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Methane Emissions from Abandoned Oil and Gas Wells in Colorado

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Executive summary

Recent research suggests that important emission estimates used to populate bottom-up methane (CH_4) inventories may be missing or incorrect. Methane is a powerful greenhouse gas and the largest component of natural gas. The most recent Greenhouse Gas inventories include emissions from plugged and unplugged abandoned oil and gas wells, where emissions are calculated from measurement of CH_4 emissions from mainly historic wells on the east coast of the US. Literature suggests the average emission from plugged wells in the US and Canada is 1.6 g CH_4 h^{-1}, and 7.5 g CH_4 h^{-1} from unplugged. To investigate if these emission factors could be used to generate representative emission estimates from abandoned wells in Colorado, we measured CH_4 emissions from 128 plugged and 206 unplugged abandoned wells in 17 counties and from 63 oil and gas fields in Colorado. Results show zero CH_4 emissions from all plugged wells observed and plugging remains effective for at least fifty years after the well has been sealed and covered in soil. The average CH_4 emission from an unplugged and abandoned wells in Colorado is 586 g CH_4 h^{-1}, over 70 times higher than the national average and with most emissions resulting from wells stranded by the recent removal of a gathering line instead of neglect of very old oil and gas wells. Emissions follow a heavily left-skewed long-tailed emission distribution typically seen by other oil and gas emission surveys, with 39% of unplugged wells not emitting. Statistical analysis indicates that emission is uncorrelated to well characteristics and 88% of the total emission from abandoned wells in Colorado are from a 20 x 20-mile area. Findings of this study suggest that newly abandoned oil and gas wells present a greater environmental and safety risk than historic wells with the largest observed emitter 200 times larger than the highest high emitting wells on the East coast. As a result, recently producing and abandoned wells should be considered as a priority for both screening and remediation.

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Introduction

Methane (CH_4) is a powerful greenhouse gas and the largest component of natural gas. Bottom-up approaches estimate 6 Tg of CH_4 is emitted from US natural gas systems each year, this includes emissions from production, processing, transmission, storage and distribution (EPA, 2018). Discrepancies between top-down and bottom-up methane emission estimates have been identified (Caulton et al., 2014; Schwietzke et al., 2014; Zavala-Araiza et al., 2015), and studies suggest inventories may be missing sources (Zavala-Araiza et al., 2015) or emission variability may exist (Lavoie et al., 2017) resulting in unrepresentative emission factors from CH_4 extraction processes (Nisbet and Weiss, 2010; Nisbet et al., 2019).

One recent addition to the US Greenhouse Gas inventory is CH_4 emissions from abandoned oil and gas wells. Emission factors used in the inventory are based on US measurement studies, conducted mainly in Eastern US states (Kang et al., 2016; Omara et al., 2016; Pekney et al., 2018; Riddick et al., 2019; Townsend-Small et al., 2016). The term *abandoned* describes a range of well types including: 1. wells with no recent production, and not plugged (inactive, temporarily abandoned, shut-in, dormant, idle); 2. wells with no recent production and no responsible operator (orphaned, deserted, long-term idle, abandoned); and 3. wells that have been plugged to prevent migration of gas or fluids.

Average CH_4 emissions from unplugged abandoned wells in the Appalachian Basin are reported as 3 g CH_4 h^{-1} $well^{-1}$ in West Virginia (Riddick et al., 2019), 17 g CH_4 h^{-1} $well^{-1}$ in Pennsylvania (Kang et al., 2016), and 28 g CH_4 h^{-1} $well^{-1}$ in Ohio (Townsend-Small et al., 2016). This suggests that differences in operator practices, state law and/or regulation could lead to differences in average emissions from abandoned wells and therefore an over/underestimate in reported GHG emissions. In Colorado, there are an estimated 33,000 unplugged and abandoned wells and 49,000 plugged and abandoned wells (COGCC, 2023). At present, few data exist on CH_4 emissions from abandoned oil and gas wells in Colorado and it is unclear which emissions factor should be used to calculate statewide emissions from abandoned wells. Also, the are no data to indicate if the average age of wells in Colorado, environmental conditions, operator's practices, state

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regulations and post-abandonment activities could affect the average emission from abandoned wells.

This aim of this study is to measure CH_4 emissions from plugged and unplugged abandoned wells in Colorado to generate a regionally representative range of emissions from each type of well. Specifically, the objectives of this study are to:

1. Review literature to investigate the relative size of CH_4 emissions from orphaned wells in different parts of the US and Canada;

2. Conduct field studies in Colorado to measure CH_4 emissions data from abandoned wells;

3. Better understand the drivers of emissions from abandoned oil and gas wells in Colorado by comparing emission rates to well characteristics, e.g. age, production rates and date abandoned.

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Report 1 Literature study of orphaned well emissions in the US and Canada

Methods

A literature review was conducted to find average CH_4 emissions from plugged and unplugged abandoned wells in Ohio, Pennsylvania, California, Ontario, West Virginia, Oklahoma and Texas. Data collected included the lead author, the year data were collected, the geographical location of the measurements, the average emission (g h^{-1}), an estimate of the percentage uncertainty of the emission estimate, the methods used to estimate the quantification uncertainty, the number of wells measured and the method of selecting wells for measurement.

Results

To date, emission data from 412 plugged and 427 unplugged wells in nine states and provinces in the US and Canada have been published. The US and Canada average emission from plugged wells is estimated at 1.6 g CH_4 h^{-1} with the largest emissions observed in Oklahoma (4 g CH_4 h^{-1} from 20 wells), Ontario (2 g CH_4 h^{-1} from 24 wells) and Pennsylvania (12 g CH_4 h^{-1} from 40 wells). Average emissions less than 1 g CH_4 h^{-1} were observed in California (0.3 g CH_4 h^{-1} from 97 wells), Ohio (0 g CH_4 h^{-1} from 6 wells) and West Virginia (0.1 g CH_4 h^{-1} from 112 wells) (Figure 1).

The US and Canada average emission from unplugged wells is estimated at 7.5 g CH_4 h^{-1} with largest emissions observed in Ohio (28 g CH_4 h^{-1} from 6 wells), Pennsylvania (24 g CH_4 h^{-1} from 81 wells) and California (11 g CH_4 h^{-1} from 1 well). The smallest emissions were observed in Oklahoma (3 g CH_4 h^{-1} from 13 wells) and West Virginia (3 g CH_4 h^{-1} from 159 wells) (Figure 1). Emissions from the Western US presented in Townsend-Small et al. (2016) were not included in this description as the state-specific emissions were not disaggregated in the analysis.

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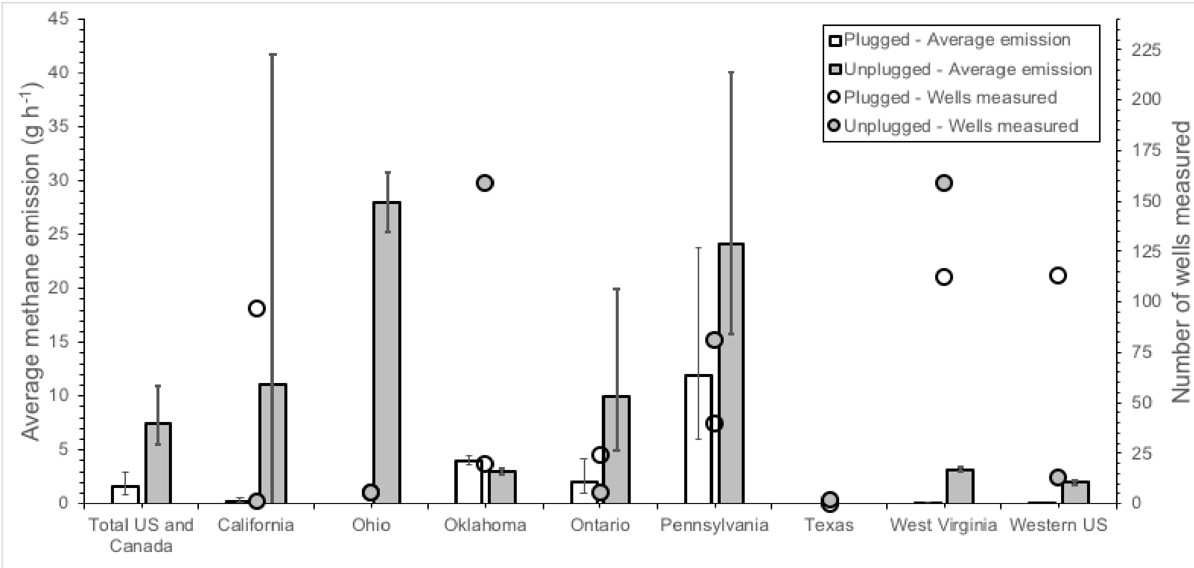

Figure 1 Average methane emission and number of wells measured from plugged and unplugged abandoned wells in the US and Canada and in separate states/provinces where data exist. Western US data are based on cumulative data for Colorado, Utah and Texas, separate state data were not presented (Townsend-Small et al., 2016).

Discussion

At time of this publication, CH_4 emissions have been measured and reported from 412 plugged and abandoned oil and gas well across the US and Canada. The average emission from these wells is 1.6 g CH_4 h^{-1} with an uncertainty of +88/-44%, based on methods' uncertainties described in the publications listed in Table 1. For the six states/provinces reported, emissions have been measured from more than 100 plugged wells in only one state, West Virginia. Additionally, only four of the studies selected wells randomly from database, while one study deliberately located high emitting wells to measure. If emissions data are filtered for random sampling, the average CH_4 emissions from plugged wells in the US is a factor of 36 lower at 44 mg CH_4 h^{-1}. However, it remains unclear if the number of measured plugged wells is a statistically representative sample size as the number of plugged wells in the US and Canada is very uncertain and significantly higher than the sample size.

For unplugged and abandoned wells, 427 have been measured across the US and Canada. The average emission is estimated at 7.5 g CH_4 h^{-1} with an uncertainty of +46, -26%. The number of

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unplugged and abandoned wells in only two states, Oklahoma and West Virginia, is more than 100. Only four studies used a random method for selecting wells to measure. Using these four studies the average emission is 3.9 g CH_4 h^{-1}. Comparing the total of plugged and unplugged wells measured in these studies (837) to the total number of abandoned wells in the US and Canada (3.2 million), the sample size is 0.026%, undermining the validity that these emission estimates are reflective of the actual average emission. Additionally, the findings of this study, as presented in the next section, underscore the crucial importance of the sample size due to the observation that emissions adhere to a left-skewed, long-tailed distribution. In this distribution, a limited number of wells contribute significantly to the overall emissions.

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Table 1 Synthesis of all data published that report methane emissions from orphaned wells in the US and Canada. Well types plugged (P) and Unplugged (Un). Un Method is the method of calculating uncertainty.

Lead author	Year	State/ Province	Type	Average emission (g h^{-1})	Uncertainty (+/- %)	Un Method	Number of wells measured	Method of well selection
El Hachem	2022	Ontario	P	2.1	N/A	N/A	24	None described
Kang	2014	Pennsylvania	P	11	+100, -50	2	5	None described
Kang	2016	Pennsylvania	P	12	+100, -50	2	35	Only high emitting wells chosen
Lebel	2020	California	P	0.286	+100, -50	2	97	Randomly from database
Riddick	2019	West Virginia	P	0.13	±7	1	112	Randomly from database
Townsend-Small	2016	Ohio	P	0	±10	3	6	Randomly from database
Townsend-Small	2016	Western US	P	0.002	±10	3	113	Randomly from database
Saint-Vincent	2020	Oklahoma	P	4	±10	3	20	Screening
El Hachem	2022	Ontario	Un	10	N/A	N/A	6	None described
Kang	2014	Pennsylvania	Un	11	+100, -50	2	5	None described
Kang	2016	Pennsylvania	Un	22	+100, -50	2	53	Only high emitting wells chosen
Lebel	2020	California	Un	11	+280, -100	4	1	Randomly from database
Pekney	2018	Pennsylvania	Un	29	±10	3	22	Subset sampling
Riddick	2020	West Virginia	Un	3	±7	1	12	Only high emitting wells chosen
Riddick	2020	Pennsylvania	Un	100	±7	1	1	Only high emitting wells chosen
Riddick	2019	West Virginia	Un	3.2	±7	1	147	Randomly from database
Saint-Vincent	2020	Oklahoma	Un	3	±10	3	159	Screening
Townsend-Small	2021	Texas	Un	0	±10	3	2	None described
Townsend-Small	2016	Western US	Un	2	±10	3	13	Randomly from database
Townsend-Small	2016	Ohio	Un	28	±10	3	6	Randomly from database

Method of calculating uncertainty: 1. Desk-based calculation; 2. Sum individual uncertainties; 3. Accuracy of Hi Flow Sampler; 4. Controlled release experiment

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Report 2 Measuring Colorado abandoned wells' methane emissions

Methods

During the field measurements, each site was screened using an ABB Micro-portable Greenhouse Gas Analyzer (MGGA; 1-sigma CH_4 precision < 0.9 ppb over 1 sec; range 0 to 100 ppm). Screening included the wellhead, wellbore, and any still-attached flow lines that may leak some distance away from the well head. When a CH_4 enhancement was detected, emission was quantified using either a chamber method or a downwind dispersion method, as described below. The lowest quantifiable emission of g CH_4 h^{-1} was defined in the Bureau of Land Management's (BLM) abandoned wells guidelines.

Dynamic chamber

Following the guidelines defined by the BLM, the dynamic chamber comprised of a plastic container (0.12 m^3) enclosing the source (Figure 2) and a propeller is used to circulate the air and a flow of air is passed through the chamber. The CH_4 flux (Q, g s^{-1}) was calculated from the CH_4 concentration at steady state (C_{eq}, g m^{-3}), the background CH_4 concentration (C_b, g m^{-3}) and the flow of air through the chamber (q, m^3 s^{-1}) (Aneja et al., 2006; Riddick et al., 2019). Following the method of Riddick et al. (2019; 2020), the emission is calculated from the steady state gas concentration using Equation 1. Methane concentrations inside the chamber were measured using the INIR-ME100% sensor mounted inside the chamber. Uncertainties in emission estimate using the dynamic chamber are estimated at ±11% (Riddick et al., 2022a).

$$Q = \left(C_{eq} - C_b\right) \cdot q \quad \text{(Equation 1)}$$

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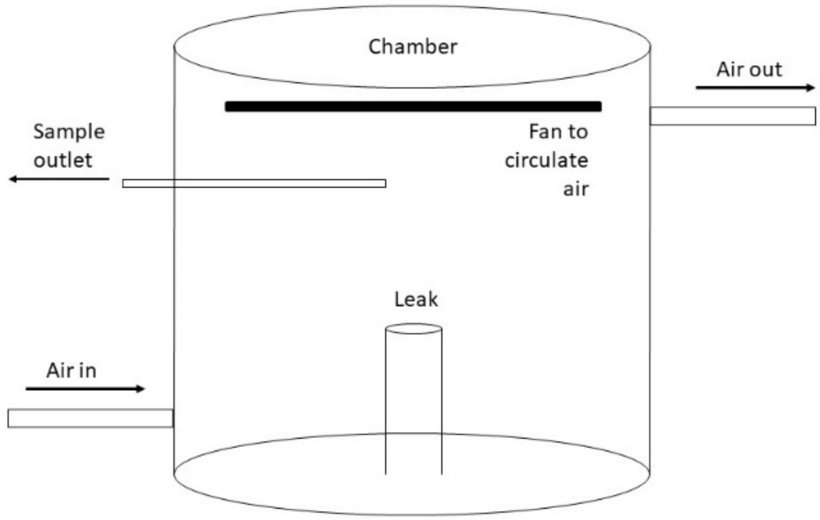

Figure 2 Schematic of the dynamic flux chamber.

Downwind dispersion method

For well heads that cannot fit inside the chamber, a downwind method can be used to quantify emissions. The Gaussian Plume (GP) model describes the concentration of a gas as a function of distance downwind from a point source (Seinfeld and Pandis, 2016). As gas is emitted from a source, it is entrained in the prevailing ambient air flow and disperses laterally and vertically with time, forming a dispersed concentration cone. The concentration of the gas (X, µg m^{-3}), at any point x meters downwind of the source, y meters laterally from the center line of the plume and z meters above ground level can be calculated (Equation 2) using the emission rate (Q, g s^{-1}), the height of the source (h_s, m) and the Pasquill-Gifford stability classification (PGSC) as a measure of air stability. The standard deviation of the lateral (σ_y, m) and vertical (σ_z, m) mixing ratio distributions are calculated from the PGSC of the air (Pasquill, 1962; Busse and Zimmerman, 1973; US EPA, 1995). The GP model assumes that the vertical eddy diffusivity and wind speed are constant and there is total reflection of CH_4 at the surface. Uncertainties in near source measurements directly downwind of the emission point are estimated at ±9% (Riddick et al., 2023). Special attention was taken to ensure measurements were made as close to the source as possible, at the same height and directly downwind. This was done due to the GP limitation to account for lateral dispersion at distances less than 100 m from the source, which could result in large measurement uncertainties (Riddick et al., 2022a).

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$$X(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-\frac{y^2}{(2\sigma_y)^2}} \left(e^{-\frac{(z-h_S)^2}{(2\sigma_z)^2}} + e^{-\frac{(z+h_S)^2}{(2\sigma_z)^2}} \right) \qquad \text{(Equation 2)}$$

CH_4 concentrations were measured directly downwind of the emission point using the MGGA, while meteorological conditions, wind speed and air temperature, were measured using a Kestrel 5500 weather meter collocated with the analyzer inlet. The measurement distance downwind was dependent on the emission size and varied such that the observed mixing rations were in the linear response range of the MGGA, i.e., between 2 and 100 ppm. To reduce any impact of mechanical turbulence while maintaining real changes to CH_4 emission caused by changing environmental or atmospheric factors, both CH_4 concentrations and meteorological data are averaged over five minutes. The PGSC during each measurement was calculated from the meteorological data using the method of Seinfeld and Pandis (2006).

The field measurement component comprised measuring CH_4 emissions using the methods described above from 334 plugged (108) and unplugged (226) abandoned wells in 17 counties and from 63 oil and gas fields in Colorado. Most wells were taken from the Colorado Oil and Gas Conservation Commission (COGCC) orphaned well list, which is a list of oil and gas wells, locations, and production facilities statewide for which there are no known responsible parties ("Orphaned Wells or Sites") or for which financial assurance instruments have been claimed. This list is annually updated, where wells that are plugged or adopted by another operator are removed from the list. Wells from bankrupt operators are typically added to the list if an operator is unable to find a buyer for a well and is unable to continue to pay for the operation of the well. The COGCC orphaned well list mainly contained unplugged wells or newly plugged wells, therefore 29 plugged wells not on the COGCC list were also measured.

Results

128 plugged and 206 unplugged abandoned wells were screened, and emissions quantified in 17 Colorado counties between August 2022 and April 2023 (Figure 3). In the majority of cases, there was no evidence of oil and gas operations at any of the plugged well sites with the well head being cut, capped and buried under 6 feet of soil. At each plugged well latitude/longitude, as recorded by the COGCC, the MGGA was left to measure CH_4 concentration for five minutes at the

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surface and at any obvious sign of disturbance nearby (depressions or cracks in the soil). No emissions were detected from the soil above any of the plugged wells regardless of date the wells were plugged (Figure 4A).

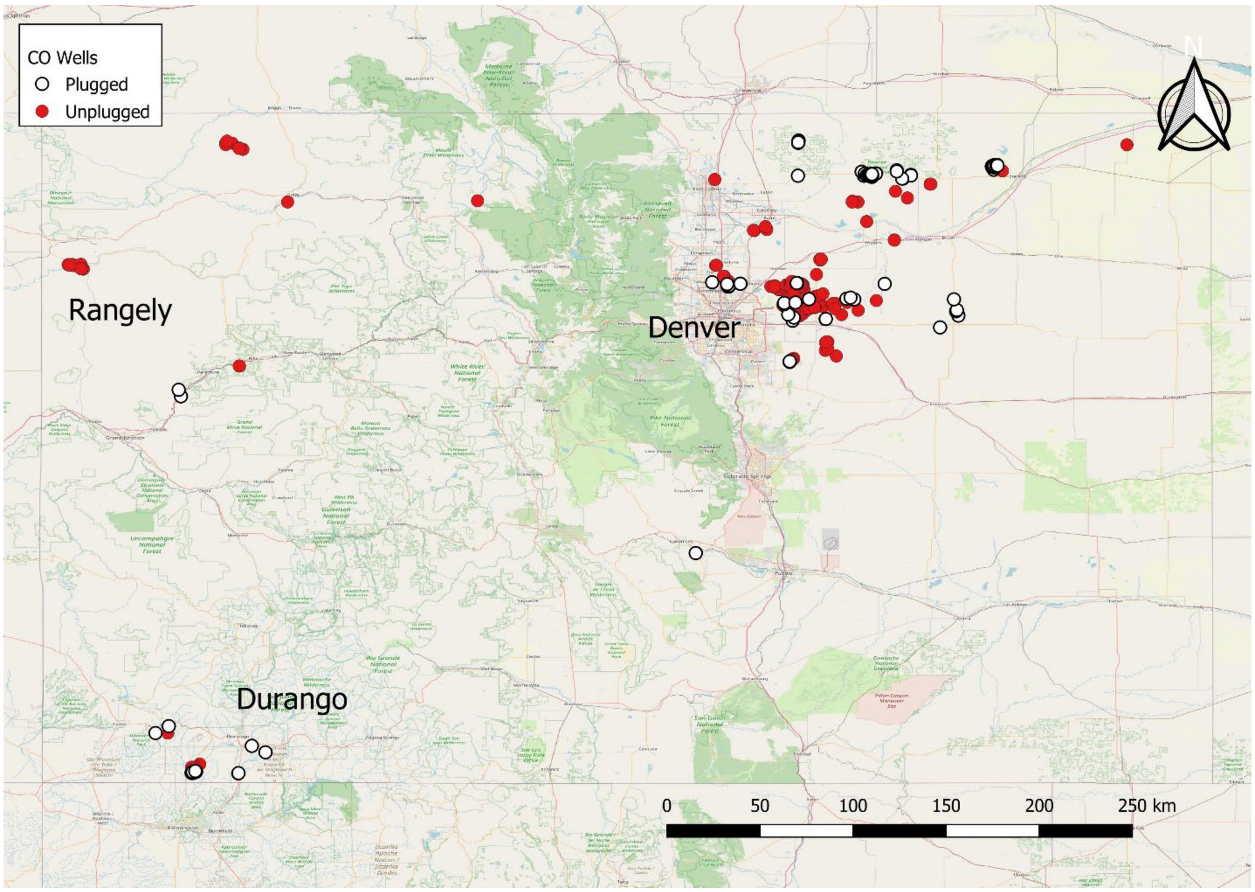

Figure 3 Locations of the 128 plugged and 206 unplugged abandoned wells measured in Colorado between August 2022 and April 2023

Table 2 Summary of plugged and unplugged wells measured during the campaign between August 2022 and April 2023

Type of well	Plugged	Unplugged
Number of wells measured	128	206
Number of emitting wells	0	127
Average emission (g CH_4 h^{-1})	0	586

Of the 206 unplugged and abandoned wells observed, 61% were emitting CH_4 (Table 2). All unplugged and abandoned wells were obvious and typically had either a hole in the ground (8%

of sites measured), "Christmas tree" valves (41%) or pump jacks (51%) visible at the sites. At many of the emitting wells, liquid could be seen where gas was being emitted and at some sites hissing gas could be heard. The average emission from unplugged and abandoned wells in CO is estimated at 586 g CH_4 h^{-1} with median emission 0.65 g CH_4 h^{-1} (Figure 4B). The largest emitting well was emitting 76 kg CH_4 h^{-1} on September 2nd 2022, 65 kg h^{-1} on 3rd October 2022 and 20.5 kg CH_4 h^{-1} on 16th March 2023.

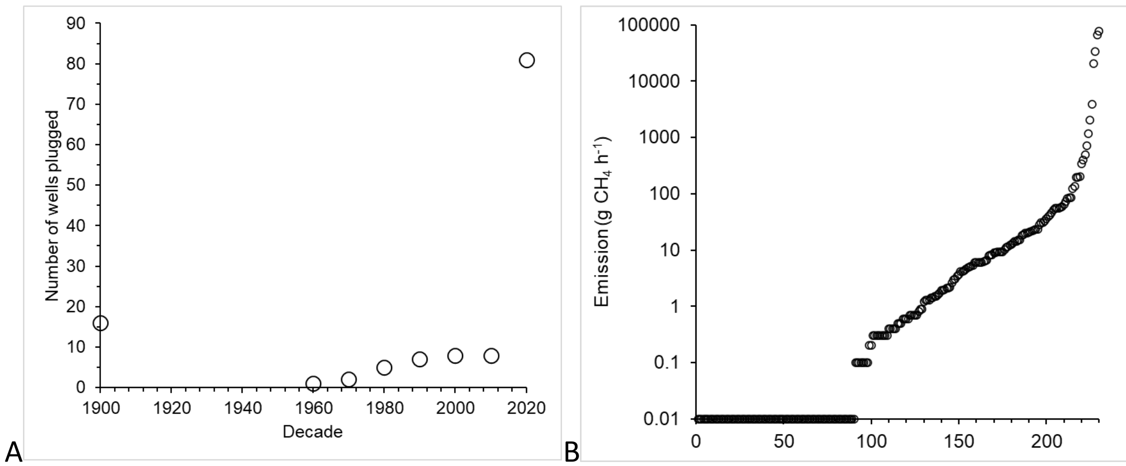

Figure 4 Number of the plugged wells observed binned by decade the well was plugged - from 1900 to 2010. Here we assume that wells plugged in 1900 were plugged before data on plugging was recorded. B Emission distribution of the 226 unplugged and abandoned wells. The 67 repeat measurement have been included in this plot.

Repeat measurements were made at a random subset of 67 wells across Colorado, with 42 plugged and 325 unplugged wells. No plugged wells were observed to emit CH_4 during the repeat measurements. Of the originally non-emitting unplugged wells, 10 wells remained non-emitters and 6 were observed to emit. Of the originally emitting wells, all of them decreased in CH_4 emission by an average of 80% over an average of 150 days between measurement (Figure 5).

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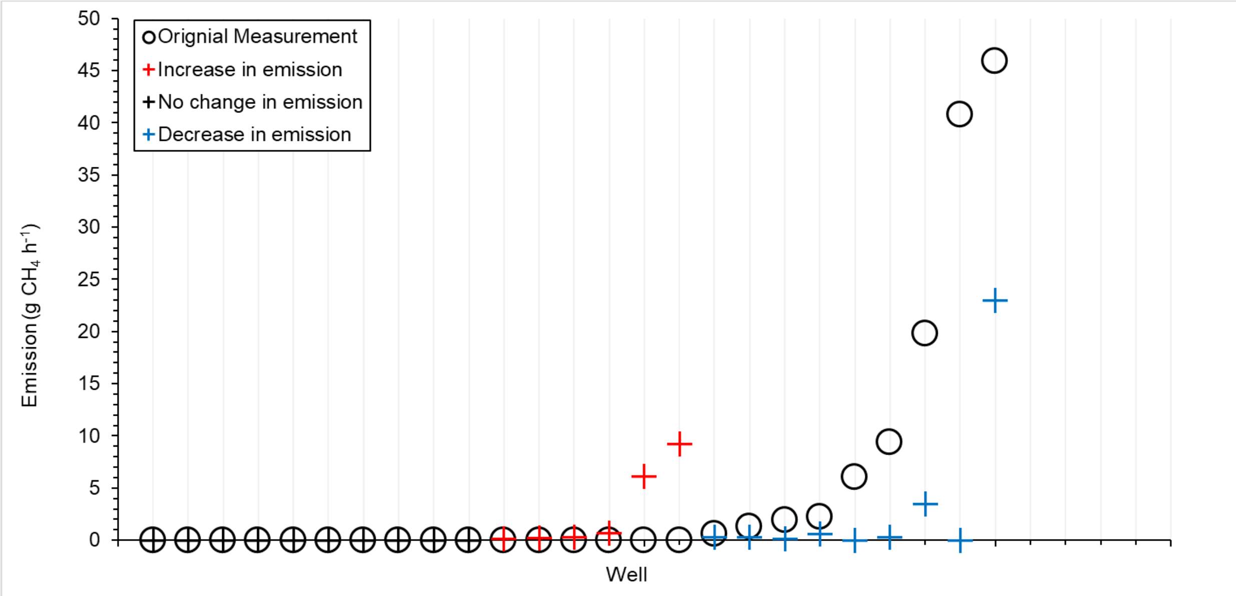

Figure 5 Original and repeat methane emission measurements from 32 unplugged and abandoned wells across Colorado. Circles indicate original measurement, back crosses indicate repeat measurements at sites that did not change in emission. Red crosses indicate originally non-emitting wells that were observed to emit on the repeat measurement. Blue crosses indicate repeat measurements at originally emitting wells. The largest emitting well emitting 76 kg CH4 h-1 on 2nd September 2022, 65 kg h-1 on 3rd October 2022 and 20.5 kg CH4 h-1 on 16th March 2023 has not been included in this figure as it is off the scale by a factor of 1,000.

Discussion

A conscious effort was made to measure at least 100 plugged and 100 unplugged abandoned wells in Colorado as this is generally accepted as a minimum statistically representative sample size. The average CH_4 emission from plugged and unplugged wells was 0 g CH_4 h^{-1} and 586 g CH_4 h^{-1}, respectively. From personal observation, the wells in Colorado are very different from wells in West Virginia, where emissions from plugged and unplugged wells are 0.13 g CH_4 h^{-1} and 3.2 g CH_4 h^{-1}, respectively.

Plugged wells in West Virginia typically have 0.3 m of well bore still exposed above the surface and when emitting, CH_4 can be detected either in cracks between the concrete filling and the metal well bore or at the base where the well bore has rusted. In Colorado, plugged wells are filled with concrete, welded shut and buried 1 m below the surface. No CH_4 was detected on the

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surface above any plugged well in Colorado regardless of age (Figure 3A), which is not to say that the well in not emitting, only that CH_4 cannot be detected.

Similarly, unplugged wells are very different in Colorado compared to West Virginia. Of the 147 unplugged and abandoned wells measured in West Virginia, the majority (~75%) were holes in the ground or the remains of old oil infrastructure, *sic*. the remains of the town Volcano in Mountwood Park, WV. Only unplugged and abandoned wells in the Rangely field, Rio Blanco County looked like WV unplugged wells, but the Rangely abandoned wells emissions were a factor of 30 higher. These higher emissions may be a result of more recent abandonment, where the average year of abandonment for the 1,585 wells in Rangely was 2004, while the wells in Volcano were likely to have been abandoned between 1870 and 1920.

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Report 3 Patterns in Colorado unplugged wells' emission

Methods

To investigate any patterns in emissions, data from the COGCC were collected on the wells' completion year, total vertical depth of well (ft), time between last production and measurement (years), active production (years), total gas production (Mcf), and total production (BOE). Statistical regressions were conducted on these variables and the measured emission to identify any causal relationships.

Results

Comparing abandoned well emission data to individual well data for completion year, total vertical depth of well (ft), time between last production and measurement (years), active production (years), total gas production (Mcf), total production (BOE), shows that there is no correlation between emission and any of the variables (Table 3). When grouped geographically, the largest emissions are observed from wells in the same counties, with Adams, Logan, Rio Blanco, La Plata and Moffat being the counties with the highest average emissions (Figure 6). The size of emission on county basis does not correlate to county gas production.

Table 3 Correlations between unplugged well characteristic variables and measured emission rate.

Variable	R^2	m
Completion year	0.008	23
Total vertical depth of well (ft)	0.00008	0.04
Time between last production and measurement (years)	0.005	-183
Active production (years)	0.003	-81
Total gas production (Mcf)	0.0004	-0.0008
Total production (BOE)	0.00001	-0.002

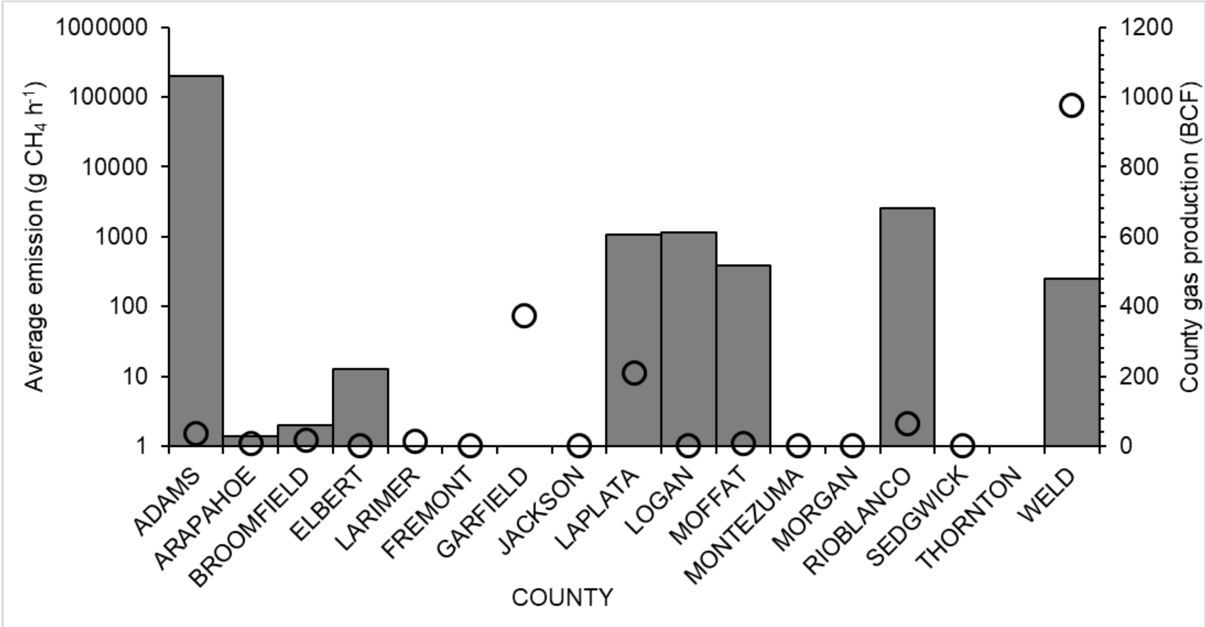

Figure 6 Average emission and gas production from abandoned well and total wells in counties in Colorado, respectively.

Discussion

The largest emission from unplugged and abandoned wells in Colorado were found in Adams County (average 1,396 g CH_4 h^{-1}) and Logan County (average 290 g CH_4 h^{-1}). Both Counties' average emission were skewed by a single large emitter 76,050 and 1,162 g CH_4 h^{-1} in Adams and Logan Counties, respectively. Long tail emission distribution with super emitters relative to the median emission are common to oil and gas emissions distributions but have not previously been seen during abandoned well measurements, which is possibly a result of sample size, a situation novel to Colorado, or a result of measuring the majority of wells in one county that were orphaned due to a shut-in pipeline on actively producing wells.

In 2017, a house explosion in Firestone, CO, resulted in the removal of a gathering pipeline system in Adams County. The pipeline removal stranded many producing wells resulting in loss of revenue and eventual financial collapse of local oil and gas operators. These stranded wells were shut in and have since become orphaned wells, with well bores still remaining at pressure. We suggest that since being shut in, valves have failed and gas is emitted at significant rate, with a maximum emission rate of 76 kg CH_4 h^{-1}. The largest emissions can be seen from the wells affected by the pipeline shutdown to the east of Denver (Figure 7), the map shows all wells

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emitting more than 1 g CH_4 h^{-1}. The smallest circle, less than 2 kg CH_4 h^{-1}, are unlikely to be detected by a mobile survey, while the mid-range emitters 2,000 to 10,000 g CH_4 h^{-1} are likely to be detected by a mobile survey (Riddick et al., 2022b). The largest emitters 10 to 100 kg CH_4 h^{-1}, are large enough to be detected during airborne surveys (Duren et al., 2019). As a result, 88% of emissions from abandoned wells in Colorado are emitted from wells in a 20 x 20-mile area in Adams County. Of note, even when the emissions from Adams County are removed, the average emission from wells in Colorado are 58 g CH_4 h^{-1} and seven times higher than the average US/Canada unplugged and abandoned emission. There is no obvious driver to which wells will emit other than geography.

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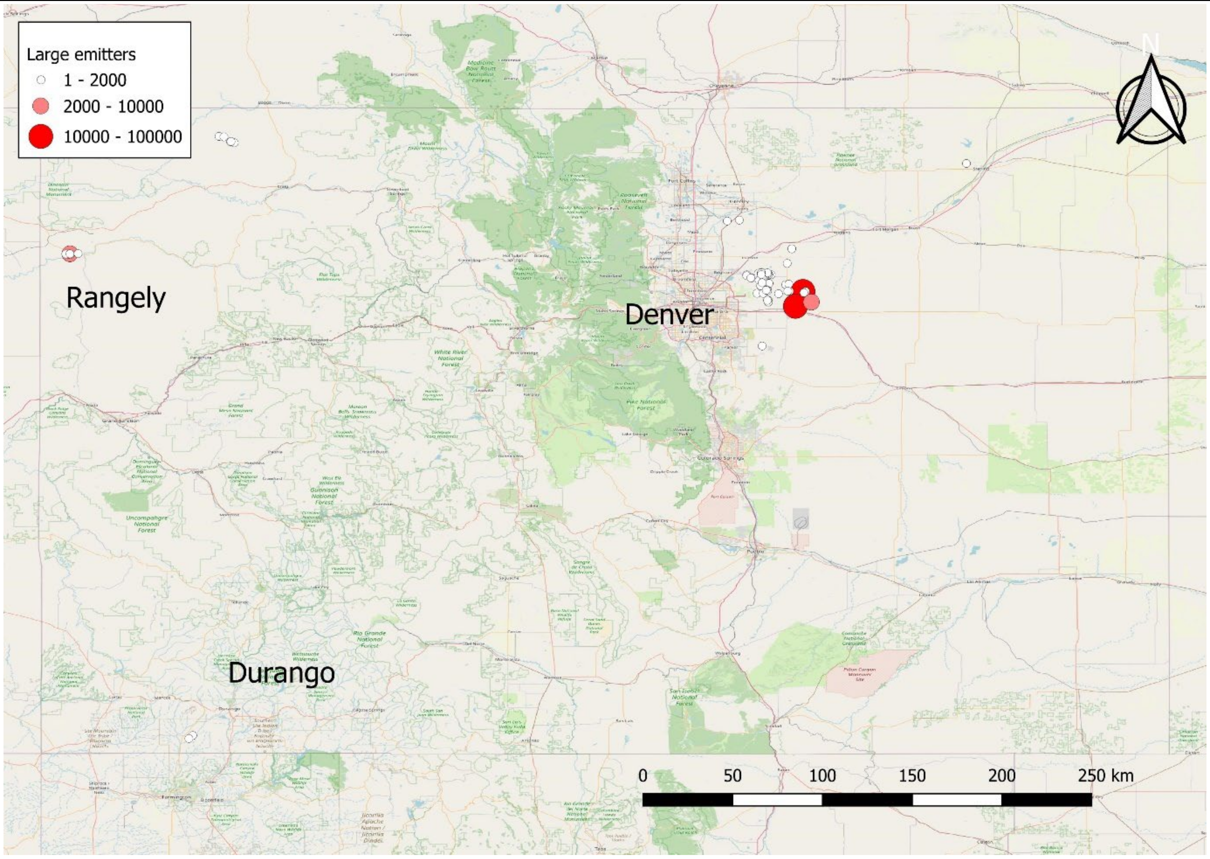

Figure 7Location and magnitude of abandoned wells emitting more than 1 g CH_4 h^{-1}. White dots represent well emitting between 1 g CH_4 h^{-1} and 2 kg CH_4 h^{-1}, pink dots indicate the location of wells emitting between 2 and 10 kg CH_4 h^{-1}, and red dots show wells emitting between 10 and 100 kg CH_4 h^{-1}.

Another interesting observation is that emissions in Colorado are rarely static. Studies in Pennsylvania observed that wells emit continuously over long periods of time (Kang et al., 2016), while unplugged abandoned wells in West Virginia and the UK vary continuously (Riddick et al., 2020). Emitting unplugged wells in Colorado were observed to decrease emissions by an average of 80% between measurements 150 days apart, while one third of originally non-emitting wells were observed to start emitting.

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Conclusions

This study reports CH_4 emissions quantified from 334 plugged (128) and unplugged (206) abandoned wells in 17 counties and from 63 oil and gas fields in Colorado. Results show that plugging remains effective for over 50 years after the well has been sealed and covered in soil. The average observed CH_4 emission from unplugged and abandoned wells in Colorado is over 70 times higher than the national average and with most emissions resulting from recent failures in engineering/management decisions instead of neglect of very old oil and gas wells. This is the first time that such a heavily skewed long tailed emission distribution, typically seen by other oil and gas emissions' surveys (Alvarez et al., 2018; Omara et al., 2016; Vaughn et al., 2017; Zavala-Araiza et al., 2015), has been observed from an abandoned well assemblage. This could be a result of the relatively large measurement sample size and that measurement campaigns should focus on increasing the number of wells measured instead of accuracy of quantification. It becomes very apparent when a large leak is encountered.

Moving forward, the findings of this study suggest that newly abandoned oil and gas wells present a greater environmental and safety risk than historic wells. Previous studies focussing largely on historic extraction sites in the Appalachia estimate emissions from a wellhead 7.5 g CH_4 h^{-1}, which is of similar magnitude to a single head of cattle, with "high emitting" wells releasing 350 g CH_4 h^{-1} (Kang et al., 2016). This study shows that orphaned wells leak, likely due to a lack of routine maintenance and service and can result in CH_4 emissions 200 times higher than the largest historic well. We estimate that a single abandoned well in Adams County, CO has emitted more than 200 tons of CH_4 to the atmosphere in the 195 days between our first and last measurement. As a result, at-risk areas, such as Adams County, should be considered as a priority for both screening and remediation.

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