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Key Points:
- Abandoned wells are likely a minor source of methane in four production regions
- Plugging of inactive wells may be an effective means to reduce gas leakage
- Coalbed and natural gas methane both contribute to emissions from abandoned wells

Supporting Information:
- Text S1 and Table S1
- Table S1

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Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States

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Abstract Recent work indicates that oil and gas methane (CH_4) inventories for the United States are underestimated. Here we present results from direct measurements of CH_4 emissions from 138 abandoned oil and gas wells, a source currently missing from inventories. Most abandoned wells do not emit CH_4, but 6.5% of wells had measurable CH_4 emissions. Twenty-five percent of wells we visited that had not been plugged emitted > 5 g CH_4 h^{-1}. Stable isotopes indicate that wells emit natural gas and/or coalbed CH_4. We estimate that abandoned wells make a small contribution (<1%) to regional CH_4 emissions in our study areas. Additional data are needed to accurately determine the contribution of abandoned wells to national CH_4 budgets, particularly measurements in other basins and better characterization of the abundance and regional distribution of high emitters.

1. Introduction

Abandoned oil and gas wells are a legacy of the long history of fossil fuel production in the United States (U.S.), but methane (CH_4) leakage from these wells is not considered in current EPA greenhouse gas (GHG) inventories for the oil and gas industry. Overall, oil and gas extraction and use represent 29% of national CH_4 emissions [*United States Environmental Protection Agency (USEPA)*, 2015]. The number of abandoned oil and gas wells in the United States is uncertain due to the lack of reporting for the oldest wells: there are at least 2.3 million abandoned wells in the onshore U.S. with records in a national database compiled from state records (DI Desktop [*Drillinginfo*, 2015]), although some estimates put the number of abandoned wells at up to 3 million [*Brandt et al.*, 2014 and references therein]. Abandoned wells are identified by state regulatory agencies in terms of the way the well is sealed, and various states have different terminology and regulations for abandoned wells. However, there are three main categories of abandoned wells: (1) wells without recent production (terminology includes inactive, temporarily abandoned, shut in, and/or dormant); (2) wells without a responsible operator (orphaned or abandoned); and (3) wells that have been plugged with a cement or mechanical plug to prevent migration of fluids (plugged) [*National Petroleum Council*, 2011].

Only three recent studies have reported CH_4 leakage rates from abandoned wells. An abandoned conventional gas well in northwest Pennsylvania, USA, emitted about 1.7 kg CH_4 h^{-1} from the former wellhead [*Etiope et al.*, 2013]. More recently, [*Kang et al.*, 2014] published CH_4 emission rates from 19 abandoned wells also in the Appalachian basin of Pennsylvania, including 5 plugged wells and 14 unplugged wells. CH_4 emission rates in this study averaged 11 g CH_4 h^{-1} $well^{-1}$ with a median of 0.05 g CH_4 h^{-1} $well^{-1}$ [*Kang et al.*, 2014]. In the United Kingdom, a study of 102 abandoned wells reported that 30% of wells had a positive CH_4 flux at the soil surface, averaging 1.7 ± 1.9 g CH_4 h^{-1} $well^{-1}$ [*Boothroyd et al.*, 2016]. These studies imply that leakage from abandoned wells could be a significant CH_4 source and one that might partially explain differences between top-down and bottom-up CH_4 emission estimates in oil and gas production areas [*Pétron et al.*, 2012, 2014; *Karion et al.*, 2013; *Brandt et al.*, 2014]; this possibility was specifically discussed as a contributor to CH_4 emissions in the Arkoma basin of Arkansas and Oklahoma [*Peischl et al.*, 2015]. However, these U.S. studies only represent small number of wells in the Appalachian basin. Additional measurements in other parts of the country are needed to understand the importance of CH_4 leakage from abandoned wells in the U.S. The Appalachian basin is the oldest oil and gas producing region in the country, so emissions from abandoned wells in more recently exploited basins may be smaller due to newer infrastructure and better regulations.

In this paper, we report results from a measurement program to assess the potential CH_4 emissions from abandoned wells in the U.S. The overall goal was to conduct an initial assessment of CH_4 emissions from abandoned wells in four active production areas in Wyoming, Colorado, Utah, and Ohio as a basis for understanding the potential contribution of emissions from abandoned wells to regional and national emission inventories. We also measured stable isotope ($\delta^{13}C$ and $\delta^{2}H$) signatures to elucidate sources of CH_4 emissions [*Townsend-Small et al*., 2012, 2015; *Kang et al*., 2014].

2. Methods

2.1. Scope of Study

To obtain information for a large number of wells in different areas of the U.S. in a short period of time (September through December 2015), a three-step approach was adopted. The first step was a random selection of target abandoned well sites from state databases, including only wells on public land. Wells on public land were selected to eliminate the need to obtain permission from private landowners and/or oil and gas companies prior to sampling. The second step was a screening measurement on well components and the ground surface surrounding the wells. When the screening measurements indicated CH_4 concentrations above background, the third step was to measure emission rates using a combination of static and dynamic flux chambers with CH_4 concentration analyzers suited to the magnitude of the CH_4 emissions. As our method relies on the screening step to select wells for emission rate determination, our approach is somewhat biased toward characterizing the largest atmospheric emission rates and may miss some small positive and all of the negative emission rates. Most studies of CH_4 emissions from the oil and gas supply chain have shown that these larger emitters are responsible for most of the emissions regionally [e.g., *Lamb et al*., 2015; *Zavala-Araiza et al*., 2015].

2.2. Well Selection

We grouped abandoned wells into two categories: "unplugged," comprising the aforementioned categories of inactive, temporarily abandoned, shut in, dormant, orphaned, and abandoned; and "plugged." Four oil and gas producing regions were selected: the Powder River Basin in Wyoming, the Denver-Julesburg Basin in Colorado, the Uintah Basin in Utah, and the Appalachian Basin in Ohio. These areas were selected because they had large numbers of plugged and unplugged abandoned wells on public land. In each of these areas, wells were randomly selected from the well database DI Desktop [*Drillinginfo*, 2015] and state well databases, and cross referenced to only include abandoned wells on public land so that we would not need permission from private landowners. In Ohio, we also sampled abandoned wells in conjunction with the U.S. Forest Service who had identified abandoned wells on federal lands, although some of the well sites in Ohio were also selected with our random method.

Wells were selected for measurement using a stratified random approach. For the three western basins, each geographic region was divided into a regular square grid having a side dimension of 16 km. The number of abandoned wells located within each grid square was tabulated from well databases. Grid squares containing fewer than 20 candidate abandoned wells were removed from consideration to improve the efficiency of the measurement crew. In each grid square, the list of individual abandoned wells was randomized, to provide the desired stratified random sampling design. Each well on the list was evaluated using maps and satellite photographs to eliminate inaccessible wells, which were mostly wells without road access or where trespassing on private property would be needed to access the wells. Well access was determined by proximity to public roads and road conditions.

2.3. Screening Measurements

Initial screening measurements were made with a range of instruments selected for the required sensitivity and the source being screened (minimum detection levels in Table S1). The Remote Methane Leak Detector (RMLD) and Detecto-Pak InfraRed (DPIR) instruments were primarily used for surface screening of the ground around the well. The RMLD is a laser-based open path instrument and is capable of screening large areas. This instrument was typically used in a 10 m radius concentric circular pattern around wells that were visible or had identification monuments or used in a rectangular grid pattern for areas where the presence of the well was less certain. It should be noted that some plugged wells were well marked with a vertical pipe and identification label, while for others there were no visible indicators beyond a concrete pad, cleared area, and/or

Table 1. Emission Rates From Abandoned Wells in the Current Study, Including Groupings Into Various Categories of Wells (g CH_4 h^{-1} $well^{-1}$)

Well Category	Number of Measurements	Mean (g CH_4 h^{-1})	95% UCL (g CH_4 h^{-1})
All wells (entire U.S.)	138	1.38	3.17
All wells (eastern U.S.)	12	14.00	32.87
All wells (western U.S.)	126	0.18	0.41
Plugged wells (entire U.S.)	119	0.002	0.005
Unplugged wells (entire U.S.)	19	10.02	22.47
Plugged (eastern U.S.)	6	0	NA
Unplugged (eastern U.S.)	6	28.01	64.00
Plugged (western U.S.)	113	0.002	0.005
Unplugged (western U.S.)	13	1.71	3.83

surface marker flag. Unplugged wells generally had existing wellhead infrastructure and/or casings in various stages of decay. The DPIR is a closed cell sensor with an internal pump equipped with a long wand and surface scanning cone, and it was used in the same patterns as the RMLD. For wells with above ground piping, the DPIR was also used for screening individual components for CH_4. The Gas Rover and Gas Sentry are both dual detector instruments that are suitable for measurements up to 100% gas. These instruments were used to screen components of above ground piping and components. Sites with zero enhancement in CH_4 were categorized as emitting 0 mg CH_4 h^{-1}, after testing at several sites confirmed that zero enhancement sites had negligible or slightly negative emissions. Some sites had elevated levels of CH_4, but the emission rate was not detectable, indicating that there was not a positive efflux of CH_4: these sites were also categorized as emitting 0 mg CH_4 h^{-1}. The time spent at each site depended on whether the screening indicated enhanced CH_4 levels, in which case the flux would be measured following the screening (see below).

2.4. Emission Measurements

Emission rate measurements were made at all wells with screening concentrations of CH_4 above local background. Emission rates were measured using a variety of techniques depending on screening concentration and emission rate, including high flow component sampling [*Indaco Air Quality Services, Inc.*, 1995; *Howard*, 2001] or with stainless steel static flux chambers using a Picarro Instruments G2301 $CO_2/CH_4/H_2O$ analyzer for measuring CH_4 concentration. We also measured CH_4 fluxes from soils in the vicinity of the abandoned well site [*Kang et al.*, 2014] using surface flux chambers and the Picarro analyzer. More details on various emission rate measurement techniques are described in the online supporting information (see Table S1). The method selected for emission rate measurements was based on the nature of the source. Emissions from pressurized leaking components or corroded pipes were measured using the high flow sampler. The DPIR instrument was also used when necessary to lower the quantifiable limits of the high flow sampler. Emissions from underground leaks or leaks below the range of the high flow sampler were measured using the surface flux chamber in either static or dynamic modes.

2.5. Stable Isotope Sampling and Analysis

Isotope samples were collected in the field in 30 mL nylon syringes with plastic stopcocks and immediately transferred via syringe and needle to 12 mL evacuated glass vials with gray butyl rubber septa. Samples for isotopic analysis were collected either directly from the leaking component and/or from flux chambers at the end of the incubation. Samples were analyzed for δ^{13}C-CH_4 and δ^{2}H-CH_4 on a Thermo Fisher Delta V isotope ratio mass spectrometer with cryogenic focusing and purification of CH_4 [*Yarnes*, 2013]. Where necessary, sample isotope ratios were corrected for the presence of background air [*Townsend-Small et al.*, 2012].

2.6. Scaling Up and Uncertainty

The 95% upper confidence limit of emission rates were estimated by a statistical bootstrapping analysis (Pro UCL version 5.0) (lower confidence limits for most categories were zero). For inventory purposes and because there were significant differences between eastern and western wells, we compiled emission factors separately for the eastern and western U.S. and for plugged and unplugged wells (Table 1). Wells with a status code of plugged and abandoned were considered plugged; wells with a status code of abandoned, orphaned, inactive, or shut-in were considered unplugged. We then applied our emission

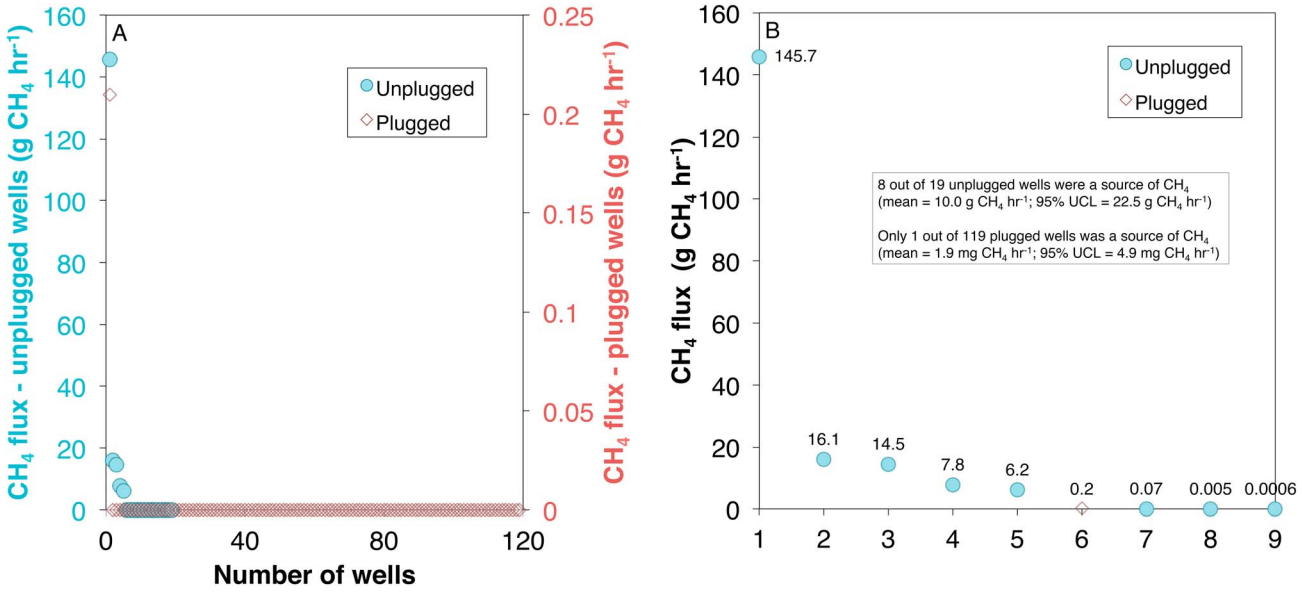

Figure 1. (a) Distribution of CH_4 emissions from plugged and unplugged abandoned wells measured in the current study. Note the different axes for plugged and unplugged wells. (b) Only nonzero emission rates are shown, and the emission rate for each well is shown.

factors and associated 95% upper confidence limits to the number of abandoned wells in each basin [*Drillinginfo*, 2015] to estimate CH_4 emissions from abandoned oil and gas wells in each of our study areas and to provide a rough estimate of the contribution of abandoned wells to CH_4 emissions nationally.

3. Results and Discussion

3.1. Emissions of CH_4 From Abandoned Wells

The majority of wells screened did not exhibit elevated CH_4 levels (Table 1 and Figure 1): only 9 of 138 wells tested were a positive source of atmospheric CH_4. Emissions from plugged and abandoned wells were significantly lower than from unplugged wells ($p < 0.001$, Table 1), although there were more measurements made at plugged wells than unplugged wells. Only one plugged well was a positive source of CH_4, emitting 0.2 g CH_4 h^{-1} (Figure 1). In contrast, 8 out of 20 unplugged wells were a positive source of atmospheric CH_4. Because of the high proportion of wells that were not emitting CH_4 and the skewed distribution of wells with positive fluxes, our measured emission rates were not normally distributed (Figure 1). This skewed pattern of emissions, where a small proportion of measurements comprises the majority of emissions, has been shown previously in other studies of CH_4 emissions across the oil and gas supply chain [e.g., *Lamb et al.*, 2015]. Furthermore, most of the observed CH_4 emissions were from unplugged wells (Figure 1), indicating that plugging is essential for mitigation of CH_4 emissions from abandoned wells. The average (and 95% upper confidence limit) emission rate from plugged and unplugged wells in the United States was 0.002 (0.005) g CH_4 h^{-1} and 10.02 (22.47) g CH_4 h^{-1} (Table 1). Higher emissions from unplugged wells were found in the eastern United States (28.01 g CH_4 h^{-1}) than in the western United States (1.71 g CH_4 h^{-1}) (Table 1).

The largest emission rates observed during this study were in Appalachian Ohio, indicating that previous studies conducted in Appalachia may not be indicative of CH_4 emissions from abandoned wells nationally [*Etiope et al.*, 2013; *Kang et al.*, 2014]. We found an average emission rate from all categories of abandoned wells in the eastern U.S. of 14 g h^{-1}, similar to the average emission rate from Pennsylvania (11 g h^{-1}) [*Kang et al.*, 2014], although the data set in the current study has a larger range of emission rates (0–146 g h^{-1}). A comparison of our Appalachian data to the study by [*Kang et al.*, 2014] indicates that emissions may be similar from abandoned wells on public land (current study) and private land [*Kang et al.*, 2014]. The abandoned wells we sampled in Ohio were among the oldest oil and gas wells in the country (drilled in the 1850s and later), likely of similar age as the wells sampled in Pennsylvania [*Etiope et al.*, 2013; *Kang et al.*, 2014]. In contrast, the majority of abandoned oil and gas wells have been drilled since 1980 Powder River Basin of Wyoming, since 1970 in the Uintah basin, and since 1980 in the Denver-Julesburg basin.

Table 2. Flux Values and Stable Isotopic Composition of CH_4 From Abandoned Wells[a]

Well ID and Leak Location	CH_4 flux (g/h)	δ^{13}C-CH_4 (‰)	δ^2H-CH_4 (‰)
UT-127, Abandoned well marker	0.21	-60.3	-222
OH-10, Middle of wellhead, broken pipe	ND	-52.1	-235
OH-10, Bottom of wellhead (active well)	0.003	-46.1	-236
OH-11, Valve on well tubing	145.7	-50.4	-213
OH-13, Well casing vent,	0.0054	-54.4	-231
OH-13, Broken well tubing	ND	-38.4	-247
OH-18, Rusted pipe	7.82	-48.6	-193
CO-115*, plugged and abandoned monument	0	-82.6	-298

[a]ND = not determined.

We also found a large geographic difference in emissions from abandoned wells in the western and eastern U.S. (Table 1). As mentioned above, the wells we sampled in Appalachian Ohio as well as those sampled in Pennsylvania during previous studies [*Etiope et al*., 2013; *Kang et al*., 2014] are from the oldest oil and gas production area in the United States. Some of these wells were likely deemed no longer productive in the era before regulations for plugging wells were introduced, and the companies that drilled them were no longer solvent, so the land they were on was purchased by the federal government or, in the case of [*Kang et al*., 2014], by new private landowners. Many of the unplugged wells we visited in Ohio were "orphaned" as opposed to "abandoned," which may lead to greater CH_4 emissions. Finally, it is also possible that wells in the eastern U.S., where soil moisture and precipitation are greater, may be a larger source due to water migration leading to greater secondary biogenic and/or coalbed CH_4 (CBM) formation (see below).

3.2. Source of CH_4 From Abandoned Wells

Stable isotope measurements (Table 2) indicate that natural gas may not be the primary source of CH_4 leaking from all abandoned wells sampled during this study. Figure 2 shows our measurements of δ^{13}C and δ^2H isotopic composition of CH_4 emitted from abandoned wells as well as ranges of values measured in other studies. While some of our measurements fall into the range of thermogenic (i.e., natural gas) CH_4 sources measured in other studies, we also measured some values in the range of biogenic CBM measured in other studies. Thermogenic CH_4 (produced by thermal alteration of plant organic matter) retains isotopic signatures similar to the original plant material, with typical δ^{13}C and δ^2H values from −50 to −30‰ and −300‰ to −150‰, respectively (Figure 2). Isotopic discrimination during anaerobic organic matter degradation leads to depleted isotope ratios in biogenic CH_4 relative to the substrate, with δ^{13}C and δ^2H values from −63‰ to −53‰ and −350‰ to −250‰, respectively (Figure 2) [*Whiticar*, 1999; *Townsend-Small et al*., 2012, 2015]. Coalbed CH_4, which is produced by biogenic CO_2 reduction, has widely varying stable isotope ratios due to variations in precursor CO_2 and H_2O isotope ratios [*Smith and Pallasser,* 1996; *Clayton,* 1998; *Whiticar*, 1999]. Previous studies of CBM in Appalachia indicate the δ^{13}C ranges from −55.1 to −42.9‰ and the δ^2H ranges from −219 to −121‰ [*Laughrey and Baldassare*, 1998] (Figure 2), in the same range as many of our samples from abandoned wells in Appalachian Ohio. Our measurement of stable isotopic composition of CH_4 emitted from abandoned wells in Utah and Colorado was even more depleted in ^{13}C than our Appalachian samples, although we only analyzed one well in each of these basins. However, CBM δ^{13}C ranging from −20‰ to −80‰ has been observed in coal fields in Australia [*Smith and Pallasser*, 1996].

Our data indicate that abandoned wells in Ohio, Colorado, and Utah are a source of both natural gas and/or CBM. All four regions of our study area are underlain with coal beds and have the potential for CBM production [*Lyons*, 1996; *United States Geological Survey*, 2003]. However, it is still unknown whether abandoned wells are providing a pathway for upward migration of CBM gas or whether well casing failures provides an additional pathway for CBM generation by allowing surface water to enter coal seams in the subsurface [*Davies et al*., 2014]. Measurements of δ^{13}C-CH_4 in a previous study of abandoned wells in Pennsylvania are in line with our findings [*Kang et al*., 2014]. That study reported δ^{13}C-CH_4 from abandoned wells ranging from −71‰ to −21‰, and while that study did not measure δ^2H-CH_4, they did report that abandoned wells emitting ^{13}C-depleted CH_4 were also a source of C_2-C_4 alkanes [*Kang et al*., 2014], which can sometimes cooccur with CBM but not with biogenic CH_4 [*Clayton*, 1998; *Whiticar*, 1999]. In addition, a natural gas well in Pennsylvania was a large source of CBM intercepted during the drilling phase [*Caulton et al*., 2014], and abandoned

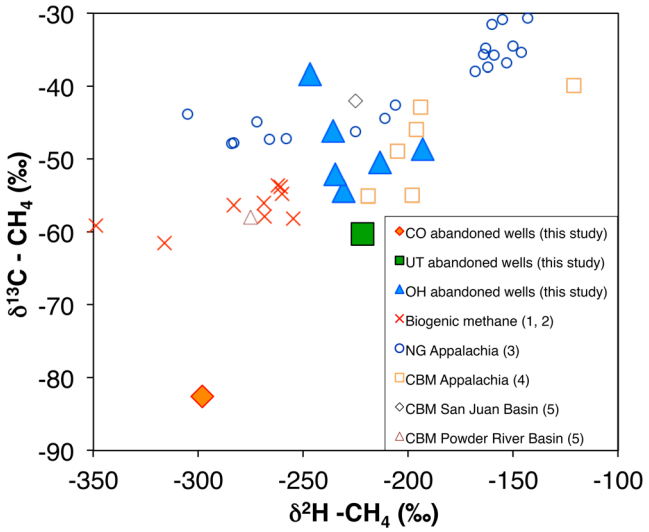

Figure 2. Stable isotopic composition of CH_4 measured in abandoned wells in Ohio, Utah, and Colorado (this study, larger filled symbols), with results from previous studies of various CH_4 sources for comparison (smaller symbols). 1 = *Townsend-Small et al.* [2012], 2 = *Townsend-Small et al.* [2015], 3 = *Jenden et al.* [1993], 4 = *Laughrey and Baldassare* [1998], and 5 = *Clayton* [1998].

wells are a source of coalbed and natural gas CH_4 in Versailles, Allegheny County, Pennsylvania [*National Energy Technology Laboratory*, 2007]. The exact mechanisms for emission of CBM from abandoned and orphaned wells is unknown, although there is likely significant horizontal and vertical fracturing throughout geologic strata in these regions [*Etiope et al.*, 2013], and a large number of abandoned wells have experienced casing failure [*Davies et al.*, 2014]. Additional studies of CH_4 composition in abandoned wells, including in regions without significant coal in the subsurface, are needed to clarify sources of CH_4 emitted from these wells.

3.3. Implications for Regional and National CH_4 Emissions

Our estimates of CH_4 emissions from abandoned wells can be directly compared to top-down measurements in some regions. Using emissions factors of 1.71 g CH_4 h^{-1} for unplugged wells and 0.002 g CH_4 h^{-1} for plugged wells, we estimated emissions of CH_4 from abandoned wells of 7.8 kg CH_4 h^{-1} in the Uintah basin, or up to 17.3 kg CH_4 h^{-1} using our 95% UCL. For comparison, [*Karion et al.*, 2013] estimated total CH_4 emissions of $5.5 \pm 1.5 \times 10^4$ kg h^{-1} in Uintah County, Utah. Applying our emission factors (Table 1) to the number of plugged (1248) and unplugged (4522) oil and gas wells in Uintah county gives us a bottom-up estimate of CH_4 emissions from abandoned wells that is 0.01–0.03% of the measured top-down emissions.

We estimate a similarly minor contribution of abandoned wells to CH_4 emissions in the Denver-Julesburg basin of Colorado. Top-down measurements in Weld County, the most intensively drilled part of the basin, indicate that total CH_4 emissions are about 26,000 kg h^{-1}, or about 3 times greater than the bottom-up estimate from USEPA for this region [*Pétron et al.*, 2014]. Using emissions factors for plugged and unplugged wells in the western U.S. (Table 1), we estimate that abandoned wells contribute about 21 kg h^{-1} of CH_4 to emissions in the Denver-Julesburg basin, or about 18 kg h^{-1} in Weld County. We estimate that abandoned wells in Weld County may contribute about 0.1% of the measured top-down emissions, with a high-end estimate of 0.2%. Weld County has 1010 plugged wells and 10,401 inactive or shut-in wells.

Additional studies, including top-down inventories of CH_4 emissions, are especially needed in Appalachia, where we found the largest CH_4 emission rates from abandoned oil and gas wells and where our isotopic data indicate emissions of CBM are prevalent (Tables 1 and 2). A recent aircraft study did quantify CH_4 emissions in an approximate five-county region of the northeastern Appalachian basin in Pennsylvania, in an active Marcellus Shale extraction area [*Peischl et al.*, 2015]. That study found a CH_4 emission rate of 1.5×10^7 g CH_4 h^{-1}, of which about 90% was from oil and gas activity [*Peischl et al.*, 2015]. There are 603 unplugged abandoned wells and 231 plugged abandoned wells in Bradford, Lackawanna, Sullivan, Susquehanna, and Wyoming counties in Pennsylvania. We estimate emissions from abandoned wells in these five counties to be 1.7×10^4 g CH_4 h^{-1} with a 95% upper confidence estimate of 3.9×10^4 g CH_4 h^{-1}, or about 0.1 to 0.3% of total measured oil and gas CH_4 emissions from this area [*Peischl et al.*, 2015]. Other regions of Appalachia, including western Pennsylvania and eastern Ohio, have a much higher density of abandoned oil and gas wells and may be useful locations for future top-down inventories of CH_4 emissions.

Using our national emission factors for plugged and unplugged wells (i.e., not specific to each region) and activity data of ~2.3 million abandoned wells, we estimate national (including Alaska) emissions from onshore abandoned wells are 1.6×10^4 (95% UCL 3.6×10^4) kg CH_4 h^{-1}, although this number may be higher

due to uncertainty in activity data [*Brandt et al.*, 2014]. The National Greenhouse Gas Inventory estimates that national CH_4 emissions from oil and gas systems are about 7.3×10^9 kg yr^{-1} [*USEPA*, 2015]. Our (admittedly rough) estimate indicates that including abandoned oil and gas wells in the inventory would increase national CH_4 emissions from oil and gas activity by 1.9–4.3%. These estimates are based on the limited available data presented in the current study, and CH_4 emissions from abandoned wells in many oil and gas producing regions of the United States have still not been characterized. Some of these regions, most notably Texas, do not have abandoned wells on accessible public land, so cooperation with oil and gas companies and/or private land owners would be needed to expand measurements in these regions.

3.4. Notes for Future Studies

Many of the orphaned and inactive wells we visited in Ohio were not listed on the state database, or were still listed as "active" wells, despite their obviously inactive state. Some states do not have any well classification system to distinguish active, plugged, or abandoned wells. These wells as classified as "N/A" status in DI Desktop; there are over 180,000 wells categorized as N/A or "unknown" in the onshore United States. In general, we also found that state databases may be more likely to include wells that have been plugged and the proper paperwork filed with the state. It is also unknown whether wells on federal land (such as those that we sampled) are more or less likely to be plugged than wells on private property or property with existing oil and gas leases. More information on locations and status of abandoned wells may also mitigate other potential environmental impacts, such as groundwater contamination and fire hazards. Finally, more information is needed to account for regional differences in CH_4 emissions and sources from abandoned wells, including more measurements to better represent the proportion of high emitters from abandoned wells, particularly from unplugged wells and in the oldest production basins such as Appalachia, where the emissions may be highest.

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