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Measuring methane emissions from abandoned and active oil and gas wells in West Virginia

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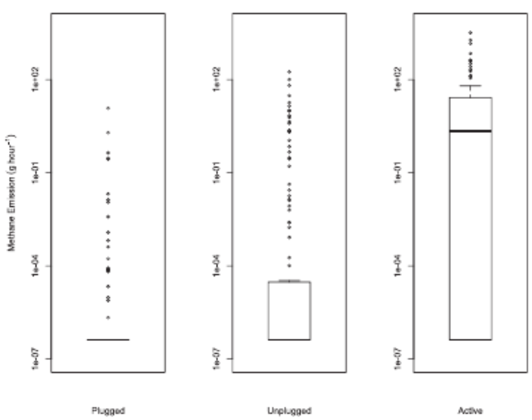
HIGHLIGHTS

- WV CH_4 emissions of plugged, unplugged and active wells were 0.1, 3.2 and 138 g CH_4 h^{-1}.
- Methane emissions were higher at active wells compared to plugged and unplugged abandoned wells.
- We estimate the number of abandoned wells in WV at between 60,000 and 760,000.
- Average emission from active wells was 7.5 times larger than the EPA emission factor.
- Well emission can vary along geologic formation and be affected by state regulations.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent studies have reported methane (CH_4) emissions from abandoned and active oil and gas infrastructure across the United States, where measured emissions show regional variability. To investigate similar phenomena in West Virginia, we measure and characterize emissions from abandoned and active conventional oil and gas wells. In addition, we reconcile divergent regional CH_4 emissions estimates by comparing our West Virginia emissions estimates with those from other states in the United States. We find the CH_4 emission factors from 112 plugged and 147 unplugged wells in West Virginia are 0.1 g CH_4 h^{-1} and 3.2 g CH_4 h^{-1}, respectively. The highest emitting unplugged abandoned wells in WV are those most recently abandoned, with the mean emission of wells abandoned between 1993 and 2015 of 16 g CH_4 h^{-1} compared to the mean of those abandoned before 1993 of 3×10^{-3} g CH_4 h^{-1}. Using field observations at a historic mining area as a proxy for state-wide drilling activity in the late 19th/early 20th century, we estimate the number of abandoned wells in WV at between 60,000 and 760,000 wells. Methane emission factors from active conventional wells were estimated at 138 g CH_4 h^{-1}. We did not find an emission pattern relating to age of wells or operator for active wells, however, the CH_4 emission factor for active conventional wells was 7.5 times larger than the emission factor used by the EPA for conventional oil and gas wells. Our results suggest that well emission factors for active and abandoned wells can vary within the same geologic formation and may be affected by differences in state regulations.

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Therefore, accounting for state-level variations is critical for accuracy in greenhouse gas emissions inventories, which are used to guide emissions reduction strategies.

1. Introduction

Methane (CH_4) is a greenhouse gas and the largest component of natural gas. In 2013, bottom up approaches estimated over 6 Tg of CH_4 leaked from US natural gas systems, including emissions from production, processing, transmission, storage and distribution (US EPA, 2017). Discrepancies have been found between top-down and bottom-up CH_4 emission estimates (Schwietzke et al., 2014; Caulton et al., 2014; Zavala-Araiza et al., 2015), and recent studies suggest inventories may be missing sources (Brandt et al., 2014) or emission variability may exist (Lavoie et al., 2017) resulting in unrepresentative emission factors used to generate bottom up estimates from active CH_4 extraction processes. Many recent studies have focused on CH_4 emissions from unconventional oil and gas production. However, to make a comprehensive CH_4 emission estimate, improved emissions estimates are needed from other parts of the oil and gas sector such as the conventional oil and gas industry. Here, we focus on abandoned and active conventional oil and gas wells and state-level variations in their CH_4 emissions.

One recent addition to GHG inventories is the CH_4 emission from abandoned oil and gas wells. This may be a significant omission and it is estimated that between 40 and 70 Gg CH_4 year^{-1} is emitted from abandoned wells in Pennsylvania (PA) alone (Kang et al., 2016). Even though West Virginia (WV) neighbors PA, differences in state law lead us to suspect that emission factors, used in bottom up inventories, for plugged and unplugged abandoned wells in WV may differ from those estimated for PA, for example, state regulation for plugging abandoned wells differs between PA and WV. In PA all wells plugged in the coal areas must be vented, whereas in WV only wells that have the protective casing inside the wellbore cemented to the surface have to be vented (WV Code, 2015). Measured emissions from plugged abandoned wells in PA coal areas (43 g CH_4 h^{-1} well^{-1}) are significantly larger than estimates of 0.045 g CH_4 h^{-1} well^{-1} for plugged wells in non-coal areas (Kang et al., 2016) and we investigated if this is similar for WV, given the differences in state regulations. Methane emission factors from unplugged abandoned wells in the Appalachian Basin are reported as 17 g CH_4 h^{-1} well^{-1} in northwestern PA (Kang et al., 2016), 24 g CH_4 h^{-1} well^{-1} in Hillman State Park, PA (Pekney et al., 2018) and 28 g CH_4 h^{-1} well^{-1} in Ohio (OH) (Townsend-Small et al., 2016).

In addition to the effects of differences in state regulations, the actual numbers of abandoned wells in WV is highly uncertain and could significantly affect the CH_4 emission estimates. Currently, the PA Department of Environmental Protection lists 31,000 abandoned wells state-wide; this is in contrast to a recent estimate of between 470,000 and 750,000 abandoned wells (Kang et al., 2016). In Appalachia, the first oil wells were drilled in the mid 19th century with oil fields mainly found in rural areas. Drilling was enthusiastically pursued throughout the late 19th and early 20th centuries with few records kept on the numbers and locations. In 2016, the WV Department of Environmental Protection (WV DEP) recognized 11,000 unplugged and 58,000 plugged abandoned gas and oil wells. Accurate well numbers are critical for estimating total state-wide CH_4 emissions from abandoned wells.

Fugitive CH_4 emissions from active conventional wells in WV are also important, given that it is the 8th largest natural gas producing state in the US. West Virginia produced nearly 30 Tg of CH_4 in 2015, with 3 Tg of CH_4 extracted by the 58,000 active conventional wells and the remainder by unconventional methods (DUKES, 2015). Currently, an average CH_4 leakage emissions factor of 18 g CH_4 h^{-1} (US GHG Inventory, 2015) per active conventional wellhead is used by the EPA to estimate fugitive CH_4 emissions from conventional oil and gas wells (EPA GHG BAAM, 2015). This emission factor is not state-specific and is used across the country. Methane leakage from active conventional wells in Doddridge county, WV is estimated at of 11% of production with the main cause of CH_4 leakage attributed to avoidable process operating conditions, i.e. unresolved equipment maintenance issues (Omara et al., 2016). We conducted additional measurements to investigate patterns in fugitive emissions, such as age, flow rate and operator, and expanded geographic coverage to include 13 counties other than Doddridge: Tyler, Marion, Taylor, Braxton, Barbour, Webster, Gilmer, Ritchie, Lewis, Wetzel, Harrison, Upshur and Wood Counties (Fig. 1).

To put these CH_4 emission estimates into a state-wide context, in 2014 it was estimated that 1.15 Tg CH_4 was emitted from WV (WRI CAIT 2.0, 2013). Most of the CH_4 was emitted from the energy sector, 95%, with smaller amounts from industrial processes, agriculture and waste, 2.5%, 1% and 1.5%, respectively. Using the EPA emissions factor of 18 g CH_4 year^{-1} wellhead^{-1}, it is estimated that 58,000 active wellheads in WV emit 9 Gg CH_4 year^{-1}, or 0.8% of the annual WV CH_4 emissions.

In this study, we measure CH_4 emissions from active and abandoned conventional gas and oil wells in WV. Our objectives are to: 1) Investigate the magnitude of CH_4 leaks from abandoned (plugged and unplugged) wells in WV and compare these emissions to neighboring states to investigate inter-state differences; 2) evaluate CH_4 leakage at operating conventional gas wells in WV at the wellhead and 3) use observations at a historic mining area as proxy for state-wide drilling practices to estimate the total number of wells drilled in WV between 1860 and the present generating under reporting factors, which can be used to scale-up historical reported data to an estimate of the total number of wells drilled. To our knowledge this is the first time that fugitive CH_4 emissions from active and abandoned conventional gas production activities in WV have been comprehensively investigated.

2. Methods

2.1. Methane emission factors – West Virginia

To calculate an emission factor for CH_4 emissions from plugged abandoned, unplugged abandoned and active oil and gas wells, methane emissions are measured from wells throughout West Virginia. The emission factor corresponds to the mean of the individual emission rates, because when it is multiplied by the total number of wells, it should give the total overall emissions. Therefore, following the methods of Kang et al. (2014, 2016) and Townsend-Small et al. (2016) that already calculate emission factors in this field, we will add up the individual emission values in the data set and then divide by the number of wells. This mean will be presented as the emission factor with the 95% upper confidence limit as calculated by a statistical bootstrapping analysis (R package 'boot'). We also note that, from previous studies (Kang et al., 2014; 2016; Townsend-Small et al., 2016), it is anticipated that these data will be heavy right-skewed and will not be normally distributed.

2.1.1. Site selection

We measured CH_4 emissions from active and abandoned oil and gas wells in WV and focused our efforts on counties in the north central region of the state where the first oil and gas wells were drilled and which still has the highest concentration of oil and gas production, as shown in Fig. 1. For the purposes of this study we classify our measurement targets into three types: 1) plugged and abandoned conventional wells

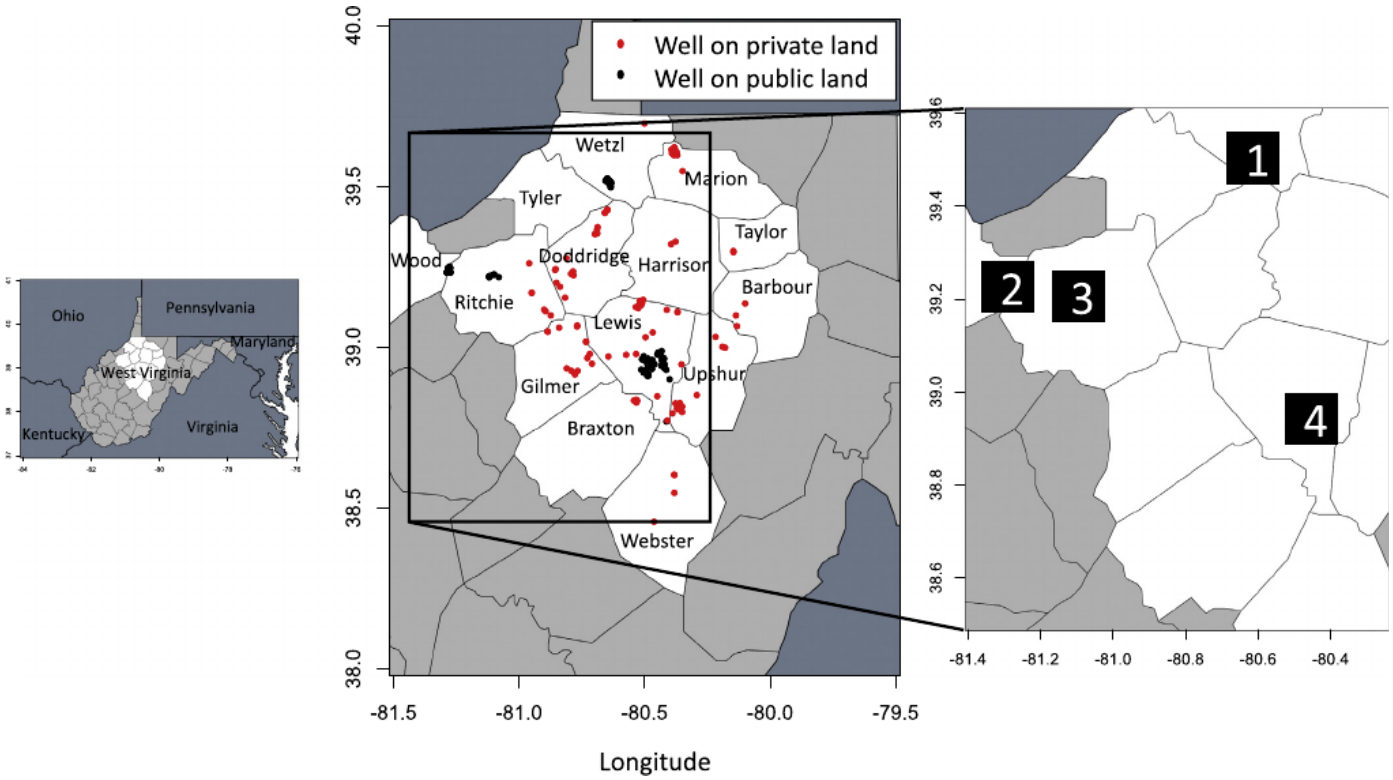

Fig. 1. Left panel - Map of West Virginia with measurements made in the counties shown in white. Centre panel - Measured wells on private land (red circles) and public land (black circles) in West Virginia. Right Panel – Approximate location of public lands in black squares: 1. Lewis Wetzel Wildlife Management Area (Wetzel Co.), 2. Mountwood Park (Wood Co.), 3. North Bend State Park (Ritchie Co.) and 4. Stonewall Jackson Wildlife Management Area (Lewis Co.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(henceforth plugged), 2) unplugged abandoned conventional wells (henceforth abandoned) and 3) active conventional wells. Specific wells were selected using the WVDEP Technical Applications and GIS (TAGIS, 2017) website and the selection of target wells was based on (i) access, (ii) absence of interfering CH_4 sources and (iii) suitability for measurement. Measurements were made between November 2015 and November 2016.

Previous studies have used random sampling approaches to identify measurement targets (Kang et al., 2016; Townsend-Small et al., 2016). Simple random sampling can be used to determine the average emissions from wells where the emissions are known to be relatively homogeneous, while a stratified random approach can be used if there is homogeneity within a sub-population of wells, i.e. similar emissions within a geographic region. In this study, there is no a priori knowledge of the homogeneity of well emissions, therefore the sampling strategy employed here was to measure as many accessible wells as possible. However, land access in WV was a significant problem, with much land private, used for hunting and posted against trespass. Thus, in the interests of health and safety, wells were measured only on public land or private land where we had either the landowner's permission or the well was within 50 m of a public road. All wells were measured on the following public lands: Mountwood Park (Wood Co.), Lewis Wetzel Wildlife Management Area (Wetzel Co.), Stonewall Jackson Wildlife Management Area (Lewis Co.) and North Bend State Park (Ritchie Co.) (Fig. 1).

2.1.2. Site attributes

Of the 338 sites measured during this study, 112 involved plugged wells, 147 were abandoned wells and 79 were active conventional wells. 109 measurement sites were on private land (either 50 m from a public road or on private land we had permission to be on) and 219 were on public land. Data on permit type (plugging, fracture, vertical well, other well), API number, age, operator, location, well status (abandoned, active, plugged) and annual gas and oil production were all obtained from the WV DEP Technical Applications and GIS Unit (TAGIS) database (TAGIS, 2017). All of the active wells produced natural gas, with average production of 33,387 kg year^{-1}; range: 0 to 177,542 kg year^{-1}, and only five wells produced oil.

2.2. Measuring methane emissions from oil and gas wells

Each well was initially screened for CH_4 using a HXG-2D (Sensit Technologies, USA) handheld CH_4 sensor (limit of detection 10 ppm). The handheld CH_4 sensor was slowly moved across all parts of the well head, surrounding infrastructure, and over the ground near the well head at a rate of around 10 cm per minute while being sheltered from the wind. When a CH_4 leak was detected at the wellhead (i.e. a reading of 10 ppm or greater on the handheld CH_4 sensor), the CH_4 emission was then measured using one of two methods. Either a dynamic flux chamber (described in full Section 2.2.1) was used to measure CH_4 emissions from the wellhead/infrastructure that fit completely inside the chamber, or an Inverse Dispersion (ID) method (described in full below in Section 2.2.2) was used to estimate CH_4 emissions from larger abandoned and active wells.

2.2.1. Dynamic flux chamber

A dynamic flux chamber was used to measure CH_4 leakage from wells that could fit entirely within the chamber. The dynamic flux chamber is made from a rigid plastic cylinder closed at one end with a diameter of 0.5 m, height of 1.5 m and volume 0.3 m^3 (Fig. 2). A propeller was used to circulate the air and a pump drew air through the chamber at 5 l min^{-1} which was measured throughout using a Cole-Palmer flowmeter. The flux chamber base was inserted into the soil and a seal was made with the ground by pressing the chamber 5 cm into the ground. The body of the HXG-2D handheld CH_4 sensor was then attached to the wall of the flux chamber so that the display was visible

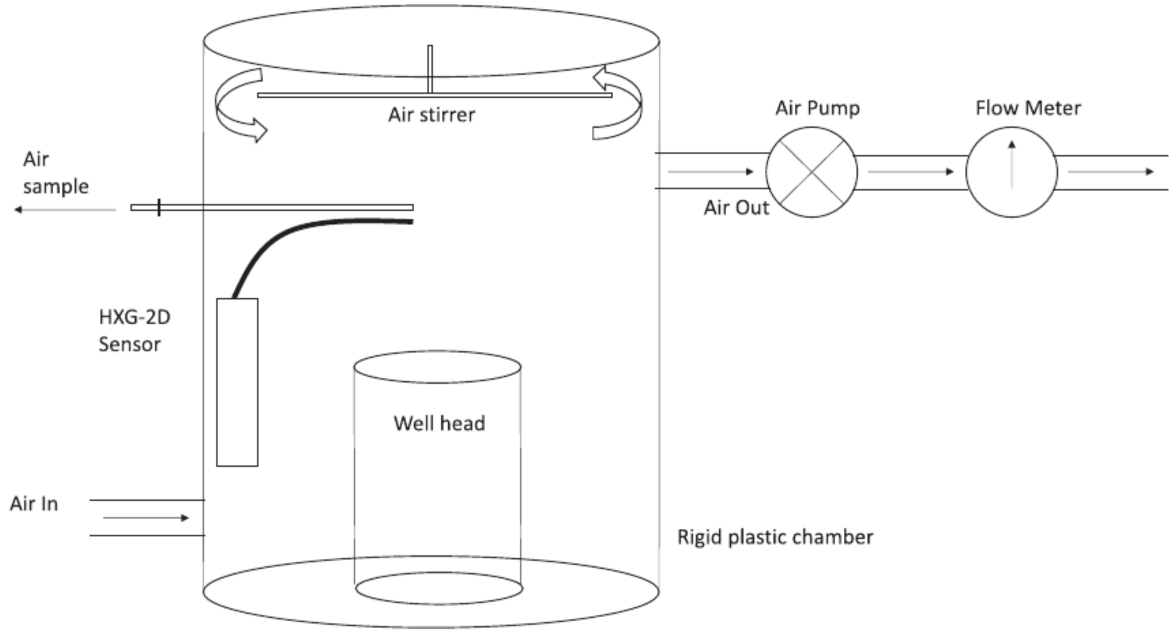

Fig. 2. Schematic of dynamic flux chamber used to measure emissions from the well head. The dynamic flux chamber is made from a rigid plastic cylinder closed at one end with a diameter of 0.5 m, height of 1.5 m and volume 0.3 m^3. A propeller was used to circulate the air and a pump drew air through the chamber measured throughout using a Cole-Palmer flowmeter.

through a window. Once steady state concentration was reached for 10 min inside the chamber, this took between took between 1 and 3 h and determined using a HXG-2D (limit of detection 40,000 ppm) inside the chamber, three 50 ml air samples were taken from the chamber. The samples were taken from the chamber at the same height as the HXG-2D probe. For wells where the limit of detection was exceeded before steady state a 60 l min^{-1} pump was used instead of the 5 l min^{-1} pump. The limits of detection were emissions of 8 g h^{-1} and 100 g h^{-1} for the 5 l min^{-1} and 60 l min^{-1} pumps, respectively.

An Ellutia 200 series (Witchford, UK) Gas Chromatograph was used to measure the CH_4 concentrations contained in the samples. The GC-FID, as used here, has a detection limit of 1.5 ppb and an uncertainty of ±0.8%. The instrument was calibrated every 8 samples using a 122 ppm gas standard. The GC was checked for linearity using 2 ppm, 122 ppm, 500 ppm, 1% and 100% CH_4 concentration air mixtures before and after each campaign. The CH_4 flux (Q, μg m^{-2} $well^{-1}$) is calculated (Eq. (1)) from the CH_4 concentration at steady state (C_{eq}, μg m^{-3}), the background CH_4 concentration (C_b, μg m^{-3}) in the air used to flush the chamber, the height of chamber (h, m), the flow of air through the chamber (q, m^3 s^{-1}), the area of the chamber (a, m^2) and the volume of the chamber (V, m^3) (Aneja et al., 2006).

$$Q = \frac{(C_{eq} - C_b)hqa}{V} \tag{1}$$

2.2.2. Inverse dispersion model

During measurement, a 5 l Tedlar bag was continuously with filled atmospheric air from downwind of the CH_4 source (<2 m) at a rate 0.33 l min^{-1} over a 15-minute period using an air pump. Wind speed (at three heights; 3 m, 2 m and 1 m), temperature (at three heights; 3 m, 2 m and 1 m) and wind direction were also recorded during the 15-minute period. After the 15 min, three 50 ml samples from within the bag were collected and transferred to glass sample vials. An upwind (background) CH_4 measurement was also taken to ensure that other sources did not affect the emission estimate. Meteorological data were measured using a Tycon Systems TP2700WC Data Logging wind and weather station which measures temperature (−40 to 65 °C, ±1 °C), wind speed (0.2 to 25 m s^{-1}, ±1%), relative humidity (1 to 99%, ±1%) and wind direction (0 to 360°, 22.5° resolution). The CH_4 concentrations of all samples collected in vials were later measured using the Ellutia 200 series GC using the method described above.

The inversion function of the WindTrax inverse dispersion model version 2.0 (Flesch et al., 1995) was used to infer the CH_4 emissions from the gas wellheads. Data used as input to WindTrax are: wind speed (u, m s^{-1}), wind direction (WD, °), temperature (T, °C), CH_4 concentration (X, μg m^{-3}), location and height of the CH_4 detector, background CH_4 concentration (X_b, μg m^{-3}), the roughness length (z_0, m) and the Pasquill-Gifford stability class. The roughness length describes the aerodynamic properties of the surface and was calculated as the exponential of the intercept of the plot of the natural logs of wind measurement heights versus wind speeds. The Pasquill-Gifford stability class, A to F, was calculated from wind speed and insolation data using the method of Seinfeld and Pandis (2006).

2.3. Estimating the total number of abandoned wells in WV

2.3.1. Recorded well numbers

Oil and gas mining started in WV in the 1860s and the 58,478 wells drilled between 1860 and 1929 were recorded in Arnold and Kemnitzer (1931). For the period 1930–1949, the number of wells drilled in WV is not available. Modern digital records (WV DEP, 2015) shows that 3317 wells were drilled between 1950 and 1990 and 14,419 drilled between 1990 and 2016. Given that there are now 58,000 plugged and abandoned wells, 12,000 documented unplugged and abandoned wells and 44,000 active conventional wells the recorded well numbers may actually be an underestimate.

An uncertainty study to investigate the potential number of wells drilled in WV between 1860 and present day was conducted. The recorded number of wells was used as the basis of this study and represents the lower estimate. The upper end of the estimate is based on observations from a case study, as detailed below.

2.3.1.1. Underestimation by method (1860–1949). Between 1860 and 1949 a five-spot method was used to enhance oil production at wells with depleting production. This meant that for every well that was drilled and documented four wells were drilled into the same formation (thus, nearby and at similar depths) (Kang et al., 2016). All wells documented in Arnold and Kemnitzer (1931) could have been underestimated by a factor of 2 or more.

2.3.1.2. Underestimation by recording (1860–1949). Before 1950 in the remote areas of West Virginia, some wells may have been drilled without being documented. Here, a case study is presented where the actual number of wells observed at a historic (pre-1950s) mining area of Volcano, Wood County could give some insight as to the number of wells actually drilled. A search area of 1.5 km × 1 km was identified in Volcano bounded by White Oak Run to the south, Volcano Road to the west, Mudlick Road to the North and the Ritchie/Wood County boundary to the East. Within the search area 23 abandoned wells were on identified using the TAGIS database (TAGIS, 2017). Transects at 20 m intervals were walked from the north to the south to find the abandoned wells on the TAGIS database. The location of any other abandoned well within this search area was also recorded.

2.3.1.3. Number of wells drilled 1930–1949. As the data was not available the numbers were estimated from a linear empirical model based on the 1860–1929 drill data in Arnold and Kemnitzer (1931).

3. Results

3.1. Methane emissions from active and abandoned oil and gas wells in WV

We estimate an average background CH_4 emission from non-oil or gas well ground in WV at 4×10^{-3} g CH_4 h^{-1} using our measurements from a grass field 5×10^{-3} g CH_4 h^{-1} and wooded area 3×10^{-3} g CH_4 h^{-1}. Of the 333 measured sites, CH_4 emission estimates were the same as the background CH_4 flux for approximately 80% (89 of the 112) of the plugged wells measured, 72% (106 out of 147) of abandoned wells and 47% of active conventional wells (Fig. 3). The highest emitters (over 100 g CH_4 h^{-1}) measured during the campaign were from active conventional gas wells (maximum 178 g CH_4 h^{-1}; Fig. 3). Only 2% of abandoned wells (6 of 259 plugged and unplugged abandoned wells) emit >10 g h^{-1}. For the purposes of this paper we will call sources emitting >10 g CH_4 h^{-1} "high-emitters", with only 0.08% of abandoned wells emit >100 g CH_4 h^{-1}. The only "super-high-emitters" were active conventional wells (1000 g CH_4 h^{-1}), with only 4% of active conventional wells emitting more. The highest emission we measured was at an active conventional well emitting 3200 g CH_4 h^{-1}.

3.1.1. Plugged and unplugged abandoned wells

The CH_4 emission factor from the plugged wells is 0.13 g CH_4 h^{-1} (range: background to 12 g CH_4 h^{-1}; Table 1). The emission factor from plugged wells is skewed by two large leaks, one on top of an underground natural gas storage area in Lewis County (2 g CH_4 h^{-1}) and a second with gas leaking audibly near a water retaining pool for unconventional gas production in Wetzl County (12 g CH_4 h^{-1}).

The CH_4 emission factor from unplugged abandoned gas wells is estimated at 3.1 g CH_4 h^{-1} (range: background to 177 g CH_4 h^{-1}). Of the 42 wells with abandonment date data, wells abandoned after 1993 emit considerably more (mean 16 g CH_4 h^{-1}) than those abandoned before 1993 (mean 3×10^{-3} g CH_4 h^{-1}). There is no clear pattern for emissions from wells abandoned before 1993.

3.1.2. Active conventional wells

We estimate the CH_4 emission factor from active conventional gas wells is estimated at 139 g CH_4 h^{-1} (range: background to 3229 g CH_4 h^{-1}). Of the 74 active conventional wells we measured, 25 had gas production data available on the TAGIS database. From this we calculated the normalized CH_4 emissions (fugitive CH_4/production) and found the mean of 8.8% of production lost (leaked) at the wellhead (range: 2×10^{-2} to 56%).

There is a significant statistical relationship between the size of production and normalized CH_4 emission ($m = 16.8$, $R^2 = 0.73$, p-value $= 1 \times 10^{-8}$) suggesting that the largest emitting wells are also the biggest

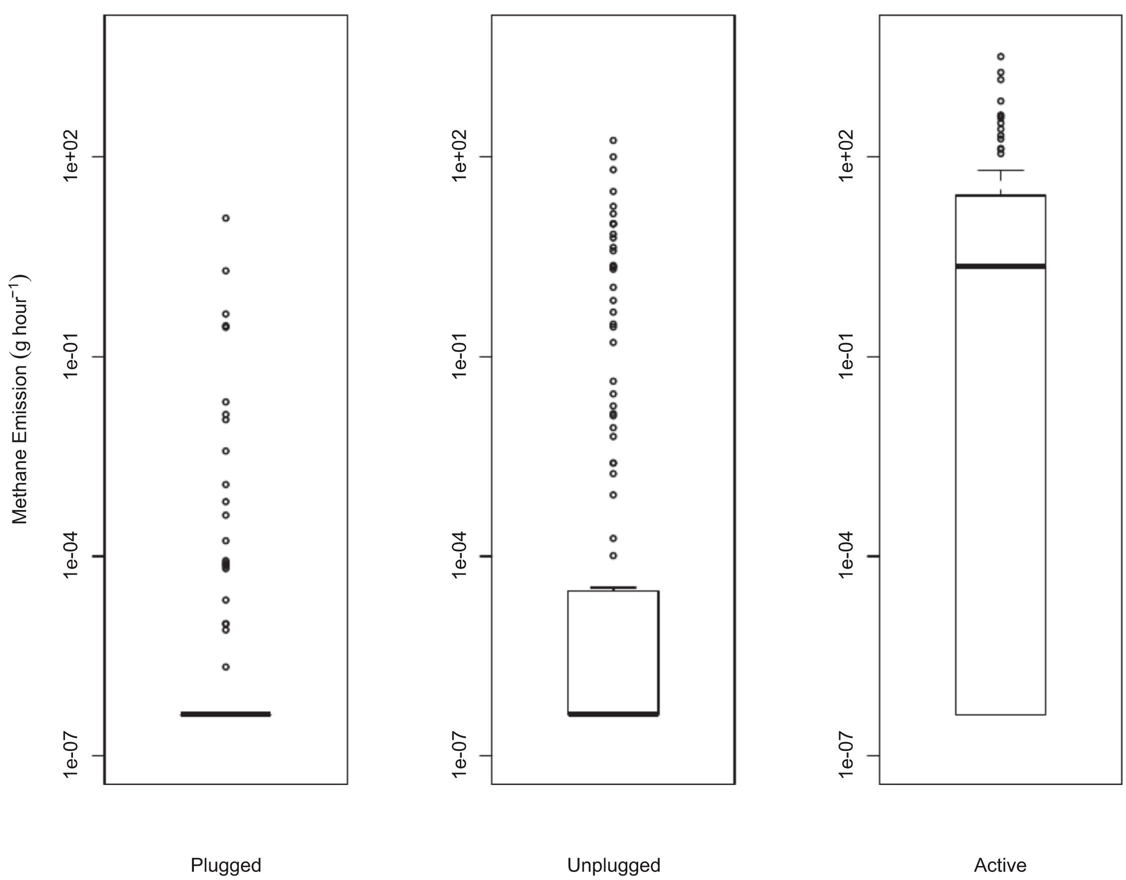

Fig. 3. Boxplots of collated methane emission data from plugged, unplugged and active wells in WV.

Table 1
Emission factor, range of emissions and 95%upper confidence limit for the plugged abandoned, unplugged abandoned and active wells measured in West Virginia.

Type	Emission factor (g CH_4 h^{-1})	Range (g CH_4 h^{-1})	95% UCL
Plugged	0.13	Background–12	0.37
Unplugged	3.1	Background–177	6.76
Active	139	Background–3229	250

producers. However, we found no statistical significance between the age of the active well and the normalized CH_4 emission ($m = -1.4 \times 10^{-2}$, $R^2 = 2 \times 10^{-2}$, p-value = 0.48) or absolute CH_4 emissions ($m = 3 \times 10^{-4}$, $R^2 = 4 \times 10^{-4}$, p-value = 0.98). In addition, there is no indication that any specific operator is particularly responsible for poor well maintenance as 11 different operators were responsible for the 25 wells with the largest leaks, with 14 wells belonging to smaller companies and 11 wells belonging to larger companies. In this paper we define a smaller company as one which owns <10 wells in the state.

3.2. Number of abandoned wells in WV

3.2.1.1. Underestimation by method (1860–1949). All wells documented in Arnold and Kemnitzer (1931) could have been underestimated by a factor of 2.

3.2.1.2. Underestimation by recording (1860–1949). Between the 1st and 11th of November 2016, 132 abandoned wells were found in the search area in Volcano. Abandoned wells were in various states, ranging from very obvious sites (the wellhead, wooden barrel used to collect oil and metal pipe infrastructure were all visible) to simple metal pipes sticking up from the ground. 32 of these wells were in the TAGIS database suggesting that there are 5.7 times more abandoned wells than in the TAGIS database. This factor is similar to what was observed in a property on the Bradford Oil Field in northwestern Pennsylvania. During field campaigns in WV we did not find any buried wells, this was checked using the metal detector.

3.2.1.3. Number of wells 1930–1949. Using the drilling data for 1860–1929 as a guide, the number of wells drilled in WV between 1930 and 1949 was estimated at 15,500, or 815 wells per year.

3.2.1.4. Total number of abandoned wells. Using the under-reporting factors calculated in this case study and historical recorded data we suggest that the total number of wells drilled and then abandoned in WV between 1860 and the present could be between 63,000 and 760,000 (Table 2), with a best-estimate lying between these values at 440,000. From observations at Volcano, there is no evidence to suggest the underreporting of plugged abandoned wells.

4. Discussion

4.1. Measurement strategies

In this study we present three methods for measuring CH_4 emissions from oil and gas wells: initial screening, the dynamic flux chamber and inverse dispersion methods. The initial screening of the wells with the HXG-2D handheld CH_4 sensor may also be a source of uncertainty in the overall emission estimate as it has a detection limit of 10 ppm and may not have detected very low emitting sources. However, as the probe can detect elevated CH_4 concentration from wells emitting as low as 4 μg CH_4 h^{-1} we suggest that any well emitting less than this will have negligible effect on the overall emission estimates as the largest sources are several orders of magnitude higher than those detected by the handheld sensor. In 40 measurements, there was a reading of 10 ppm on the HXG-2D sensor and the chamber was then used to measure the emissions, in all cases the emission was the same as background. Our observations suggest that the HXG-2D was conservative at low concentrations and could give false positives.

Despite difference in the uncertainty estimate, dynamic chamber ± 7% and ID ± 38%, there is good agreement between the two methods which may be a result of measuring the CH_4 concentration so close to the source (<2 m) for the ID method (Supplementary material Section 2 Fig. SM2.1). In this application, we were able to get very close to the source (<2 m) from the leak which mitigated the effects of turbulence, buoyancy or uncertainty in wind direction. We were also able to describe the emission area within the ID model very accurately. Following the uncertainty analysis, if we were to take out the uncertainty caused by these values, the total uncertainty would be ±3%.

4.2. Methane leaks from plugged and unplugged abandoned wells

Our results show that in most cases plugging of oil and gas wells in WV with cement reduces CH_4 emissions to very low average emissions of 0.1 g CH_4 h^{-1}. This emission estimate is considerably smaller than the estimate of 12 g CH_4 h^{-1} for plugged wells in PA (Kang et al., 2016). However, our estimate agrees better with is the PA estimate of 0.42 g CH_4 h^{-1} for plugged wells in non-coal areas (Kang et al., 2016). Unlike PA, it is not mandatory in WV for plugged wells in coal areas to be vented (WV Code, 2015). Wells that do not penetrate coal beds or have casing cemented to the surface do not need to be vented when plugged. We did not find any vented-plugged wells in WV during our measurement campaign. For the 58,000 plugged wells in WV we estimate a total emission of 0.07 Gg CH_4 $year^{-1}$ (Table 3).

Table 2
Estimation of number of abandoned wells in West Virginia.

Years	Documented wells	Lower estimate		Upper estimate	
		Factor	Wells	Factor	Wells
1860–1929	58,478[1]	2[a]	116,956	5.7[b]	667,337
1930–1949	15,500[2]	2[a]	31,000	5.7[b]	176,882
1950–1990	3317[3]		3317		3317
1990–2016	14,419[3]		14,419		14,419
Total			165,692		861,955

	Lower estimate	Upper estimate
Number of active wells	44,612	44,612
Number of plugged wells	58,000	58,000
Total number of abandoned wells	63,080	759,343

Sources: [1]Arnold and Kemnitzer (1931); [2]Model 1919–1929 based on Arnold and Kemnitzer (1931); [3]Modern digital records.
Under-reporting factors: [a]Factor based on the assumption that the five-spot method is used (Kang et al., 2016); [b]factor is used to account for the difference between the wells drilled between 1860 and 1949 and those that were reported using the TAGIS database as a measure of reported wells. Of the 132 wells found during the 2016 Volcano measurement campaign, 23 were matched to wells on the TAGIS (2017) map, resulting in under-estimation by a factor of 5.7.

Table 3
Summary of emission sources and emission estimates.

Type	Region	Number of sources measured	% that leak >4 µg CH_4 h^{-1}	% high emitters >10 g CH_4 h^{-1}	Average emission (g CH_4 h^{-1})	Estimated number of wells in WV	Total WV emission (Gg CH_4 $year^{-1}$)
Plugged	WV[1]	112	21	0	0.1	58,000	0.07[a]
	PA[2]	*35*	*69*	*0*	*12*		
	OH[3]	*19*	*0*	*0*	*0*		
	USA[3]	*119*	*1*	*0*	*0.002*		
Unplugged	WV[1]	147	28	2	3.2	440,000	12[a]
	PA[2]	*53*	*77*	*13*	*17*		
	PA[4]	*51*			*24*		
	OH[3]	*6*	*50*	*17*	*28*		
	USA[3]	*20*	*40*	*15*	*10*		
Active	WV[1]	74	53	38	138	44,000	268[b]
	WV[5]						*331*
	USA[6]				*18*		

[1] This study.
[2] Kang et al. (2016).
[3] Townsend-Small et al. (2016).
[4] Pekney et al. (2018).
[5] Omara et al. (2016).
[6] US GHG Inventory (2015).
[a] Calculated by multiplying the average emission (g CH_4 h^{-1}) by the number of wells and scaling up to an annual value.
[b] Calculation based on an average of 8.8% of production is lost. In 2014 WV produced 3 Tg CH_4 from conventional wells.

The CH_4 emission factor for unplugged abandoned wells in WV (3.2 g CH_4 h^{-1}) is one order of magnitude higher than emissions from plugged abandoned wells (0.1 g CH_4 h^{-1}) in WV. Even though the VW emission factor is lower than the both the PA and OH emission factors for unplugged abandoned wells of 17 g CH_4 h^{-1} (Kang et al., 2016) and 28 g CH_4 h^{-1} (Townsend-Small et al., 2016), respectively, it is more similar to the emission factor from all unplugged abandoned wells in the US of 10 g CH_4 h^{-1} (Townsend-Small et al., 2016). Our data suggests that there are a larger percentage of abandoned wells that do not leak in WV (72%) compared to PA (60%; Kang et al., 2016) and OH (50%; Townsend-Small et al., 2016), which results in a lower emission factor from unplugged abandoned wells than neighboring states.

We estimate well emissions which are not significantly different from the background CH_4 flux for 79% of plugged wells and 72% of abandoned wells. In contrast, observed CH_4 flow rates below detection limit from only 29% and 10% of plugged and abandoned wells in PA, respectively (Kang et al., 2016). Despite the difference in average emission estimates per well between our study and PA, the highest emitters measured in both studies are of the order 100 g CH_4 h^{-1}. This study estimates the percentage of “high-emitters” (those emitting >10 g h^{-1}) at 2% of the abandoned (plugged and unplugged) wells in WV. In contrast, 13% of abandoned wells in PA are “high-emitters” (Kang et al., 2016). In summary, our results suggest that abandoned well emission factors can vary within the same geologic formation as they may be affected by different state regulations. For example, the CH_4 emissions from abandoned oil and gas wells in PA are estimated at between 4 and 7% of the state-wide anthropogenic emissions, whereas in this study the estimate of CH_4 emissions from 58,000 plugged and 440,000 unplugged abandoned oil and gas wells in WV is ~1% of anthropogenic emissions.

4.3. Methane leakage from active conventional gas wells

Active conventional wells in WV are a significant source of CH_4 emitted to the atmosphere. In 2014, an estimated 3 Tg of natural gas was produced from 44,612 active conventional wells in WV (TAGIS., 2017). Our measurements suggest that, on average, each well loses 8.8% of production resulting in 268 Gg CH_4 (range 161–376 Gg CH_4) emitted by active conventional well activities in 2014. This emission estimate from active conventional oil and gas wells is 23% of the anthropogenic CH_4 emissions in WV. These values are very similar to the estimate of 331 Gg CH_4 $year^{-1}$ (10.5% of WV CH_4 production; range 240–450 Gg CH_4 $year^{-1}$) based on emissions from Doddridge County alone (Omara et al., 2016). The emissions from active conventional wells in WV are considerably more than the 0.07 Gg CH_4 $year^{-1}$ emitted from the 58,000 plugged wells in the WV DEP database and from unconventional wells in the state (91 Gg CH_4 $year^{-1}$; Omara et al., 2016).

The CH_4 emission factor per active conventional well estimated in this study (138 g CH_4 h^{-1}) is significantly larger than the emission factor (18 g CH_4 h^{-1}) used by the EPA to estimate the CH_4 emissions from conventional oil and gas wells (US GHG Inventory, 2015), suggesting that the current CH_4 emission estimate from conventional active wells in WV is underestimated by a factor of 7.5. This difference between the emission factor for active conventional wells calculated by this study and the EPA emission factor suggests significant state-level variability and how a single, national emission may not be appropriate to use in national inventories.

4.4. Total number of abandoned wells in WV

Observations at Volcano suggest that the number of abandoned wells in WV is significantly underestimated. Using data gathered from a field-based study at a historical mining site, we suggest the number of abandoned wells in WV lies between 60,000 and 760,000 wells, with a best-estimate of 440,000. Without further observation at different historic mining areas it is difficult to assess the veracity of this estimate, as drilling practices may vary throughout the state. However, early 20th century USGS maps of other oil mining towns in WV, such as Burning Springs and Mannington, show many more sites of former oil and gas wells than there are plugged wells, which could suggest that the intensive drilling practices at Volcano were not unique. This is also not unique to WV and has been observed in other states such has Pennsylvania.

4.5. Limitations and future work

With regard to the limitations of this study, we present an emission factor based on the measurement of emissions from 0.2%, 0.02% and 0.2% of the plugged, unplugged and active wells in WV, respectively. Even though this is the largest study to date, it is still not clear whether the findings of this study's sample is representative of the entire assemblage of plugged, unplugged or active wells in WV. Put simply, future work with regard to sample size is to measure more wells. However, to measure a representative sample of wells the measurement strategies need to be streamlined to be as efficient as possible and faster,

lower-precision methods, such as the initial screening using the HXD-2D and the use of ID methods, need to be employed.

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Appendix A. Supplementary data

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