Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States - Supporting Information

James P. Williams,* Amara Regehr, and Mary Kang*

Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada

E-mail: philip.williams@mail.mcgill.ca; mary.kang@mcgill.ca

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Supporting Information

Field measurements: Oklahoma and British Columbia

We performed direct measurements of methane flow rates from 53 unplugged oil and gas (O&G) wells across Oklahoma in August 2019 and 17 wells in British Columbia in July 2018 (Figure S1). We sampled methane flow rates in Oklahoma and British Columbia using the static chamber methodology employed in Kang et al.[1] We tested each chamber in the laboratory using a mass flow controller and found that the error was within ±10%. In the field, we measured methane flow rates using the chambers and a Picarro G4301 Gas Scouter or a Sensit Portable Methane Detector.

Well classifications

Well classifications are determined based on two key parameters: plugging status and well type. The number of AOG wells for each state/province/territory is shown in Table S1. The plugging status of an AOG well is a key variable in determining emission factors and well counts in current inventories. There are differences in terminology depending on the state/province/territory. Unplugged wells are generally classified as "inactive", "suspended", "idle", and "orphaned", whereas plugged wells are usually classified as "plugged and abandoned" or "plugged".

The Alberta Energy Regulator (AER) defines well abandonment as the permanent dismantling of a well taking place over three stages: 1) project planning - the oil and gas (O&G) company designs an abandonment program that they will use to identify any potential leaks or cracks in the wellbore to all groundwater and O&G formations the well passes through; 2) subsurface abandonment - groundwater and O&G formations are isolated using plugging material (e.g. concrete) and then the well is filled with freshwater or other fluids devoid of contaminants; 3) surface abandonment - the well casing is cut at a minimum of 1 meter below the surface with an underground vented cap placed on the casing top. With the exception of an underground vented cap, similar steps are recommended by the Environmental Defence Fund (EDF)[2] who provides model guidelines for the state agencies in the U.S..

We define unplugged wells as wells with no indication of plugging, including holes in the ground with or without visible casing. These classifications are determined using observations at the surface and information available in government databases, and all direct measurements we use in this study are classified as either unplugged or plugged wells in our published measurements. One exception is Williams et al[3] in New Brunswick (Canada), for which we classify all direct measurements from static chambers as plugged wells since they measured soil gas fluxes instead of the entire exposed well head. In regional databases, plugging status is recorded in 32 of 36 regional databases and 10 of 11 provincial databases. Where plugging status is not clearly available we assign the ratios of unplugged to plugged wells. Most databases that do not record plugging status are in regions with relatively few wells (i.e. $< 1\%$), with the exception of Texas.

For Texas, we compile all data on O&G wells using the online well search tool from the Texas Railroad Commission.[4] From this well total, we subtract all noted active wells for Texas provided by the Energy Information Agency (EIA) for 2018 to determine a total AOG well count for the state. Applying the database ratios of unplugged to plugged wells from all states in the U.S. to Texas yields a total unplugged well count of 382,368 unplugged wells and 509,350 plugged wells. The Texas Railroad Commission (Texas RRC) does not provide a comprehensive tally of historical plugged wells (i.e. pre 1980's), but they do report recent annual plugging reports from 2007 to 2019. Over the course of these 12 years, the Texas RRC reports an average of 7344 wells abandoned per year over this timeframe. Assuming this plugging rate is consistent over the past 70 years, the total number of plugged wells in the state should be roughly 514,000, which is similar to our estimate of 509,350 plugged wells in the state.

In addition to plugging status, we also classify AOG wells and direct measurements based on well type (i.e. gas, O&G, and unknown). No well types are reported for the 53 wells measured in Oklahoma by the state well database. To assign well types for these sites, a map of oil and gas fields provided by the Oklahoma Geological Survey was used to estimate the fluid type attributed to the wells measured for methane flow rates (Figure S2). Wells located within an oil and gas field are assigned a well type based on the gas to oil ratio, with O&G wells defined as <6000 ft^3 gas per barrel of oil (ft^3/bbl) and gas wells as ≥6000 ft^3/bbl, which is the criteria used by the EIA.[5] For the wells sampled in Oklahoma, a total of 34 wells are classified as O&G wells and 19 as gas wells. Well types for wells measured in British Columbia are provided in the provincial database,[6] resulting in 12 O&G wells and 5 gas wells. Several studies report well type in their data such as Townsend-Small et al.[7] who provides classifications of "Gas", "Oil", and "OG" (i.e. oil and gas). Kang et al.[1] classifies wells as "Gas" or "Non-Gas", the later of which we assign as "O&G" since we can not characterize these wells as gas wells. Pekney et al.[8] notes that the wells they measure are unmarked and originally drilled for oil, and therefore we classify their measurements as O&G wells. No well types are provided in the direct measurement data from West Virginia,[9] so well types are assigned based on matching American Petroleum Institute (API) identifiers resulting in 15 gas wells and the rest classified as unknown.

We use all available measurement data grouped by plugging status to determine our emission factors under the "unknown" designation because there are a large number of AOG wells in regional databases that have an unknown well type relative to our methane flow rate data. Therefore, we base emission factors for these unknown wells solely on plugging status and use the average of both O&G and gas wells for their emission factors.

Annual anthropogenic methane emissions - national inventory reports

Annual anthropogenic methane emissions in the United States and Canada (Table S1) found in national inventory reports show that the oil and gas, agricultural, and waste sectors are the principal contributors to annual anthropogenic methane emissions. In both national inventories, AOG wells are within the top 15 anthropogenic methane emission sources. The top anthropogenic methane sources in both inventories are enteric fermentation, natural gas systems, and solid waste disposal sites (i.e. landfills). Methane emissions from AOG wells are placed above categories such as fuel combustion from pipeline transport in the Canadian inventory, and mobile combustion and abandoned underground coal mines in the U.S. inventory (Table S1). It should be noted that for Canada, annual anthropogenic methane emissions from AOG wells are not separated from the source category Fugitive Sources: Oil and Gas. In the U.S. inventory, AOG wells are assigned their own source category.

Treatment of zeroes

The detection limit for flow rates varies between the studies. All studies used some form of well screening using portable gas detectors to measure atmospheric methane concentrations on the well sites[1,3,7,9] followed by direct methane flow rate measurements using chambers. Townsend-Small et al.[7] used the screening step to select wells at which chambers are deployed to measure methane emission rates. If methane concentrations above background are not detected during the screening step+-, Townsend-Small et al.[7] present the methane flow rate as zero. In contrast, Kang et al.,[1] Riddick et al.,[9] Pekney et al.,[8] and Williams et al.[3] deployed chambers at all wells. Therefore, zeros in Townsend-Small et al.[7] are different from those in other studies presented in this work. While emissions may be minimal (i.e. <0.1 g/hour) from these wells showing no atmospheric methane enhancements, the true methane flow rates from these sites are not likely to be 0 g/hour as reported. In the interest of preserving data and not skewing results, we keep all measurements from Townsend-Small et al.,[7] but in instances where emission factors are calculated solely from 0 ppmv methane screening results from their study (e.g. plugged O&G wells in Utah in Scenario 2), we assign the total dataset average of methane flow rate data for that well classification and region.

Emission factor cut-off

We assign a cut-off of 15 measurements to assign an emission factor to any well classification such that we can assume at least one high emitter at a confidence level of 80% is included. To do this, we use the probability of at least one success of a binomial trial defined as $n = \frac{log(1-y)}{log(1-p)}$, where n is the number of trials, x is probability of at least one success given n trials, and p is the probability of a successful trial. Current measurement data shows that 10% of measurements are responsible for 99% of cumulative emissions from AOG wells, therefore we define p as 10%. We set y as 80%, such that we have at least 80% confidence of measuring at least one AOG well within the heavy-tail of emissions. The cut-off value n changes depending on how p and y are defined (Figure S3), where p is controlled by the current status of measurement data and governing the "heavy-tail" (i.e. the percentage, p, of wells that contribute x% of cumulative emissions), and y depends on the acceptable confidence in measuring at least one high-emitting site. We select values of y and p based on a trade-off between sacrificing the ability to account for regional heterogeneity and assigning emission factors to well counts based on too few measurements.

Distributions of methane emissions by region and well classification

We observe several trends in the distributions of methane emissions by well classification and region (Figure S5 and Figure S6). It is clear that unplugged gas and unknown well type wells represent the majority of methane emissions in the U.S. and Canada. Emissions from unplugged O&G wells are substantial in Texas, Pennsylvania, Alberta, and Saskatchewan, which have the highest counts of unplugged O&G wells for their respective countries. Plugged gas wells are a significant source for Texas representing 9-12% of methane emissions from AOG wells, which is due to a large number of plugged gas wells in the state rather than emission factors. In Alberta, plugged gas wells contribute 5-6% of the provinces total annual methane emissions from AOG wells.

Uncertainties in the number of AOG wells

We use an asymmetrical triangular distribution based on two main assumptions: that the number of AOG wells in our study can be an underestimate and that the likelihood of the number of AOG wells being near the upper and lower bounds is lower. We select lower bounds based on the percent difference between our final well counts (Table S2) and the results of the state/provincial/territorial database compilation of well numbers which we assume to be all documented AOG wells. We estimate a default upper bound of +100% based on the upper range of undocumented wells from Oklahoma, Pennsylvania, and West Virginia, including data on the estimated number of undocumented orphan wells from the Interstate Oil and Gas Compact Commission,[10] compared to the number of documented wells for the respective states/provinces/territories (1,233,144) (Table S3).

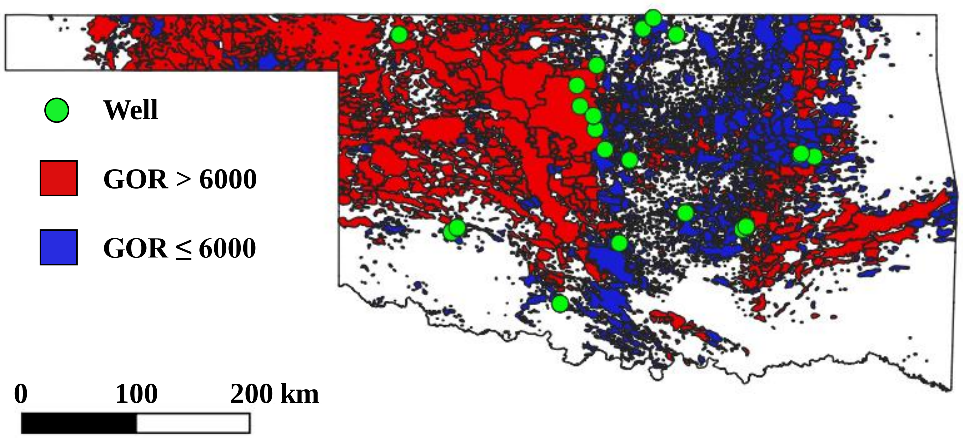

Figure S1: Locations of methane flow rate measurements in Oklahoma with the produced gas to oil ratio (GOR) in ft^3/bbl. Wells located within an oil and gas field with a GOR ≤ 6000 are classified as O&G wells and wells located in a region with a GOR > 6000 are defined as gas wells. Map of Oklahoma oil and gas fields provided by the Oklahoma Geological Survey - Geologic Map 39.[11]

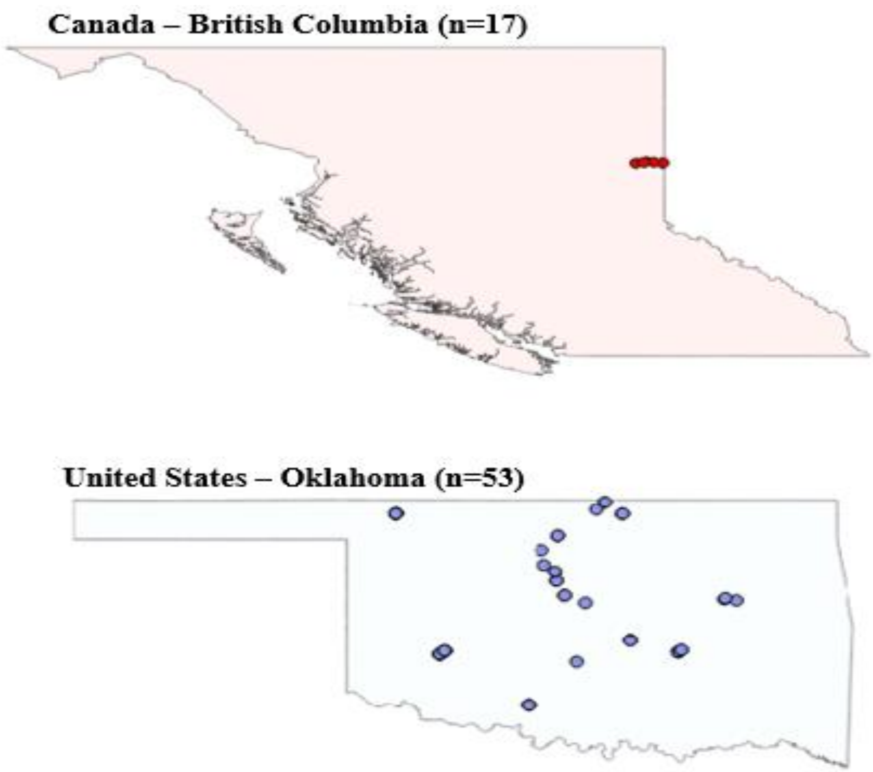

Figure S2: Locations of methane flow rate measurements from AOG wells in British Columbia (top – red points), and Oklahoma (bottom – blue points). Maps are not to scale.

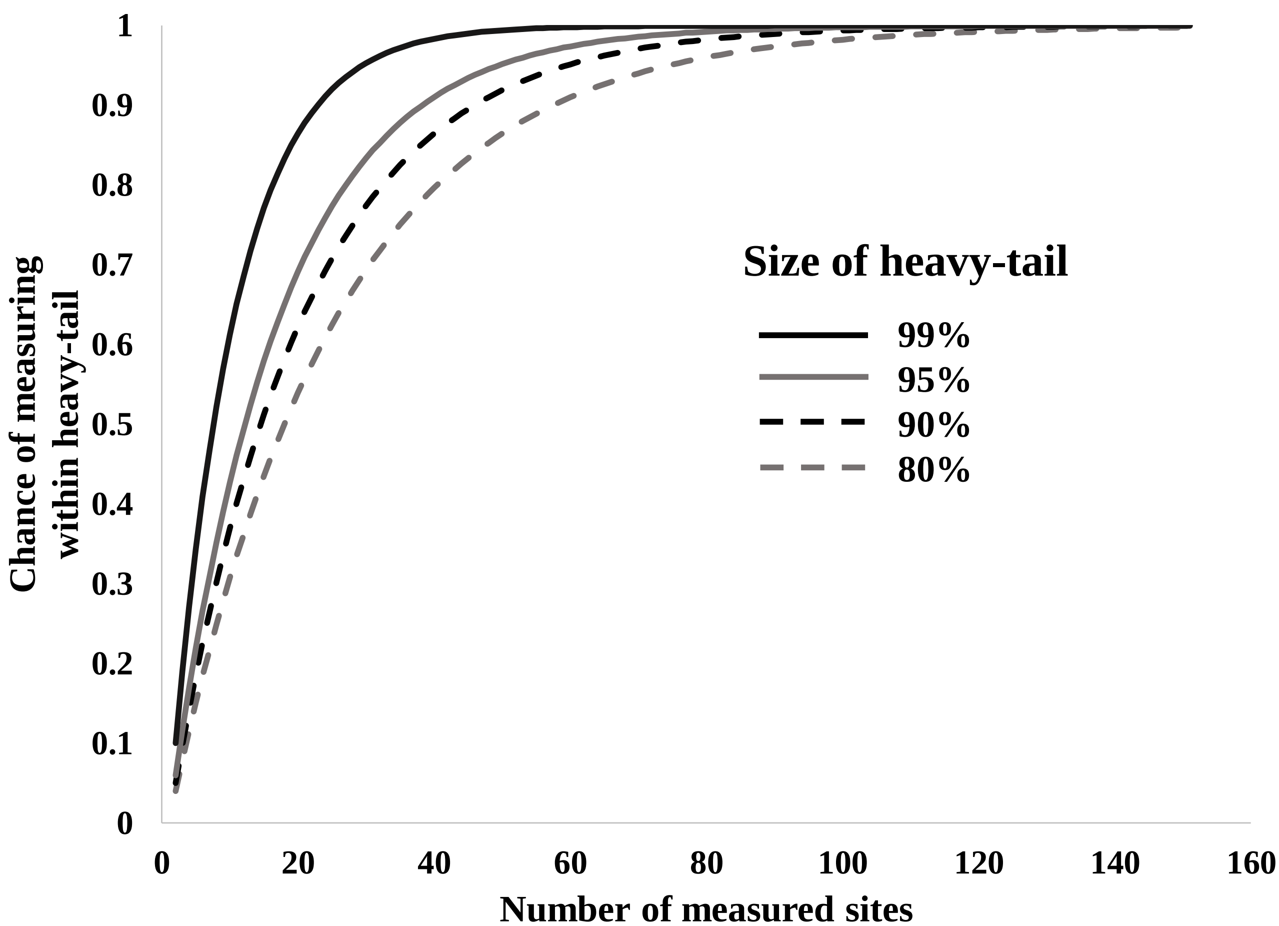

Figure S3: Probability plots showing the chance of measuring an AOG well within a subset of high-emitting wells that contribute 80 (grey dashed line), 90 (black dashed line), 95 (grey line), and 99% (black line) of cumulative methane emissions.

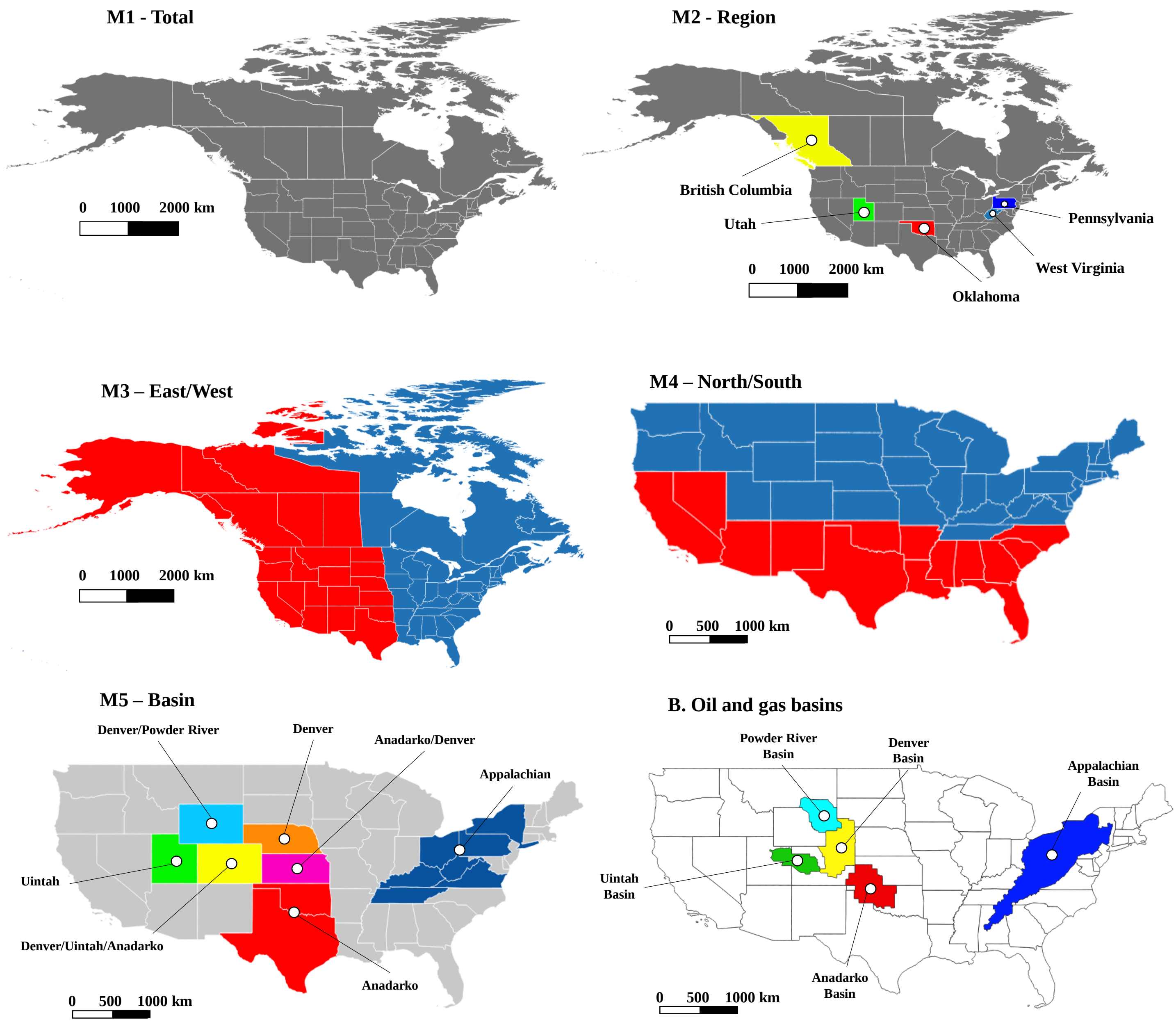

Figure S4: Maps of five emission factor attribution scenarios as summarized in Table 1 (M1 to M5), and map of oil and gas basins (bottom-right - B. Oil and gas basins) used to obtain emission factors for scenario M5. Oil and gas basin shapefiles are obtained from the United States Geological Survey: Central Energy Resources Science Center.[12] Regions coloured grey represent the "U.S." and "Canada" in M1 or "Remainder" in M2 and M5.

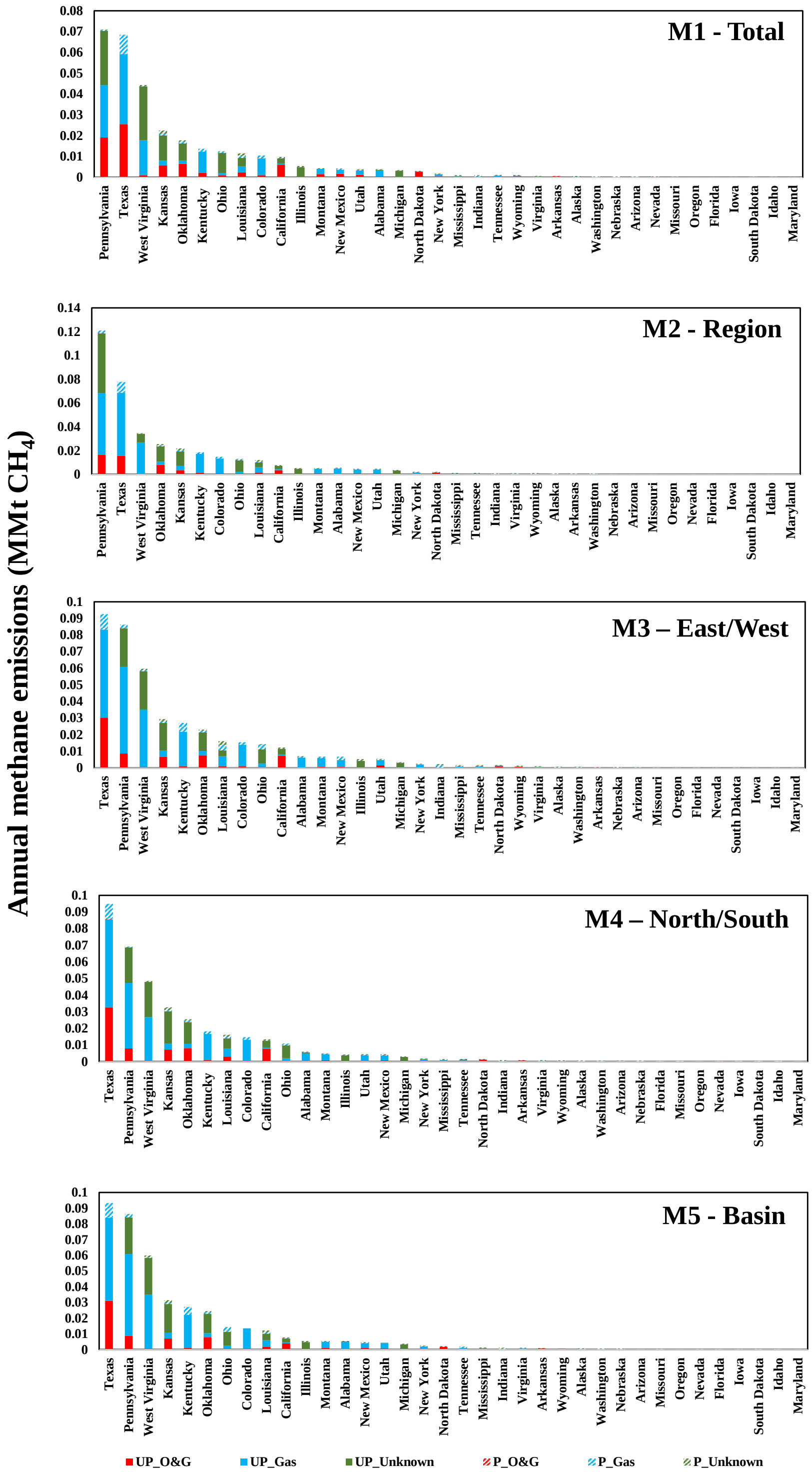

Figure S5: Barplots of methane emissions from each state in the U.S. based on well type and plugging status for all five emission factor attribution scenarios. Note: UP = Unplugged, P = Plugged, O&G = Oil and gas.

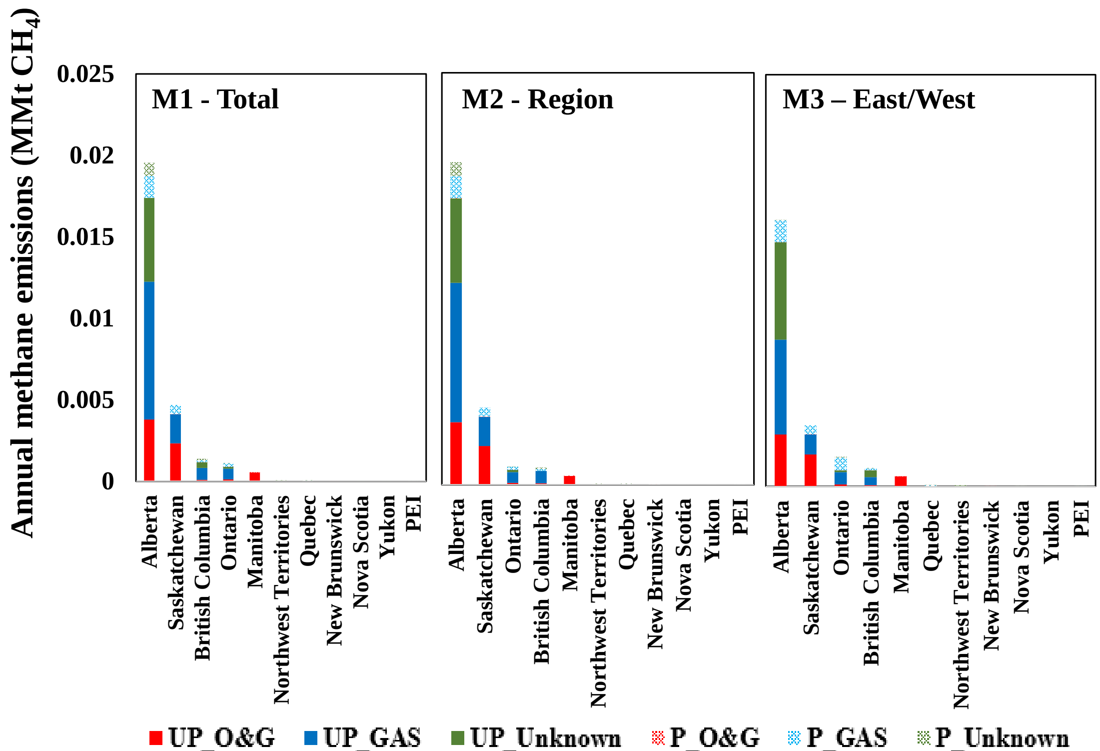

Figure S6: Barplots of methane emissions from each province/territory in Canada based on well type and plugging status for all three emission factor attribution scenarios. Note: UP = Unplugged, P = Plugged, O&G = Oil and gas.

Table S1: Annual anthropogenic methane emissions and associated uncertainties for Canada and the U.S. All data is taken from the national greenhouse gas inventory reports for Canada[13] and the U.S..[14]

Canada[13]			
Rank - Emissions	Anthropogenic Emissions Source	2018 Methane Emissions (kt/year)	Combined Uncertainty (%)
1	Agriculture - Enteric Fermentation	966	22
2	Fugitive Sources - Venting and Flaring	852	10
3	Fugitive Sources - Oil and Gas	683	22
4	Managed Waste Disposal Sites	491	40
5	Agriculture - Manure Management	154	32
6	Unmanaged Waste Disposal - Wood Waste Landfills	136	190
7	Fuel Combustion - Other Sectors	129	15
8	Manufacture of Solid Fuels and Other Energy Industries	100	140
9	Fugitive Sources - Coal Mining and Handling	53.2	57
10	Wastewater Treatment and Discharge	26.2	45
11	Fuel Combustion - Off-Road	21.2	11
12-13	Biological Treatment of Solid Waste - Composting	10.4	170
12-13	Abandoned Oil and Gas Wells*	10.4	117
14	Road Transportation (Gas, Diesel, Natural Gas, Propane)	9.84	110
15	Fuel Combustion - Pipeline Transport	8.04	15

U.S.[14]			
Rank - Emissions	Anthropogenic Emissions Source	2018 Methane Emissions (kt/year)	Combined Uncertainty (%)
1	Enteric Fermentation	7100	29
2	Natural Gas Systems	5600	29
3	Landfills	4420	45
4	Manure Management	2470	38
5	Coal Mining	2110	29
6	Petroleum Systems	1450	65
7	Wastewater Treatment	568	51
8	Rice Cultivation	532	93
9	Stationary Combustion	344	165
10	Abandoned Oil and Gas Wells	280	302
11	Abandoned Underground Coal Mines	248	35
12	Mobile Combustion	124	35
13	Composting	100	100
14	Field Burning of Agricultural Residues	16.0	32
15	Petrochemical Products	12.0	103

*Abandoned Oil and Gas Wells are a sub-category of Fugitive Sources - Oil and Gas.

Table S2: Counts of unplugged and plugged AOG wells assigned to each state/province/territory in the U.S. and Canada with the corresponding data sources.

Region	AOG Wells	Source
U.S.		
Alabama	25,913	Geological Survey of Alabama O&G Board
Alaska	6338	Alaska Oil and Gas Conservation Commission
Arizona	1622	Arizona Oil and Gas Conservation Commission
Arkansas	13,696	Arkansas Oil and Gas Commission
California	204,769	California's Division of Oil, Gas, and Geothermal Resources
Colorado	91,075	Colorado Oil and Gas Conservation Commission
Florida	1331	Florida Department of Environmental Protection
Idaho	25	Idaho Geological Survey and/or Idaho Department of Lands
Illinois	139,611	Illinois Natural Resources Geospatial Data Clearinghouse
Indiana	67,159	Indiana Department of Natural Resources
Iowa	334	Iowa Department of Natural Resources
Kansas	426,142	Kansas Geological Survey
Kentucky	114,643	Kentucky Geological Survey / University of Kentucky
Louisiana	232,917	Louisiana Department of Natural Resources
Maryland	24	Maryland Oil and Gas Viewer
Michigan	36,818	Michigan Department of Environmental Quality
Mississippi	30,286	Mississippi Oil and Gas Board
Missouri	5694	Missouri Department of Natural Resources
Montana	50,086	Montana Board of Oil and Gas Conservation
Nebraska	6349	Nebraska Oil and Gas Commission
Nevada	1587	Nevada Commission on Mineral Resources
New Mexico	68,229	New Mexico Oil Conservation Division
New York	28,056	New York State Department of Environmental Conservation
North Dakota	30,341	North Dakota Department of Mineral Resources
Ohio	183,090	Ohio Department of Natural Resources
Oklahoma	280,034	Oklahoma Corporation Commission, IPAA[15]
Oregon	968	State of Oregon Department of Geology and Mineral Industries
Pennsylvania	610,000	The Pennsylvania Department of Environmental Protection, Kang et al.[1]
South Dakota	1312	South Dakota Geological Survey
Tennessee	15,066	Tennessee Department of Environment and Conservation
Texas	891,718	Texas Railroad Commission
Utah	41,504	Utah Department of Natural Resources
Virginia	10,321	Virginia Department of Mines, Minerals and Energy
Washington	1295	Washington State Department of Natural Resources
West Virginia	410,000	West Virginia Department of Environmental Protection, Riddick et al.[9]
Wyoming	20,175	Wyoming Oil and Gas Conservation Commission
Canada		
Alberta	250,513	Alberta Energy Regulator - ST37: List of Wells in Alberta
British Columbia	19,930	British Columbia Oil and Gas Commission
Manitoba	10,139	Manitoba Petroleum: Interactive GIS Gallery
New Brunswick	346	Government of New Brunswick - Natural Resources and Energy Development
Nova Scotia	156	Geoscience Data and Maps - Nova Scotia Department of Energy
Ontario	13,626	Ontario Oil, Gas, and Salt Resources Library
Quebec	970	ArcGIS Home: Quebec wells
Saskatchewan	75,955	Saskatchewan Mining and Petroleum GeoAtlas
Yukon	90	Yukon Government - Energy, Mines and Resources
Northwest Territories	1168	NWT Government - Office of the Regulator of Oil and Gas Operations
Prince Edward Island	27	PEI - Transportation, Infrastructure, and Energy

Table S3: Number of AOG wells obtained from state/provincial/territorial databases and the estimated number of undocumented AOG wells for the respective states/province/territories.

State/Province/Territory	Database AOG well number	Estimate of undocumented wells
Oklahoma	140,283	139,717 [15]
Pennsylvania	61,077	408,923 - 688,923 [1]
West Virginia	79,198	0 - 680,802 [9]
Alabama	16,810	0 [10]
Alaska	5172	0 [10]
Arizona	987	0 [10]
Arkansas	11,653	0 [10]
California	172,679	2500 [10]
Colorado	72,115	200 [10]
Idaho	18	0 [10]
Indiana	66,074	<100 [10]
Kentucky	87,558	5000 [10]
Michigan	23,526	0 [10]
Mississippi	27,892	6 [10]
Montana	39,949	0 [10]
Nevada	1126	0 [10]
New York	23,679	34,000 [10]
North Dakota	20,528	0 [10]
Ohio	137,692	35,133 [10]
Virginia	8761	<10 [10]
Alberta	154,977	0 [10]
British Columbia	16,698	0 [10]
Saskatchewan	63,637	0 [10]
Yukon	76	0 [10]
Northwest Territories	979	0 [10]
Total	1,233,144	625,589 - 1,586,391

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