Direct measurements from shut-in and other abandoned wells in the Permian Basin of Texas indicate some wells are a major source of methane emissions and produced water

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Abstract
Oil and gas production wells are a major anthropogenic source of the greenhouse gas methane (CH$_4$) in the United States. Oil and gas production rates from these wells fluctuate due to changes in demand, and is expected to decline over the coming decades to centuries due to the transition to renewable energy. The CH$_4$ emissions profile from wells that are ‘shut-in’ to accommodate changes in demand has not been previously measured, and thus it is unclear whether reduced demand will actually result in reduced CH$_4$ emissions from oil and gas production. Here we present the results of a measurement campaign of CH$_4$ emissions from shut-in and other non-producing oil wells in the Permian Basin, Texas, the largest oil production basin on Earth. All the wells we measured were conventionally drilled oil wells, and we did not measure CH$_4$ emissions from any shut-in unconventional wells. We found that, of 37 wells measured, two-thirds had an emission rate of less than 1 g CH$_4$ hr$^{-1}$, with the remaining seven wells ranging from 1.3 to 132.0 g CH$_4$ hr$^{-1}$. The average CH$_4$ emission rate from all wells was 6.2 g CH$_4$ hr$^{-1}$, lower than previous measurements of CH$_4$ emissions from active conventional wells in the Permian Basin (∼400 g CH$_4$ hr$^{-1}$) (Robertson et al. 2020 Environ. Sci. Technol. 54 13926–34)). Some shut-in wells could be a substantial source of CH$_4$ emissions if this category is not subject to leak detection and repair regulations. We also found five orphaned wells that were a source of produced water to the surface, sometimes in very large quantities (1000s of liters per minute), with evidence for emissions of CH$_4$, hydrogen sulfide, brine, and possibly other hazardous chemicals such as oil residue. Future work should further characterize the impacts of shut-in and orphaned wells on greenhouse gas emissions, water quality and human health.

1. Introduction
Methane (CH$_4$) is a powerful climate forcer with multiple anthropogenic and natural sources (Jackson et al 2020, Saunois et al 2020). In the United States, CH$_4$ from the oil and gas supply chain is among the largest anthropogenic sources (US EPA 2020), although government inventories are likely underestimated (Alvarez et al 2018). Abandoned oil and gas wells are thought to represent approximately 3%–4% of CH$_4$ emissions from oil and gas systems in the United States (Kang et al 2014, Townsend-Small et al 2016, US EPA 2020). However, there is a lack of geographic diversity in studies that support this estimate (Lebel et al 2020, Saint-Vincent et al 2020), including no measurements to date from Texas, one of the oldest and largest oil and gas producing states.

There are a variety of terms for wells that are no longer in production, including different definitions from state to state. The oil and gas industry uses the term ‘abandoned’ to define a well that is no longer producing commercial quantities of oil or gas, and is then plugged with cement or bentonite in the wellbore (Milliken Biven 2021). However, the scientific
community has generally used the term ‘abandoned’ to mean all wells that are no longer in production, including plugged and unplugged wells (Kang et al. 2014, Townsend-Small et al. 2016, Lebel et al. 2020), and we continue to use that definition here. ‘Orphan’ wells are those that have no responsible operator to decommission and plug the well (Milliken Biven 2021). ‘Idle’ wells are those that are not in use for production, injection, or any other useful purpose, but have also not been permanently plugged, and may include wells in the category of ‘shut-in’ and ‘no production’ (Milliken Biven 2021). The United States federal government defines a shut-in well as one that is ‘considered physically and mechanically capable of producing in paying quantities, though low market value for its product or transportation (pipeline) availability issues result in nonproduction’ (Office of Inspector General, U.S. Department of the Interior 2018). As oil and gas prices decline in the short and long term in response to demand for petrochemicals, there may be an increase in wells that are ‘shut-in’ to reduce supply. When operators give up responsibility for these wells, they may eventually fall into the orphaned category (Schuwerk and Rogers 2020). Greenhouse gas emissions from shut-in wells have not been previously categorized.

Since the rise of horizontal drilling and hydraulic fracturing in the beginning of this century, the Permian Basin in west Texas and southeast New Mexico is now the largest oil producing basin in the United States, with production above 4000 barrels per day in October 2020 (U.S. Energy Information Administration 2020). Recent research using remote sensing data indicated that the Permian basin emits 2.7 ± 0.5 Tg CH₄ yr⁻¹, or 3.7% of the gas extracted per year, which is 60% higher than the average CH₄ emissions in oil and gas production regions nationally (Zhang et al. 2020). This was attributed to high rates of venting and flaring due to lack of natural gas pipelines and other gas production infrastructure (Zhang et al. 2020). Methane emissions, including fugitive and vented emissions, measured at ground level from active oil and gas wells in the Permian basin of New Mexico are between five to nine times higher than EPA inventory estimates, ranging from around 0.4 kg CH₄ hr⁻¹ for conventional wells and about 7.5 kg CH₄ hr⁻¹ for complex newly drilled hydraulic fracturing well sites (Robertson et al. 2020).

Here we present the first study of inactive wells of any kind in Texas and the first study of CH₄ emissions from shut-in oil wells. Our measurements were conducted during the COVID-19 pandemic and associated economic recession, which caused a period of historically low oil prices (around $40 per barrel in October 2020). Typically, when prices are low, producers shut-in wells to reduce supply and maintain the market as much as possible, so our study was conducted at a time when the number of shut-in wells was likely at a high nationally (Barron 2020). We made emission rate measurements at 37 wells, most of which had the status of ‘shut-in’, but some of which were categorized as ‘no production’ or other non-producing status. We also visited five orphaned wells that were an active source of produced water to the surface.

2. Methods

Study area—The wells in this study were located in Pecos County, Texas, in the Permian Basin. Wells were located on private property and access was coordinated with landowners. The Permian Basin is now the largest oil-producing basin in the US, with many new wells added in the last ~10 years and oil production that has increased by approximately 400% from 2007 to 2018 (Zhang et al. 2020). Satellite measurements indicate this region has the highest CH₄ emission rate of any oil and gas basin (Zhang et al. 2020).

Measurement methods—Upon arrival at each well site, wells were screened using a Bascom-Turner Gas Rover for elevated levels of CH₄ that would indicate a leaking component (supplemental information, figure S1 (available online at stacks.iop.org/ERL/16/054081/mmedia)). The Gas Rover is a hand-held dual detector instrument with a catalytic combustion detector for measurement of CH₄ concentrations from 10 to 50,000 ppm and a thermal conductivity detector for measurement of CH₄ concentrations of 5%–100% (www.bascomturner.com/documentation). Components screened included the entire well head, casing, and pipes, valves, and fittings on the wellhead. Oil and water tanks were not screened or otherwise quantified in this study.

In previous studies, we have used a screening value threshold of over 500 ppm to conduct emission rate measurements, but in the current study, we made emission rate measurements on components with a screening value of 100 ppm or higher. We use 100 ppm as a screening cutoff because of the nature of the emission quantification method, described below. In this measurement method, the CH₄ emitting from the source is mixed with a large amount of background air in order to create enough volume for the flow measurement. For this reason, we need a relatively high enhancement (above 100 ppm) in our leak in order to detect CH₄ in the mixture of background air and leaking gas. The majority of studies of CH₄ leaks from the oil and gas supply chain have found that most CH₄ comes from a few ‘super-emitters’ (Zavala-Araiza et al. 2015, Townsend-Small et al. 2016, Alvarez et al. 2018, Deighton et al. 2020). The advantage of our method is that it allows us to quickly quantify emitters above our screening threshold and move on to the next site, so that during our field work period, we will hopefully find the correct population of these large emitters.
When a component with a CH$_4$ concentration over 100 ppm was identified, we quantified the emission rate, and when the well had no components that screened above that threshold, we assigned an emission rate of 0 g hr$^{-1}$ to the well, as per EPA method 21 (United States Code of Federal Regulations (US CFR) 2017). Emission rate was quantified using an Indaco high flow sampler, which uses a loose enclosure, a high flow rate of air, and CH$_4$ sensors for background air and the leak plus the background air to quantify emissions from a known CH$_4$ source (Howard 2001, Howard et al 2015). This method has been used throughout the oil and gas supply chain to directly quantify CH$_4$ emissions (Brantley et al 2015, Lamb et al 2015, Townsend-Small et al 2016). Photographs showing the screening and emission rate methods used in this study are available in the supplemental information (figures S1–S4).

In this study, as in previous work (Deighton et al 2020), we took air samples from the outlet of the high flow sampler to analyze for CH$_4$ concentration in the laboratory at University of Cincinnati. Samples were taken with a 60 ml syringe and injected into pre-evacuated 20 ml glass vials sealed with gray butyl rubber stoppers and aluminum crimps. Samples were analyzed by gas chromatography-flame ionization detection (GC-FID) at the University of Cincinnati on a Shimadzu Scientific Instruments GC-2014 Greenhouse Gas Analyzer using standards that bracketed the concentrations of samples (standard CH$_4$ concentrations = 2.18, 2.66, and 3.64 ppm and 0.1%, 1%, 5%, and 10%). Using a GC-FID measurement instead of the CH$_4$ 'sample' sensor in the high flow sampler lowers the detection limit of the method and alleviates the need to correct for the non-CH$_4$ hydrocarbon response factor of the CH$_4$ sensors in the high flow sampler (Howard et al 2015, Deighton et al 2020).

CH$_4$ emissions were calculated using the following equation (Howard et al 2015):

\[ Q_{\text{CH}_4} = F_{\text{sampler}} \times (C_{\text{sample}} - C_{\text{background}}) \]

where $Q_{\text{CH}_4}$ is the emission rate of CH$_4$ from the source, $F_{\text{sampler}}$ is the flow rate of the sampler, $C_{\text{sample}}$ is the concentration of CH$_4$ in the sample flow, as measured by GC-FID, and $C_{\text{background}}$ is the concentration of CH$_4$ in the background near the component, measured by the high flow sampler. Four or five samples for GC analysis were taken during each measurement, and these CH$_4$ concentrations were used for subsequent calculation of CH$_4$ emission rate from each site. In other words, each reported measurement is an average of four of five emission rate measurements at each emitting component and we also report the standard error of each measurement (standard deviation divided by the square root of the number of measurements).

Methane sensors on the Gas Rover and the high flow sampler were calibrated daily on each day of use using standards of 2.5% and 100% CH$_4$, as well as using background air (which the Gas Rover reads as 0 ppm), as per manufacturer guidelines. The flow velocity sensor on the high flow was also calibrated regularly during field sampling using a four- or five-point calibration curve, and this calibration was checked daily. Samples were analyzed on the GC with seven bracketed standards ranging from sub-ambient concentrations to 10% CH$_4$, using a standard curve tailored to the peak area of each sample.

At each site, we recorded the GPS coordinates of each well and then used these coordinates to find the well API number and status using the Texas Railroad Commission Public GIS Viewer (https://gis.rrc.texas.gov/GISViewer/). All of the wells in the current study are vertical conventional oil wells drilled in approximately the 1980s. We visited 41 wells in total: at 37 wells, we made emission rate assessments, and at four wells, we were only able to take air samples because the presence of large amounts of produced water made them inaccessible (at one water producing well, we did make an emission rate measurement). Of the 37 wells where emission rate was assessed, 26 had the status of 'shut-in', indicating that production has ceased. For the shut-in wells we measured, there was no oil production recorded in the past 3–5 years. Another eight were categorized by the Texas Railroad Commission as 'no production', indicating the wells were not producing, but no further definition of this category was provided by the state. Two wells had a status of 'canceled/abandoned' and one well had apparently been converted from an oil extraction well to the status of 'injection/disposal well' (all well status codes shown in table 1).

We also visited five wells that were actively producing brine onto the ground surface (referred to as 'flowing wells'). None of these wells were actively producing oil or gas nor did they have any recent production. They had the status of canceled/abandoned in the Railroad Commission Database. At only one of these flowing wells were we able to make a measurement of CH$_4$ emissions using our high flow instrument (well number 23 in table 1). At the other four flowing wells, the site was either inaccessible due to large pools of produced water around the wellhead, or the flow of produced water was too rapid to safely measure with our instrument, which is sensitive to water and water vapor. At these sites, we took air samples as close to the wellhead as possible for laboratory analysis of CH$_4$ concentration, as well as background air samples ~100 feet away from the wellhead for comparison. Water flow rate at some of these sites was provided by the Middle Pecos Groundwater Conservation District (table 2).
Table 1. Well status, average CH$_4$ emission rate, and noted maintenance issues at all wells measured in the current study. Data are also shown in figure 1. For wells where we did not make an emission rate measurement because of a screening level below the threshold for emission rate measurement, an emission rate of zero is assigned and no standard error value is listed. For other wells, each measurement is an average of four or five discrete measurements and the standard error is the standard deviation of these measurements divided by the square root of the number of measurements.

| Site no. | Well status          | Average CH$_4$ emission rate (g hr$^{-1}$) | Std error | Maintenance notes |
|---------|----------------------|------------------------------------------|-----------|-------------------|
| 1       | Shut-in              | 0.0                                      |           | Rusty wellhead    |
| 2       | Shut-in              | 0.0                                      |           | Salt encrusted wellhead. Appears capped on top and sides. Not connected to pump jack. |
| 3       | Canceled/Abandoned   | 0.0                                      |           | Well has a pump jack that is freshly painted but the well is not connected. Wellhead capped off at an angle. |
| 4       | Shut-in              | 0.0                                      |           | Wellhead is disconnected from pump jack. Whole pad is surrounded by crusty mud and pipe segments. No oil leaks. Top of casing is open and two pipes on side of well are open. Valves may be closed. |
| 5       | Shut-in              | 0.0                                      |           | Oily smell.       |
| 6       | Shut-in              | 0.0                                      |           | Rusty wellhead with dried oil on casing |
| 7       | Shut-in              | 0.0                                      |           | Well is connected to pump jack. Wellhead is caked with dried oil and there are open-ended pipes coming from wellhead. Can hear gurgling in well. |
| 8       | Shut-in              | 0.0                                      |           | Rusty wellhead. Pressure gauge reads zero. |
| 9       | Shut-in              | 0.0                                      |           | Well is not connected to pump jack. Pipes sticking out of casing with valves. Very rusty. |
| 10      | No production        | 0.0                                      |           | Pump jack and well are connected. Pipeline connected to valves look damaged. |
| 11      | No production        | 0.0                                      |           | Wellhead connected to pumpjack. Wellhead is rusty and corroded casing. Gas gathering line is connected but cut off within 5 feet. |
| 12      | Shut-in              | 0.0                                      |           | Wellhead is covered with dried oil |
| 13      | No production        | 0.0                                      |           | Wellhead is kind of an oily mess |
| 14      | Shut-in              | 0.0                                      |           | None noted |
| 15      | No production        | 0.0                                      |           | None noted |
| 16      | Injection/Disposal   | 0.0                                      |           | None noted |
| 17      | Shut-in              | 0.0                                      |           | Dilapidated pump jack and well. Old rusty and abandoned looking trucks at site as well. |
| 18      | No production        | 0.0                                      |           | No sign. Pump jack not connected to well. Pump ~100 feet away from wellhead. |
| 19      | Shut-in              | 0.01                                     | 0.0       | Rusty well and pump jack. Casing has open hole on side. |
| 20      | Shut-in              | 0.02                                     | 0.0       | Leak at ball valve and disconnected pipeline. |
| 21      | Shut-in              | 0.03                                     | 0.0       | Leak at fitting on open pipe from side of well casing—corroded threads on pipe. |
| 22      | No production        | 0.03                                     | 0.0       | Some kind of nozzle or vent on well head is leaking |
| 23      | Canceled/Abandoned   | 0.09                                     | 0.0       | Well is gushing out hundreds of liters per minute of brine. Strong H$_2$S smell. Crusty salt everywhere. Produced water pond formed downstream of well. |
| 24      | Shut-in              | 0.10                                     | 0.0       | Pump jack disconnected from wellhead. Casing is completely open to air. Screening 250–300 ppm inside casing. Salt crust on ground and dead trees everywhere. |
| 25      | Shut-in              | 0.11                                     | 0.0       | Just a wellhead in the middle of nowhere with no pump jack. Very old looking. Old timey valve on top of wellhead is leaking. |
| 26      | No production        | 0.12                                     | 0.0       | Old looking pump and wellhead. Ground is cracked around casing and leaking gas. Also an open hole/pipe in casing with high gas concentrations. |
| 27      | Shut-in              | 0.26                                     | 0.0       | Pump jack off to side that is obviously broken. Wellhead 100 feet from pump jack with no pipelines connected. Leak is from a fitting on the top of the wellhead. |
| 28      | Shut-in              | 0.47                                     | 0.0       | Pump jack disconnected from wellhead. Wellhead has an active oil leak with gas bubbles. Oil is trickling down onto gravel pad. |

(Continued.)
### 3. Results

Similar to previous studies (Townsend-Small et al. 2016), most wells tested were not a large source of CH$_4$ emissions (figure 1, table 1). Of the 37 wells where emission rates were measured, 18 had a screening value below 100 ppm and were assigned a CH$_4$ emission rate of 0 g CH$_4$ hr$^{-1}$ (figure 1, table 1). Another 12 wells had a CH$_4$ emission rate less than 1 g CH$_4$ hr$^{-1}$ (0.01–0.84 g CH$_4$ hr$^{-1}$) (figure 1, table 1). The remaining seven wells had an emission rate more than 1 g CH$_4$ hr$^{-1}$, with values ranging from 1.33 to 132.0 g CH$_4$ hr$^{-1}$. The average emission rate from all wells was 6.2 ± 3.8 g CH$_4$ hr$^{-1}$ (±standard error). The three largest CH$_4$ sources were responsible for 94% of all emissions observed throughout the entire study (figure 1, table 1).

Location and average CH$_4$ concentration near flowing wells is shown in table 2. The average CH$_4$ concentration in background air as measured with GC-FID (∼100 feet away from the wellhead) at all four sites (not including the MRK East site, where we did not sample for background air) was 2.3 ± 0.1 ppm CH$_4$ (n = 7). Two of the four flowing wells had a significantly higher CH$_4$ concentration near the wellhead than away from the well according to a two tailed t test: the MRK West site (2.8 ppm; p = 0.007) and the Westmoreland 1 site (2.6 ppm; p = 0.005). At the other two sites, CH$_4$ concentrations were slightly elevated, but not significantly above background air (table 2). At the MRK East site, we measured approximate CH$_4$ concentration in air near the wellhead with the Gas Rover (table 2), and we were able to construct an enclosure around this wellhead and make an emission rate measurement (table 1). Many of these wells also had a strong hydrogen sulfide (H$_2$S) odor, but we did not quantify H$_2$S concentrations or emissions at any site. Some sites also had an oily sheen on the water surface and/or a large amount of salt crust on the soil, or evidence of dead plants in the area (figure 2).

### 4. Discussion

Currently, EPA uses a national emission factor for unplugged abandoned wells from (Townsend-Small
et al 2016) to estimate CH₄ emissions from abandoned wells in Texas (US EPA 2020), despite evidence that there are higher CH₄ emissions from abandoned wells in the Appalachian basin than in other basins (Kang et al 2014, Townsend-Small et al 2016). This may be due to the high number of wells in Appalachia that were drilled before plugging regulations, or due to the type of well measured, well status, or fluid type (oil versus gas) (Williams et al 2021). Unplugged abandoned wells in Appalachia emitted CH₄ at a rate to 16 times higher (28.01 g CH₄ hr⁻¹) than unplugged abandoned wells in the western states of Colorado, Utah, and Wyoming (1.71 g CH₄ hr⁻¹) (Townsend-Small et al 2016). The results of the current study indicate that Texas may have a higher CH₄ emission factor for abandoned wells than other western states. In general, our results are in line with those of other recent studies indicating that more geographic studies are needed to determine whether, indeed, abandoned wells in western states have lower CH₄ emission rates than those in Appalachia (Lebel et al 2020, Saint-Vincent et al 2020).

Scaling up this average emission rate to the basin or national level is not straightforward. It is difficult to obtain information on the number of shut-in wells (or wells of any status, for that matter) in Texas from the Texas Railroad Commission website. Furthermore, the number of shut-in wells changes frequently with fluctuations in oil and gas prices, especially for low producing conventional wells, and was likely at a recent high level during the sampling period (fall 2020). An analysis by the Energy Information Administration found that sharp decreases in oil and gas production from conventional wells, such as the wells visited in the current study, was the main cause in decreased overall production from the Permian basin in late 2020, which also saw increasing production from newly drilled wells (U.S. Energy Information Administration 2020). This implies that shutting-in of conventional wells is a popular way to curtail production during price declines and that emissions from these wells should be studied further. However, the shut-in wells we visited had been closed for 3–5 years, preceding the price slump from the pandemic. Other future studies should seek to compare emissions from wells that have been recently shut-in to those that have been waiting for years to return to producing status, as well as those from newly drilled and higher producing wells.

Previous work has indicated that reduced natural gas price may be linked to higher CH₄ emissions in the Permian relative to other basins (Zhang et al 2020). However, our study indicates that shutting-in wells, which may be a response to low oil and gas prices, may help reduce CH₄ emissions, because shut-in wells have lower CH₄ emissions than active wells. Measurements of actively producing conventional oil and gas wells in the western Permian Basin of New Mexico emitted CH₄ at a rate of around 400 g CH₄ hr⁻¹ (Robertson et al 2020), indicating that they are a larger source of CH₄ when actively producing than when they are shut-in. Conventional wells in the Appalachian basin of Pennsylvania and Ohio also had an average emission rate of 820 g CH₄ hr⁻¹ and 128 g CH₄ hr⁻¹, respectively (Omara et al 2016, Deighton et al 2020). A true calculation of the effect of shutting in conventional wells on regional CH₄ emissions will depend on the number of high emitters, which are the source of the majority of emissions (figure 1) (Zavala-Araiza et al 2015).

We observed some significant maintenance issues at shut-in and no production wells while making measurements during the current study (table 1). In some cases, we observed oil actively leaking onto the ground at wells, or evidence that oil had previously spilled. We also saw evidence for brine spills at well pads, including salt crusts on the soil and on the well head, and dead vegetation surrounding wells. We observed open valves and gathering lines, holes in casings, and damaged components (see table 1 for a list of all noted maintenance issues). In a previous study of CH₄ emissions from marginally producing conventional wells in the Appalachian Basin, we found that wells with noted maintenance deficits had significantly higher CH₄ emissions than wells without noted maintenance issues (Deighton et al 2020). However, in the current study, almost all wells visited had evidence of neglect, even those that were not emitting CH₄. Regular inspection and repair of these wells would likely help to mitigate CH₄ emissions as well as other environmental damage.

Our results indicate that abandoned wells in the Permian Basin may be causing significant alterations to local hydrology and/or water quality. We found that at least five abandoned oil and gas wells in Pecos County are a source of produced water to the surface, with unknown impacts to subsurface water.

![Figure 1. Emission rate of CH₄ from shut-in and abandoned wells in the current study (n = 37). Error bars represent standard error of all measurements from the same site (from four to ten replicates). Data are also shown in table 1.](image-url)
resources (table 2, figure 2). We also found evidence of previous brine leaks at other sites, such as salt crusts and dead vegetation (table 1). Previous studies have investigated the potential impacts of abandoned wells on groundwater (Kang et al. 2015), and an analysis of groundwater investigations associated with the oil and gas industry in Ohio and Texas found that orphaned wells were a primary cause for contamination (Kell 2011). To our knowledge, this is the first documentation of artesian flowing abandoned wells, some with high flow rates, particularly notable for an arid, water-stressed region. One well, colloquially named 'Boehmer Lake' was producing so much water that it had formed a pond of brine water on surface soil and was causing an overwhelming smell of H\(_2\)S. Other flowing wells also formed surface ponds of produced water (figure 2).

We also show preliminary evidence that wells producing brine are also a source of atmospheric CH\(_4\) (table 2). The EPA greenhouse gas emissions inventory has emissions factors for CH\(_4\) from produced water tanks, but not from water wells or injection wells (US EPA 2020). Abandoned wells in the Permian basin may also be a source of harmful air pollutants (HAPs), as we noted the presence of H\(_2\)S, and conventional wells are a source of these HAPs (Deighton et al. 2020). These wells, particularly high emitters, could have negative health impacts on nearby residents and oil and gas workers (Harrison et al. 2016, García-Gonzalez et al. 2019, Tran et al. 2020). Future work should include measurements of H\(_2\)S and air toxics emissions from artesian wells and other high emitting wells.

5. Conclusions

Our measurements of shut-in oil wells indicate that, similar to most previous studies of the oil and gas supply chain, a few sites are the source of the majority of emissions. This poses a remediation challenge, but one that could be solved with regular inspections, such as with infrared cameras. As this region and
nation transition away from oil and natural gas in the short and long term, abandoned wells will continue to emit CH₄ unless they are inspected and repaired; however, our work indicates the average emission rate from shut-in wells is likely lower than from actively producing wells. Future work should attempt to measure emissions from newer hydraulically fractured wells that may also have been shut-in as a consequence of the low price environment. A novel finding of our work is that some abandoned wells are a significant source of produced water to the surface, with massive potential consequences for human health, agriculture, and surface water quality.

Data availability

All data that support the findings of this study are included within the article (and any supplementary files).

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