fayetteville Shale in 2017, identified a single pipeline leak of 4.0 kg h^{-1} and a number of small leaks from auxiliary equipment totaling 0.8 kg h^{-1}.[5] Further analyses in the study used the hypergeometric distribution to extend the immediate survey findings to estimate aggregate emissions for a larger region, though the authors cautioned that their results might not be sufficiently representative to derive a basinwide estimate. The second of these surveys, conducted in 2019, covered 73 km of gathering pipelines in the Utica Shale. The survey identified no leaks from gathering pipelines and two small leaks, measuring 0.01 and 0.03 kg h^{-1}, from accessory block valves.[10] The third survey, also conducted in 2019, covered 187 km of gathering pipelines and found no explicit pipeline leaks, one small leak from a pig launcher door, and another small leak from a block valve.[11] EF estimates produced from each of the three ground surveys would be at most 0.75 Mg year^{-1} km^{-1} (after hypergeometric modeling),[5] significantly lower than all estimates derived in this study.

There are several possible explanations for this discrepancy in estimates between the ground-based and aerial-based campaigns. One is that differences in pipeline characteristics and activity across basins may lead to different EFs. Recent studies of methane emissions from O&G infrastructure in the Permian Basin have identified higher levels of midstream activity than predicted by inventories, perhaps driven by limited haul-away capacity.[13,24] That said, none of the three ground surveys mentioned above covered gathering pipelines in any portion of the Permian Basin, and no published study has used an aerial approach to quantify a gathering pipeline EF in any other basin; therefore, we cannot directly address this question by comparing results across basins.

A second and more important reason, we believe, is the significantly different sample sizes of the aerial and ground surveys. Each of the four aerial surveys covered at least 16000 km in linear distance of gathering pipelines, while the largest ground survey of gathering pipelines (in a published study) covered 187 km.[11] We argue that the limited scope of ground surveys is often insufficient to locate high-emitting pipeline sources, which aerial surveys indicate are responsible for a large part of aggregate emissions. A Monte Carlo experiment (methods detailed in section S5 and results displayed in Figure S2) reveals that a simulated survey of 100 km of gathering pipelines would have a 58% chance of finding none of the sources that could be identified from an aircraft, and an even higher chance of missing all of the high-emitting sources. This result is consistent with the past ground surveys of gathering pipelines in other major O&G basins, which found only very small leaks from gathering pipelines and associated equipment.[5,10,11] Additionally, accounting for sources below the aerial detection limit has an only modest effect on aggregate estimates because the high-emitting sources comprise a significant portion of the total (section S5).

This study, which provides EF estimates for gathering pipelines in one productive basin, demonstrates the importance of a large sample size when calculating aggregate pipeline emissions. Although there is no single minimum size of a survey that guarantees an accurate basinwide estimate, our results show that estimates derived from surveys with coverages of <500 km of gathering pipeline linear distance will likely be significantly and negatively biased. Indeed, EF estimates derived from recent limited-scope ground surveys may be one or more orders of magnitude lower than our calculated range of 2.7 (+1.9/−1.8) to 10.0 (+6.4/−6.2) Mg year^{-1} km^{-1}.

In November 2021, the Pipeline and Hazardous Materials Safety Administration (PHMSA) issued a final rule to expand regulatory oversight of gathering pipelines, establishing annual and incident reporting requirements for all 700000 km of U.S. on-shore gas gathering lines and applying leak survey and repair requirements to more than 30000 km of gathering pipelines.[25] The rule took effect May 16, 2022, though some provisions will not be enforced until 2024.[26] We recognize this development as a point of forward progress; however, the results from this study imply a need for increased pipeline-specific leak detection and repair (LDAR) programs that account for the heavy-tailed nature of the emissions distribution. The research presented here highlights the operational utility that aerial detection platforms provide by locating large emission sources from gathering pipelines, which conventional ground-based surveys are generally not well-equipped to do. Numerous aerial spectroscopy approaches[27,28] similar to the platform used in this study exist, demonstrating the availability of technology for large-scale implementation of pipeline-specific advanced LDAR programs.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.2c00380.

Additional methodological details, including the treatment of ambiguous and below-detection-limit emission sources, spatial calculations, uncertainty quantification, and a Monte Carlo simulation experiment (PDF)

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Notes

The authors declare the following competing financial interest(s): E.C.M. is a member of the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration's Gas Pipeline Advisory Committee.

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