Methane emissions and environmental impacts of oil and natural gas systems: well sites in northern regions and natural gas appliances

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Contribution of Authors

Chapter 3 corresponds to a paper: *Oil and natural gas wells across the NASA ABoVE domain: fugitive methane emissions and broader environmental impacts,* which was submitted to Environmental Research Letters in November 2022. I am the corresponding author of this paper and the research and writing are my own. It is co-authored by Oliver Sonnentag and Ziming Wang from the Department of Geography at Université de Montréal and my supervisor, Mary Kang from the Civil Engineering Department at McGill University. Chapter 4, entitled *Methane emissions from commercial and residential natural gas appliances: testing in a controlled setting and field-based screening*, contains work that is indented to be part of a paper to be submitted to Measurements, as well as another paper to be submitted to Environmental Research: Infrastructure and Sustainability. This work is co-authored by James P. Williams, Kevin Mayeux and my supervisor Mary Kang, from the Civil Engineering Department at McGill University.

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Abstract

Oil and natural gas (OG) activities are associated with many climate and environmental impacts. Methane (CH_4), which is the primary constituent of natural gas is a potent greenhouse gas (GHG) with a short atmospheric lifetime of about 12 years, meaning reductions in CH_4 emissions can have a major impact in limiting climate warming in the near-future. Fugitive CH_4 emissions arise throughout the supply chain of OG fuels, from production, processing, storage to distribution and end-use, from either intentional (e.g., venting and flaring processes) or unintentional (leaks) gas releases. Here, we identified and investigated two understudied segments of the OG sector, namely the OG production (OG wells) impacts in northern regions and the end-use of natural gas, focusing on leaks from natural gas appliances and piping, as well as CH_4 emissions from the incomplete combustion of natural gas. OG wells are a large source of CH_4 emissions with underestimated subcategories (inactive or abandoned OG wells). In addition, OG wells are associated with many local environmental impacts, such as vegetation clearing, contamination of the surrounding water and soil and noise pollution, to name a few. This is especially important to consider as many OG reserves are located in remote regions with vulnerable ecosystems. At the end-use of natural gas, CH_4 emissions can occur from incomplete combustion of natural gas, considered stationary combustion emissions, or from leaks in natural gas piping connecting the customer natural gas metering device to the natural gas appliance or in natural gas appliances themselves, referred to as post-meter emissions. These latter emissions are currently not consistently included in national GHG inventories.

First, we analysed the distribution of OG wells drilled between 1984 and 2018 across the Core Domain of the NASA Arctic-Boreal Vulnerability Experiment (“ABoVE domain”) using public OG well databases. We identified 242,007 OG wells drilled as of 2018 in the ABoVE domain, of which almost two thirds are now inactive or abandoned OG wells. Fugitive CH_4 emissions from active and abandoned OG wells drilled in the Canadian portion of the ABoVE domain accounted for approximately 13% of the total anthropogenic CH_4 emissions in Canada in 2018. Our analysis identified OG wells as an

anthropogenic disturbance in the ABoVE domain with potentially non-negligible consequences to local populations, ecosystems, and the climate system.

Second, we investigated natural gas appliance emissions by conducting direct measurements of 34 appliances at an educational facility (Ecole de Technologie Gazière, ETG) and at McGill University student residences. We implemented three different measurement techniques, namely concentration screening (n = 20), high flow sampling (n = 24) and chamber-based measurements (n = 24). We found CH_4 leaks around natural gas piping and appliance exhaust vents. This study provides new insight on CH_4 emissions occurring at the end-use segment of the natural gas supply chain, such as the location and relative magnitude of emissions or the dependence to appliance ignition and extinguishment. We show how emissions differ based on appliance natural gas consumption and appliance type, highlighting the importance of using technology-specific emission factors when estimating these emissions in national GHG inventories.

To conclude, we found that both segments contribute non-negligibly to CH_4 emissions and highlighted the importance to consider broader environmental impacts of the OG sector. Additional studies are required on potential interactions between OG wells, permafrost and other Arctic-boreal ecosystem components. Moreover, direct measurements of a wide range of natural gas appliances, are required to improve reporting of these sources in national GHG inventories.

Abstract in French

Les impacts climatiques et environnementaux du secteur pétrolier et gazier sont multiples. Le méthane (CH_4), principal constituant du gaz naturel, est un puissant gaz à effet de serre (GES) dont la durée de vie dans l'atmosphère est d'environ 12 ans. De ce fait, réduire nos émissions de CH_4 pourrait jouer un rôle majeur dans la lutte contre le réchauffement climatique dans les années à venir. Des émissions fugitives de CH_4 se produisent tout au long de la chaine de production du pétrole et gaz naturel, depuis l'extraction, en passant par le traitement et stockage jusqu'à la distribution et combustion finale du carburant. Dans cette étude, nous avons identifié et étudié deux segments de la chaine de production de pétrole et gaz naturel: d'une part au stade de l'extraction, en particulier les impacts des puits de pétrole et gaz naturel dans les régions arctiques et boréales mais également la part des émissions au niveau des appareils électroménagers fonctionnant au gaz naturel. Les puits de pétrole et gaz naturel sont des sources importantes de CH_4 dont les émissions sont souvent sous-estimées. Outre les émissions de méthane, ces sites sont des zones de contamination de l'eau et des sols, de déforestation et de pollution sonore. Les émissions de CH_4 liées aux appareils électroménagers sont dues à des fuites provenant des appareils, des conduites de gaz connectant le compteur aux appareils, ainsi que des émissions dues à la combustion incomplète du gaz naturel, appelées émissions post-compteur.

Dans une première partie de notre étude, nous avons analysé la distribution spatiale des puits de pétrole et gaz naturel forés entre 1984 et 2014 dans le domaine ABoVE à partir de bases de données publiques. Nous avons compté 254998 de ces puits, en majorité forés en Alberta (n = 211747) et en Colombie-Britannique (n = 35012). Nous avons estimé la portion provenant des puits de pétrole et gaz naturel actifs et inactifs situés dans la partie canadienne du domaine ABoVE à environ 13% des émissions anthropiques totales de CH_4 au Canada en 2018. Notre analyse fournit un aperçu nouveau des interactions complexes entre les puits de pétrole et gaz naturel et leur environnement local, dans l'état actuel de réchauffement climatique ayant des conséquences potentiellement non négligeables sur les régions arctiques et boréales, ainsi que ses populations et écosystèmes locaux.

Dans une deuxième partie, nous avons étudié les émissions des appareils électroménagers à gaz en effectuant des mesures directes sur 34 appareils. Nous avons testé trois méthodes de mesure différentes, à savoir la mesure directe de concentration (n = 20), l'échantillonnage à haut débit (n = 24) et la chambre statique (n = 24). Nous avons trouvé des fuites de CH_4 provenant des conduites à gaz, autours des appareils, ainsi que dans le pot d'échappement de ces mêmes appareils. Cette étude apporte des informations nouvelles sur les caractéristiques des émissions provenant des appareils à gaz, tels que l'emplacement, la récurrence et l'importance relative des émissions. Nous avons mis en lumière l'importance d'utiliser des facteurs d'émission spécifiques pour chaque type d'appareil électroménagers lors de l'estimation de ces émissions dans les inventaires nationaux de GES puisque les émissions diffèrent en fonction de la consommation de gaz ou du type d'appareil.

Pour conclure, nous avons montré que les deux segments (production et post-compteur) émettent des quantités non-négligeables de CH_4, et qu'il est en outre nécessaire de lier ces émissions aux autres impacts environnementaux des chaines de production du pétrole et gaz naturel. Plus d'études sur les interactions entre les puits de pétrole et gaz naturel, le pergélisol et les systèmes environnementaux de la région arctique-boréale sont requises, ainsi que plus de mesures des émissions des appareils électroménagers à gaz, afin de les inclure dans l'inventaire canadien de GES.

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1. Introduction

1.1. Methane emissions from oil and natural gas systems

1.1.1. Methane in the context of the current climate crisis

Mean surface temperatures have increased by 1.09˚C between 1850-1990 and 2011-2020, with some regions of the world already experiencing warming above 1.5˚C (Gulev *et al.*, 2021). Temperatures are expected to continue to rise due to continued emissions of greenhouse gases (GHG) to the atmosphere. The impacts of such warming include increased frequency and intensity of extreme weather events, resource and food scarcity, biodiversity loss or ecosystem damage and are exacerbated by major natural and anthropogenic disturbances. Although carbon dioxide (CO_2) is often at the forefront of discussions, methane (CH_4) is a potent GHG that has a global warming potential of 82.5 and 29.8 over a 20- and 100-year time frame (Forster *et al.*, 2021). The global warming potential is a measure of the radiative forcing of a given gas in comparison to CO_2. Hence, 1 ton of CH_4 released to the atmosphere will have a much higher radiative forcing than 1 ton of CO_2. Additionally, CH_4 has a much shorter lifetime (~12 years) than CO_2 (~100 years), meaning that CH_4 emissions reductions can translate to atmospheric concentrations reductions in the near future and are necessary to achieve long-term temperature targets. A 45% reduction of anthropogenic CH_4 emissions can prevent a 0.3˚C increase in global surface temperatures by 2030 (Ravishankara *et al.,* 2021). Moreover, there are many technically and economically feasible mitigation opportunities that are available today focusing on CH_4 (Ocko *et al.,* 2021). Therefore, reducing CH_4 emissions can play a key role in tackling climate change.

1.1.2. Methane emissions from the oil and natural gas sector

Anthropogenic CH_4 sources account for 60% of global emissions, with most emissions coming from the fossil fuel (35%), agriculture (40%) and waste (20%) sectors. The remaining 40% are natural sources, which are dominated by wetlands accounting for about a quarter of global emissions (Ravishankara *et al.,* 2021). Oil and natural gas (OG) systems are a major anthropogenic source of CH_4 emissions. Saunois *et al.* (2020)

estimated global CH_4 emissions from the OG sector in 2017 to be 84 Tg CH_4, accounting for 62% of fossil fuel CH_4 emissions and 22% of total anthropogenic CH_4 emissions. CH_4 is the primary constituent of natural gas, and is also generally co-produced with oil, therefore fugitive CH_4 emissions occur throughout the OG supply chain, from well drilling to extraction, transportation, storage, distribution and end-use of OG. Fugitive emissions can be due to unintentional leaks from the OG infrastructure and distribution network or to intentional gas releases for maintenance purposes (e.g., venting or flaring). In addition to being one of the largest sources of anthropogenic CH_4 emissions, the OG sector offers many economically feasible mitigation options and could contribute to 80% of avoided warming (Ocko *et al.*, 2021).

Large discrepancies have been found between top-down and bottom-up CH_4 inventories (Cheewaphongphan *et al.*, 2019, Alvarez *et al.*, 2018, Tyner and Johnson, 2021, Lu *et al.,*2022). Typically, top-down methods estimate emissions based on atmospheric measurements, whereas bottom-up inventories focus on individual source emissions, typically expressed as the product of an emission factor with corresponding activity data. CH_4 emissions from the OG sector are highly uncertain and global and national estimates often vary significantly among studies, due to the usage of different methodologies and datasets (Saunois *et al*, 2020). For national GHG inventories, the preferred option is to use technology- and country-specific emission factors for each step of the supply chain derived from direct measurement of every fugitive emission source. However, when such measurements are unavailable, national inventory compilers use default emission factors derived from measurements made outside of the country. Moreover, OG emissions are dominated by a few high-emitting facilities, or super-emitters, which can be difficult to characterize through measurements and represent in inventories (Williams *et al.*, 2021, Duren *et al.*, 2019, Zavala-Araiza *et al.*, 2015). In addition, there can be sources that are unaccounted for in emission inventories.

1.2. Methane emissions measurement and quantification techniques

Methods to measure CH_4 emissions are numerous, they can be qualitative or quantitative, from source detection to emission flux rate measurements. Here, we focus on methods that are well-suited for sources such as abandoned OG wells and natural gas appliances with CH_4 emission rates ranging from 10^{-2} to 10^4 mg/hr. Gas screening can involve moving around with a portable gas analyzer, placing the screening rod on potential sources for about 30 seconds. Concentration screening is useful for leak detection but cannot be used for emission rate quantification without additional atmospheric parameters and higher uncertainties. For inventory purposes, emission rate measurements (i.e., amount of CH_4 released per unit of time), rather than emission concentration, are required. Methods for direct emission rate measurements include static and dynamic chambers, high flow sampling, eddy covariance systems, tracer flux methods, inverse modeling. Each method has advantages and disadvantages and the choice of the appropriate methodology depends on the characteristics of the source. For example, for a point source, chamber-based and high flow sampling may be more appropriate, whereas for diffuse sources, tower-based approaches may be better suited. Since OG wells and natural gas appliances are point sources, we focus on high flow sampling and chamber-based methods in this work. High flow samplers measure leaks at high flow rates (~12,000 g/hr or 300 slpm), assuming the complete capture of the leak. The leak rate is derived by the instrument, based on the Equation 1.1, where Q_{leak} is the leak rate, Q_{blower} is the flow rate at which the instrument samples the leak, C_{leak} is the CH_4 concentration of the sample and C_{bkg} is the background CH_4 concentration.

$$Q_{leak}\ [lpm] = Q_{blower}\ [lpm] * \left(C_{leak}\ [\%] - C_{bkg}\ [\%]\right) * 10^{-2} \qquad \text{(Eq. 1.1)}$$

The static chamber method consists of enclosing the source in a sealed chamber of known volume and monitoring the gas concentration build-up over time. The leak rate is derived based Equation 1.2, where Q_{leak} is the leak rate, $V_{chamber}$ the chamber volume, $\frac{dC}{dt}$ the slope of the linear regression curve passing through the CH_4 concentration data retrieved from inside the chamber, p the atmospheric pressure, R the gas constant ($R = 0.08206\ \frac{L\ atm}{mol\ K}$), T the temperature and M the molar mass of CH_4 ($M = 16\frac{g}{mol}$).

$$Q_{leak}\ \left[\frac{g}{min}\right] = V_{chamber}\ [L] * \frac{dC\ [ppm]}{dt\ [min]} * \frac{P\ [atm]}{R\left[\frac{L\ atm}{mol\ K}\right] * T\ [K]} * M\left[\frac{g}{mol}\right] * 10^{-6}\ \left[\frac{1}{ppm}\right] \qquad \text{(Eq. 1.2)}$$

1.3. Other environmental impacts of oil and natural gas systems

The environmental impacts of OG exploration and extraction activities are numerous. Direct impacts of OG well drilling on the surrounding environment include the physical clearing of vegetation for well pad preparation, landscape fragmentation, the compaction of the soil by machinery and noise pollution, causing habitat destruction and ecosystem disturbance (Dabros *et al.,* 2018, Drohan *et al.,* 2012, Moran *et al.,* 2015, Pickell *et al.*, 2015). Once drilled, OG wells can leak gas, saline water, radionuclides and other contaminants leading to groundwater and soil contamination (Jackson *et al.,* 2013, Rice *et al.*, 2018, Garner *et al.,* 2015, Olmstead *et al.,* 2013). In addition to releasing CH_4 to the atmosphere, OG production is often associated with emissions of volatile organic compounds (VOCs), nitrogen and sulfur oxides (NO_x and SO_x) and particulate matter (PM) (Litovitz *et al.*, 2013, Petron *et al.*, 2014, Jaramillo and Muller, 2016, Caron-Beaudoin *et al.*, 2018, Fann *et al.,* 2018, Michanowicz *et al.,* 2021), which are all harmful to human and ecosystem health. Moreover, the significant contribution of OG systems to GHG emissions leads to many indirect environmental impacts associated with the changing global climate.

Arctic and boreal regions are especially vulnerable to disturbances and are already experiencing amplified climate warming in recent decades (Meredith *et al.*, 2019). Permafrost soils, which are perennially frozen soils, are thawing at a rapid rate, in turn altering hydrological and biochemical regimes. Since, OG development is ubiquitous in these regions, understanding how OG activities affect permafrost soils and Arctic-Boreal biomes, as well as how permafrost thaw and other altered disturbance regimes will affect OG wells.

Due to the complex interactions between the various environmental systems, namely the atmosphere (air), biosphere (living organisms), hydrosphere (water), cryosphere (ice) and geosphere (solid Earth), understanding the main drivers of ecosystem changes occurring in recent decades and assessing the role OG activities play in the global environmental system is very challenging. Additional studies are required to further our understanding of OG systems. Long-term monitoring of ecosystem composition and structure in areas where OG activities are predominant is necessary to capture the changes occurring in these regions.

1.4. Objectives and approach

To mitigate CH_4 emissions from the OG sector, it is necessary to investigate all emission sources across the OG supply chain and identify knowledge gaps or unknown sources. In this work, we focus on two segments of the OG supply chain that require further investigation, namely OG exploration and extraction, especially in the vulnerable Artic-Boreal region of Western North America, and the natural gas end-use segment, including leaks in natural gas piping and natural gas appliances, as well as emissions from the incomplete combustion of the fuel found at the exhaust vents of the natural gas appliances. In the first case, we base our study on public spatial geoinformation, such as state, provincial and territorial OG well databases, gridded emission inventories and thematic maps (permafrost and land cover maps). In the second study, we perform our own direct measurements on emission sources including natural gas piping and natural gas exhaust vents, using various point-source measurement methods. Both studies identify non-negligible CH_4 emission sources and inadequate monitoring of these sources.

1.5. Organization of the thesis

After introducing the subject of CH_4 emissions and broader environmental impacts of OG systems, the second chapter presents the current state of scientific research on GHG inventories, CH_4 emissions from the OG supply chain and other environmental impacts associated with OG activities. The third chapter investigates the impacts of OG exploration and extraction in the Artic-Boreal region of Western North America, studying various impacts of these activities on the local ecosystems and the interactions between OG wells and permafrost. In the fourth chapter, we focus on the end-use segment of the natural gas supply chain. Using various point source measurement techniques, we present new insights on post-meter leaks and incomplete combustion CH_4 emissions, which are necessary to efficiently characterize these sources and derive a representative emission factor to be used in future GHG inventories. The fifth and sixth chapters discuss the significance of our findings and places them in the present context of tackling climate change, as well as providing recommendations on future research work.

2. Literature review

2.1. GHG reporting and the gap between “bottom-up” and “top-down” inventories

Since 2002, each Annex I Party is required to provide a national GHG inventory, reporting direct emissions of various GHGs including CO_2, CH_4, nitrous oxides and hydrofluorocarbons, following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These national inventories are based on a bottom-up approach. One method used for bottom-up estimates is based on an emission factor derived for each emission source through measurements and multiplied by the activity data for the corresponding source (Equation 1.3). For example, for natural gas production-related CH_4 emissions, the volume of natural gas produced (m^3) constitutes the activity data and the mass of CH_4 emitted per unit of natural gas produced (kiloton/m^3) is the emission factor.

$$Emissions = \sum_i EF_i \times AD_i \quad \text{(Eq. 1.3)}$$

Another approach commonly used for reporting emissions is the top-down method, which focuses on overall emissions rather than individual sources. Top-down methods infer surface emission sources at a global and regional scale based on atmospheric measurements (e.g., atmospheric gas mixing ratios or remote sensing observations). Many inverse modelling studies have been conducted on CH_4 emissions in North America (Kort *et al.*, 2008; Miller *et al.*, 2013; Zhao *et al.*, 2009) and Europe (Bergamaschi *et al.*, 2018; Manning *et al.*, 2011).

Large discrepancies have been reported amongst top-down studies due to the use of different modeling approaches, different atmospheric transport models or different optimization techniques, as well as between top-down and bottom-up estimates (Kort *et al.,* 2008; Miller *et al.* 2013; Turner *et al.*, 2015; Bergmaschi *et al.,* 2018; Desjardins *et al.,* 2018; Zhao *et al.,* 2009; Manning *et al.*, 2011). For example, Miller *et al.* (2013) estimated anthropogenic CH_4 emissions in the U.S. following an inverse modelling approach, where they combined CH_4 observations from the surface, telecommunication towers and aircrafts with an atmospheric transport model. They reported emissions 1.5 and 1.7 times larger than the U.S. GHG inventory estimate and the Emission Database for Global

Atmospheric Research (EDGAR) estimates. Top-down estimates are increasingly being used to verify bottom-up inventories (Maasakkers *et al.,* 2018, Mays *et al.*, 2009, Karion *et al.,* 2013, Miller *et al.,* 2012, Scarpelli *et al.,* 2021).

2.2. Methane emissions across the oil and natural gas supply chain

Even though natural gas emits less CO_2 upon combustion than many other fossil fuels, emissions of CH_4, which is the primary constituent of natural gas, occur across the supply chain, from OG production, processing, transmission, storage, to distribution and end-use. Emissions occur either due to the unintentional (leaks) or intentional (venting, flaring) releases of gas.

Although, natural gas is seen as a greener energy source relative to more conventional fossil fuels, switching from coal to natural gas is only beneficial if leakage across the supply chain is less than 2.7% of the produced natural gas (Alvarez *et al.*, 2012). Emission rates from the OG sector are highly uncertain and studies report leak rates from 1 to 10% (Allen *et al.*, 2014). These uncertainties are mainly due to the large number of sources, the uncertainties related to emission factors and activity data and the heavy-tailed skewed distribution of emitters, where only a small fraction of sources account for most of the sector's emissions. These emitters are commonly called super-emitters and are difficult to capture in bottom-up emission inventories (Alvarez et al, 2018, Lamb *et al.,* 2015, Subramanian et al 2015, Mitchell *et al.,* 2015, Brandt et al 2014, 2015).

2.2.1. Production and processing

The production segment of the supply chain includes the exploration, drilling and extraction activities. CH_4 emissions from OG production sites, where wellheads are located, have been measured using various methods, from direct measurements (Albertson *et al.*, 2016; Allen *et al.,* 2013; Allen *et al.,* 2015a; Allen *et al.,* 2015b) to mobile ground-based (Zavala-Araiza *et al.,* 2018; Zhou *et al.*, 2021) and airborne measurements (Karion *et al.,* 2013; Tratt *et al.*, 2014; Thorpe *et al.,* 2016; Johnson *et al.,* 2017). For example, Zavala-Araiza *et al.* (2018) quantified emission rates using the tracer flux method, where a controlled volume of a tracer gas is released upwind from the OG producing site and gas concentrations are measured downwind. They found total measured CH_4 emissions over the OG producing region of Red Deer, Alberta, Canada of 0.4 to 2.5 Gg/yr, with most sites having leak rates higher than 1% of their natural gas production and 21% sites emitting more than 10% of their natural gas production. These emissions accounted for 67% of total measured emissions, according to the skewed distribution of emissions from this sector. CH_4 emissions from natural gas gathering and processing facilities were investigated from 114 natural gas gathering stations and 16 processing sites by Mitchell *et al.* (2015). They found that facility level emission rates varied with facility type, design, size and operations. Marchese *et al.* (2015) combined the facility-level emission factors developed by Mitchell *et al.* (2015) with U.S. facility counts and natural gas throughput to estimate total annual CH_4 emissions from U.S. gathering and processing stations, namely 2,421 Gg/yr corresponding to a 0.47% natural gas loss rate.

When OG wells no longer produce OG, they are considered inactive or abandoned. CH_4 emissions don't cease with abandonment, as abandoned OG wells can act as a subsurface pathway for CH_4 to reach the atmosphere. In the U.S. and Canada, the plugging of abandoned OG wells is required by state, territorial and provincial regulations. This consists of isolating the well from groundwater aquifers or the ground surface to prevent CH_4 leakage using a cement plug. However, even plugged OG wells emit non-negligible CH_4 emissions (Williams *et al.,* 2021). They estimated CH_4 emissions from plugged and unplugged abandoned OG wells s in the U.S and Canada. using direct measurement of CH_4 emission rates and measurements from previously published work and found annual CH_4 emissions of 320 Gg/yr and 26 Gg/yr in the U.S. and Canada, respectively.

Upon extraction, the fuels are transported to refineries for processing, where compounds such as water, CO_2, hydrogen sulfides or other hydrocarbons are separated from the OG. OG refineries are major CH_4 emitting sources, which are required to report their emissions to the Greenhouse Gas Reporting Program (GHGRP; Environment and Climate Change Canada, ECCC, 2021; EPA, 2021). The GHGRP compiles annual GHG emissions from facilities emitting more than 10 kilotons $CO_{2\text{-eq}}$ from a wide range of sectors (e.g., OG processing, coal mining, pulp and paper, waste).

2.2.2. Transmission and storage

Transmission of natural gas to the distribution system or industrial end-users is achieved by a network of high-pressure pipelines, compressor stations, metering and regulation stations and storage facilities. Emissions from this sector can arise from unintentional releases of gas from connectors, valves or meters, from engine and turbine exhausts due to incomplete combustion of CH_4 or from station venting, which consists of intentionally releasing gas to depressurise the equipment. Subramanian *et al.* (2015) measured emissions from 677 transmission and below ground storage facilities in the U.S. and estimated total CH_4 emissions from the transmission and storage sector to be 1,503 Gg/yr, with fugitive emissions accounting for most emissions, followed by engine exhaust emissions and then pneumatic devices and station venting emissions. They compared their estimate to the U.S. GHG inventory estimate for transmission and storage emissions and found that the GHG inventory was overestimating emissions. This was explained by the fact that the GHG inventory used emission factor and activity data based on studies from the 1990s, whereas engines have become less emission intensive and facility counts decreased significantly in the last decades. Since then, the EPA updated their emission factor and activity data based on data from the Greenhouse Gas Reporting Program (EPA, 2021), accounting for technology advances and upgraded infrastructure (EPA, 2022)

2.2.3. Distribution and end-use

The local distribution of natural gas to end-user involves a complex network of underground pipelines (mains and service pipelines), metering and regulation stations, customer meters and finally, natural gas piping in residential and commercial buildings and natural gas appliances. Distribution sources are complex since they show a large temporal variability and distribution networks vary widely amongst cities. Top-down atmospheric measurements (McKain *et al.*, 2015) or mobile sampling methods have been employed to identify leaks (Weller *et al.*, 2020, Ars *et al.*, 2020). McKain *et al.* (2015) measured continuous atmospheric CH_4 concentration in the urban region of Boston, Massachusetts, U.S. and found an annual CH_4 emission flux of 18.5 $g/m^2/yr$, corresponding to a 2.7% natural gas loss rate and a two to three times higher estimate than the Massachusetts GHG inventory.

At the very end of the natural gas supply chain is the end user. Emissions car arise from the incomplete combustion of the fuel or from the unintentional release of CH_4 prior to combustions due to leaks in the natural gas piping leading to the appliances or in the appliance itself, commonly referred to as post-meter emissions. This segment of the supply chain is understudied, especially post-meter emissions. Only a few studies have been conducted on natural gas appliance methane emissions in North America, all in the U.S. (Fischer *et al.*, 2018, Lebel *et al.*, 2020, Merrin *et al.*, 2019) and all employing different sampling methodologies leading to high discrepancies between results. For examples, Lebel *et al.* (2020) focused on gas water heaters, whereas Merrin *et al.* (2019) investigates emissions from a range of different appliances, including water heaters, furnaces and stoves. They estimated total annual post-meter CH_4 emissions at 82.3 and 29.5 Gg/yr, respectively. In Canada, ECCC is working on including post-meter CH_4 emissions (ECCC, 2022) but Canada-specific measurements are not available in published literature.

2.3. Other environmental impacts of oil and natural gas systems

2.3.1. Air pollution

In addition to CH_4, other pollutants are released to the atmosphere by OG systems, including volatile organic compounds (VOCs), nitrous oxides (NO_x), carbon monoxide (CO), and particulate matter (PM). Air pollutants are emitted by two major sources in OG systems, namely fugitive emissions occurring prior to the combustion of the fuels and combustion by-products. Fugitive emissions are mainly CH_4 and VOCs, which are naturally occurring in OG, whereas combustion emissions include a wide range of other pollutants such as NO_x, sulfur oxides (SO_x), CO, and PM. The impacts of these pollutants, unlike CH_4, are localized, affecting the surrounding ecosystems and possibly contributing to public health impacts. Studies focusing on OG extraction sites identified VOC emissions (Hildenbrand *et al.,* 2016, Long *et al.,* 2019, Khalaj and Sattler, 2019), PM emissions (Allshouse *et al.,* 2019, Banan and Gernand, 2018, Long *et al.,* 2019), NO_x and

SO_x emissions (Islam *et al.,* 2016, Khalaj and Sattler, 2019, Long *et al.,* 2019), with only a few sites exceeding public health recommendations. Other studies have focused on compressor stations emissions, which consist mainly of NO_x, CO and VOCs (Russo and Carpenter, 2019), on refineries emitting VOCs, hydrogen sulfide (H_2S) and PM at levels not exceeding the public health recommendations (Sanchez *et al.*, 2019) or on residential appliances emitting NO_x and CO and sometimes exceeding the 1-h exposure recommendations (Mullen *et al.*, 2015, Lebel *et al.*, 2022). Moreover, studies have shown that pollutants are often co-emitted with CH_4. Therefore, high CH_4 emitters are often also releasing large amounts of air-polluting gases and particles (Oltmans *et al.*, 2016, Michanowicz *et al.*, 2021).

2.3.2. Subsurface contamination

CH_4 migration into the surrounding soil and groundwater aquifers is another environmental impact associated with OG wells. Wells can act as a subsurface leakage pathway that connects OG reservoirs to aquifers. Although CH_4 is naturally occurring in the subsurface, due to microbial methanogenesis, enhanced CH_4 concentrations in the vicinity of OG activities is often indicative of OG well leakage (Lefebvre *et al.*, 2017, Reagan *et al.,* 2015, Jackson *et al.*, 2013). Isotopic analyses of CH_4 found in the subsurface can give insight into its origin, whether biogenic (i.e., from microbial activity) or thermogenic (i.e., from OG activities) (Schoell, 1988, Whiticar, 1999, Jackson *et al.*, 2013). Well integrity failures and faulty OG wells are the major cause of leakage to the surrounding subsurface (Wisen *et al.,* 2019, Abboud *et al.,* 2021*,* Kang *et al.*, 2014, 2016, Pétron *et al.*, 2014). Even though CH_4 is not considered harmful, microbial oxidation of dissolved CH_4 can lead to iron and sulfate reduction and H_2S release, causing groundwater quality degradation (Osborn *et al.*, 2011, Jackson *et al.*, 2013, El Hachem and Kang, 2022). Other contaminants such as saline water, heavy metals and radionuclides can also leak into groundwater aquifers (Jackson *et al.*, 2013).

2.3.3. Ecosystem disturbances

OG exploration and extraction activities impact the surrounding ecosystems contributing to land cover changes, habitat degradation, biodiversity loss, and more. Even before a well is drilled, OG exploration requires vegetation clearing to give access to machinery that perform seismic exploration, which uses the reflection of sound waves by subsurface geological formations or by vibrating a heavy plate on the surface. The environmental impacts of these practices include vegetation clearing, soil compaction by the involved machineries, hydrological and thermal regime disturbance due to lower water intake, decreasing evapotranspiration, lower albedo leading to increased heat absorbance, fragmentation of the landscape leading to habitat destruction and increased risk of predation (Dabros *et al.*, 2018). Long-term remote sensing studies have been used to detect land cover and land use changes associated with OG infrastructures, such as well pads, road infrastructures, pipelines and vehicle tracks (Yu *et al.,* 2015, Unger *et al.,* 2015, Preston and Kevin, 2016). For example, Yu *et al. (*2015) used high resolution remote sensing imagery to detect land cover change over an OG producing region in Northwestern Siberia. They processed the images and derived various indexes, such as Normalized Difference Vegetation Index and albedo to detect land cover changes, and they identified and characterized linear features (e.g., roads, pipelines) and industrial facilities to link them to anthropogenic disturbances. They attributed a total reduction in vegetated area of 9.1% to OG related developments that happened in the study region between 1986 and 2006. In addition to all the direct impacts of OG development on surrounding ecosystems, the large amounts of GHG emissions contribute to global climate warming, intensifying natural and anthropogenic disturbance regimes.

3. Oil and natural gas wells across the ABoVE domain: fugitive methane emissions and broader environmental impacts

3.1. Introduction

Arctic-boreal regions are experiencing intensifying disturbance regimes through accelerating climate change and anthropogenic activities (Foster *et al.*, 2022). Large numbers of oil and natural gas (OG) wells have been drilled and are being drilled in these regions. The direct and indirect impacts of OG drilling include emissions of methane (CH_4), physical ecosystem disturbance due to the clearing of vegetation, soil compaction, air quality degradation from emissions of volatile organic compounds (VOCs), nitrous and sulphur oxides (NO_x and SO_x), and soil and groundwater contamination due to leaks of saline water, various hydrocarbons and/ or radionuclides (Dabros *et al.*, 2018; Rice *et al.*, 2018; Kang *et al.*, 2021; El Hachem and Kang, 2022). These impacts of OG wells can occur at every phase of their development from OG exploration, pad preparation, drilling, and production (Dabros *et al.*, 2018; Brandt *et al.*, 2014; Alvarez *et al.*, 2018), and do not necessarily cease with OG well abandonment (Kang *et al.*, 2014; Jackson *et al.*, 2020; Williams *et al.*, 2021; Lebel *et al.*, 2020). Here, we consider OG wells as anthropogenic disturbances themselves, but also as a potential source of fugitive CH_4 emissions to the atmosphere and a proxy for broader OG development related disturbances (e.g., access roads, waste handling and disposal, processing).

Focusing on western North America, the NASA Arctic-Boreal Vulnerability Experiment (ABoVE) aims to provide a mechanistic understanding of rapidly changing Arctic and boreal biomes, and their present and future ecosystem services (Fischer *et al.*, 2018; Miller *et al.*, 2019). A recent study found that 13.6% of the ABoVE Core Domain ("ABoVE domain", Figure 3.3) experienced a shift in land cover type between 1984 and 2014 (Wang *et al.*, 2020). Two dominating modes of land cover change have been identified, namely a notable loss in "Evergreen Forest" and gain in "Deciduous Forest" classes in the boreal biome, and gains in "Shrubland" and "Herbaceous" classes in the Arctic biome. Wildfire and climate change were identified as the main causes of these land cover changes, respectively, both with non-negligible local, regional and global consequences. However, the role of OG wells, and of OG development more broadly, in these land cover changes remains largely understudied.

A large portion of the ABoVE domain is underlain by permafrost, i.e., perennially frozen ground (Biskaborn *et al.*, 2019; Gruber, 2012). In northern Canada, permafrost temperatures are rising at rapid rates of 0.1 to 0.5 ˚C per decade, leading to a deepening of the hydrologically and biogeochemically active layer and to changes in land cover types (Derksen *et al.*, 2019; Fraser *et al.*, 2018). Collectively, such drastic changes in landform and/ or land cover affect many physical, ecological, and biogeochemical processes governing ecosystem composition, structure, functioning and services (Schuur *et al.*, 2015; Dabros *et al.*, 2018; Turestsky *et al.*, 2020). How these Arctic-boreal region-specific processes may be additionally influenced by anthropogenic activities and infrastructures, such as OG wells, remains largely unknown (Foster *et al.* 2022).

Up to 26% of OG wells in Canada and the U.S. have well integrity failures that result in leakage (Wisen *et al.*, 2020; Abboud *et al.*, 2021; Lackey *et al.*, 2021). Permafrost thaw can lead to ground surface subsidence and collapse of soil structures (“thermokarst”), causing additional stress on the OG wells (Vaganova *et al.*, 2015; Lukyanov *et al.*, 2019; Mikhienkova *et al.*, 2020), potentially affecting the well integrity and creating additional pathways for fugitive CH_4 emissions and contaminants (Figure 3.1). At the same time, OG wells may alter the thermal regime of their direct surroundings due to heat release from various well components, which may accelerate permafrost thaw (Figure 3.1; Vaganova *et al.*, 2015; Lukyanov *et al.*, 2019; Mikhienkova *et al.*, 2020). This is especially true during the OG well drilling process, where warm mud is used to drill into the frozen ground, creating a thawed zone of up to 10 m radius in the direct vicinity of the borehole (Eppelbaum *et al.*, 2019; Chuvilin *et al.*, 2022). Overall, how OG wells and their direct surroundings may interact with permafrost thaw, exacerbate leakage and associated environmental and ecosystem impacts is currently understudied.

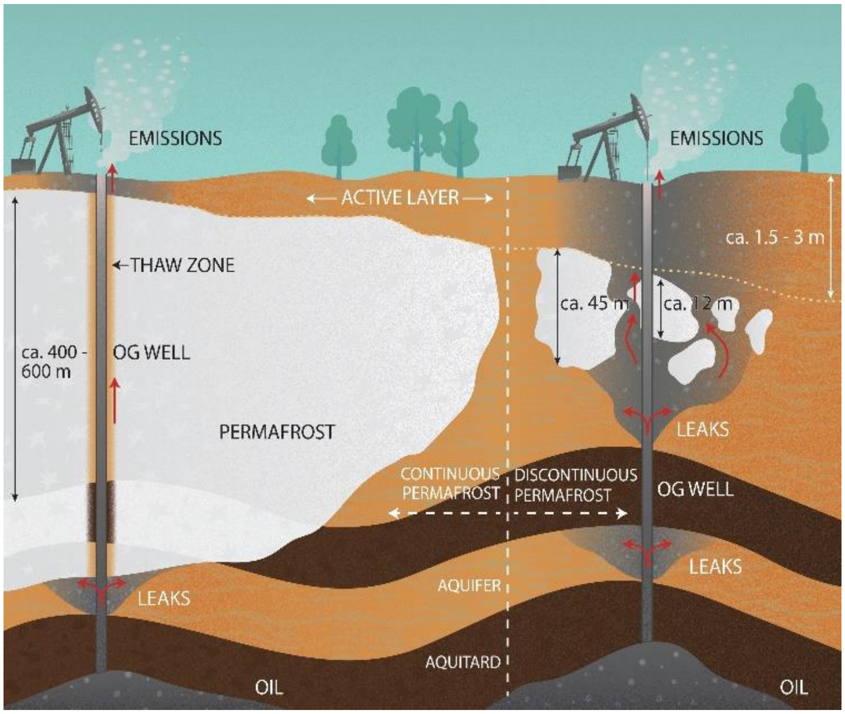

Figure 3.1 Schematic of oil and gas (OG) well and permafrost interactions in the subsurface (Figure by: Cory Anne Michelle Savage)

Oil and natural gas wells represent a major source of CH_4, a short-lived but potent greenhouse gas (GHG) with a global warming potential of 82.5 over a 20-year time frame (Forster *et al.*, 2021). Several studies have quantified CH_4 emissions from the OG sector and have shown that current national GHG inventories are likely underestimating emissions from OG wells (Lyon *et al.*, 2021; MacKay *et al.*, 2021; Johnson and Tyner, 2021; Alvarez *et al.*, 2018). Fugitive OG well CH_4 emissions arise from venting and flaring processes, as well as from leakage from OG well infrastructure (Zavala-Araiza *et al.*, 2018; Omara *et al.*, 2016; Kang *et al.*, 2021). When an OG well is no longer economical to operate, OG production stops and the well is abandoned. State, provincial, and territorial regulations require the plugging of abandoned OG wells, which involves isolating groundwater aquifers and OG reservoirs through cementing (King and Valencia, 2014). Methane emissions from active and inactive/ abandoned OG wells remain highly uncertain, but were estimated to account for 32.6% and 19.3% of the national anthropogenic CH_4 emissions in Canada and the U.S., respectively (Environment and Climate Change Canada, ECCC, 2022; U.S. Environmental Protection Agency, EPA, 2022). These emission estimates include emissions from OG wells and supporting infrastructure (e.g., batteries, storage tanks, pneumatic devices). Given the uncertainties in CH_4 emissions from OG wells, the availability of technical and economical mitigation options (Ocko *et al.*, 2021) and the potential for CH_4 emissions to serve as a proxy for broader environmental impacts, it is important to quantify CH_4 emissions from OG wells for the ABoVE domain.

The goal of this study was to identify OG well site locations in the ABoVE domain in the context of climate change-induced land cover change, permafrost thaw, and potentially non-negligible contributions to the atmospheric CH_4 burden. To meet this goal, we compiled publicly available information on active and abandoned OG well site locations and characteristics (i.e., production type, drilling date) to map OG well distribution across the ABoVE domain over time in relation to land cover change occurring between 1984 and 2014. We also evaluated OG well site locations with respect to permafrost distribution in 2012. In addition, we estimated annual CH_4 emissions from active and abandoned OG wells in the ABoVE domain in 2018 using a gridded national inventory of anthropogenic CH_4 emissions (Scarpelli *et al.*, 2021) and published emission factors for OG wells (Williams *et al.*, 2021).

3.2. Material and methods

3.2.1. Oil and natural gas well database for the ABoVE domain

We collected publicly available information on drilled OG wells in six Canadian Provinces and Territories, namely Alberta, British Columbia, Manitoba, Saskatchewan, the Northwest Territories, and the Yukon, as well as in one U.S. state, Alaska. (Table S1, SI-4). Each jurisdiction provides some information on well status (i.e., active, abandoned not plugged, abandoned and plugged) and well production type (i.e., gas producing, OG producing or unknown) (Kang *et al.*, 2021). However, the databases are often missing some attributes and employ differing terms to describe the OG wells. We carefully screened them to develop a harmonized OG well database with common terminology for well status, type and drilling date (SI-1 in Annex).

3.2.2. Oil and natural gas well distribution across the ABoVE domain

We mapped OG wells according to their drilling date between 1984 and 2014 on the permafrost zonation index, an indicator of permafrost occurrence probability (PZI; Gruber, 2012) and a recent land cover and land cover change data product (1984-2014) for the ABoVE domain (Wang *et al.*, 2020).

3.2.2.1. Oil and natural gas wells and permafrost

We classified the PZI raster dataset into four permafrost zones (Helbig *et al.*, 2016), i.e., isolated (PZI < 0.1), sporadic (0.1 <= PZI < 0.5), discontinuous (0.5 <= PZI < 0.9) and continuous (PZI >= 0.9), and derived OG well counts in each of them. Since the map was published in 2012, only OG wells drilled up to 2012 were included in this count.

3.2.2.2. Oil and natural gas wells and land cover

Wang *et al.* (2020) used Landsat satellite imagery to detect breaks in land surface reflectance and assign land cover labels to statistical clusters of stable land cover over 1984 to 2014. The ABoVE domain was classified into 15 domain-specific land cover classes, further simplified into 10 classes (Table S3, SI-4). For each year between 1984 and 2014, we mapped the annual number of drilled OG wells onto the simplified land cover map of the given year. We extracted the land cover class at each OG well site location to investigate in which land cover class OG wells were drilled and how annual OG well drilling changed over the years in each class.

3.2.3. Fugitive methane from emissions from oil and natural gas wells

For comparison purposes, we focused only on the Canadian portion of the ABoVE domain (excluding Alaska) when estimating CH_4 emission from OG wells. We extracted annual fugitive CH_4 emissions from active and inactive/ abandoned OG wells in this domain from the Canadian gridded inventory (Scarpelli *et al.*, 2021). To provide context for OG well CH_4 emissions, we also extracted CH_4 emissions from high GHG emitting facilities reported in the Canadian GHGRP (ECCC, 2019), which compiles annual GHG emissions from facilities emitting more than 10 kilotons $CO_{2\text{-eq}}$ across various sectors, and wetland emissions from the global WetCHARTs data product (Bloom *et al.*, 2021).

For all these data sources, we clipped out the contributions from the Canadian portion of the ABoVE domain for the year 2018.

Additionally, we estimated CH_4 emissions from abandoned OG wells in the domain by multiplying the number of OG wells drilled up to 2018 with published emission factors developed for abandoned OG wells (SI-2, Williams *et al.*, 2021). Canada-wide estimates of abandoned OG well CH_4 emissions for the year 2018 were retrieved from Williams *et al.* (2021) and the Canadian National Inventory Report (ECCC, 2022).

3.3. Results

3.3.1. Oil and natural gas well database

The total number of OG wells drilled in the ABoVE domain was 242,007 as of 2018. The majority were located in Alberta (n = 204,496) and British Columbia (n = 29,502) (Table S5, SI-4). 6,778, 654, 501 and 76 OG wells were located in Alaska, the Northwest Territories, Saskatchewan and the Yukon, respectively. In Manitoba, no OG wells were located inside the ABoVE domain. Oil and natural gas wells in the ABoVE domain accounted for more than 30% of all OG wells in Canada (n = 787,553; Kang *et al.*, 2021). 63% of all reported OG wells were abandoned (n = 152,790) and 19% of abandoned OG wells were unplugged (n = 29,582). The highest proportion of unplugged OG wells was found in British Columbia (30% of all abandoned OG wells were unplugged) and all abandoned OG wells in Saskatchewan were plugged. Most active OG wells were gas producing (30%), compared to 20% of OG producing wells and 50% of wells with unknown fluid production type. As for abandoned OG wells, 24% were gas producing, 15% were OG producing and 61% were of unknown fluid type.

3.3.2. Oil and natural gas well distribution across the ABoVE domain

A substantial increase in drilled OG wells occurred during the 2000's, with OG wells drilled annually in British Columbia and Alberta increasing from around 400 to 700 in the 1980s and 1990s to 2000 to 7000 in the 2000s (Figure 3.2). As of 2014, 61% of the OG wells were abandoned, of which 20% were left unplugged.

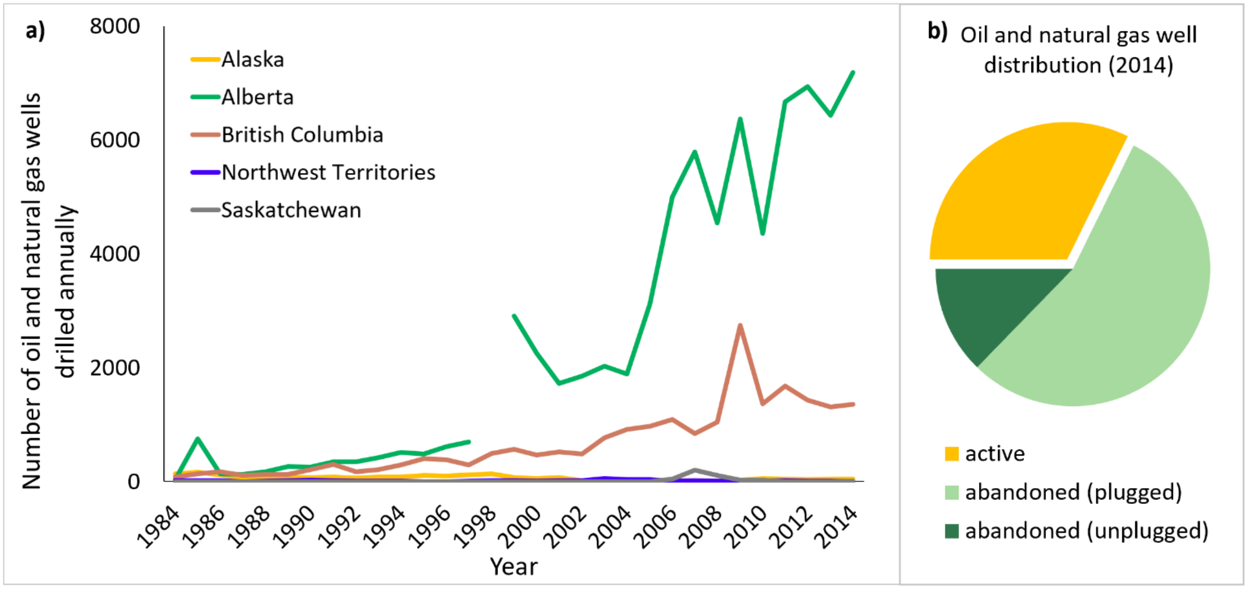

Figure 3.2 a) Oil and natural gas well drilling in the ABoVE Core Domain in each province/ state/ territory from 1984-2014, and b) distribution of oil and natural gas wells drilled before and in 2014. No information on drilling date was included in the Yukon well database.

3.3.2.1. Oil and natural gas wells and permafrost

In 2012, 37% of the ABoVE domain was underlain by continuous permafrost, whereas 24%, 24% and 7% was underlain, from north to south, by discontinuous, isolated and sporadic permafrost, respectively (Figure 3.3). However, most OG wells were located in the permafrost-free portion of the ABoVE domain (n = 146,242; 69%). Nevertheless, 65,588 OG wells were located in permafrost zones, of which 24% were located in the sporadic permafrost zone, followed by the isolated (4%) and continuous (3%) and discontinuous (<1%) permafrost zones (Figure S1, SI-5).

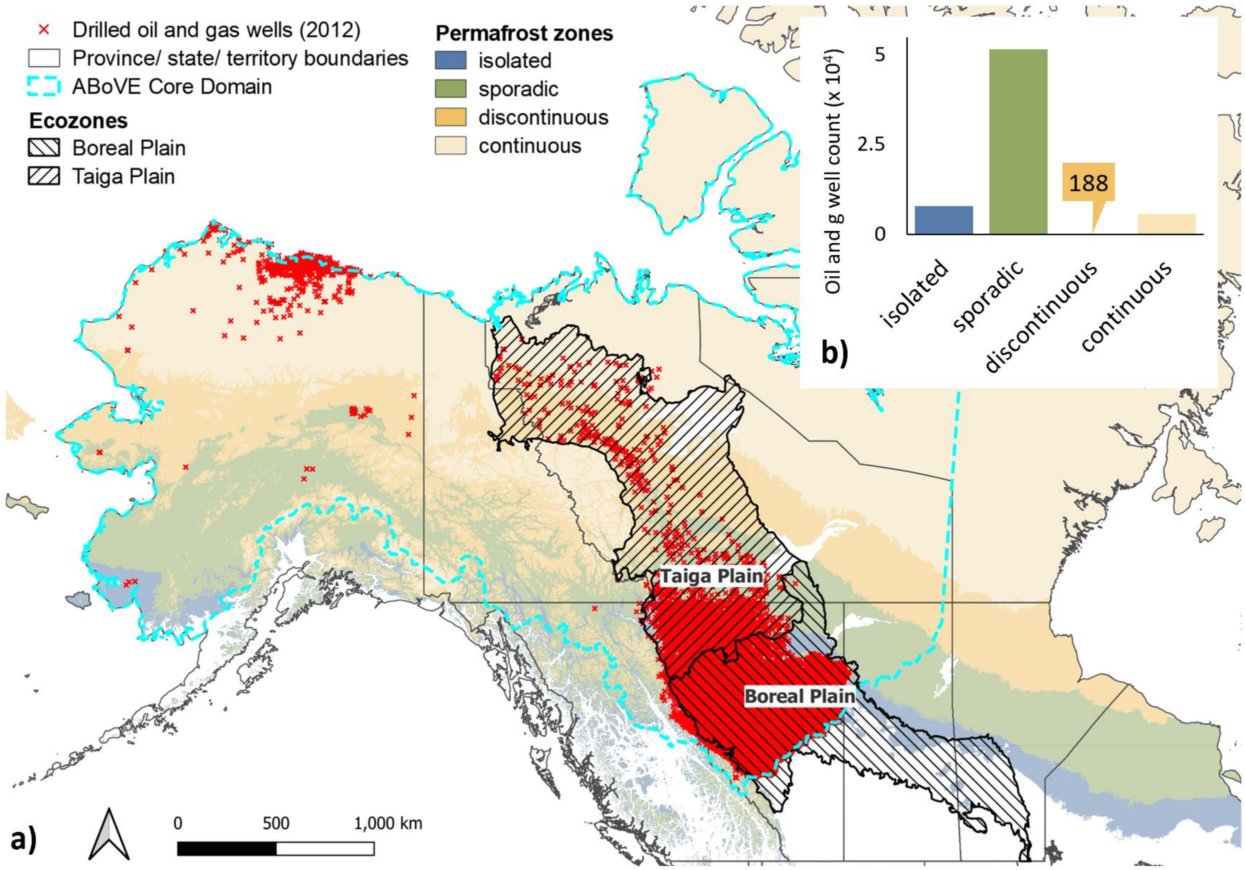

Figure 3.3 a) Oil and natural gas wells in the ABoVE domain in different permafrost zones (derived from the Permafrost Zonation Index [PZI]; Gruber, 2012), i.e., isolated PZI < 0.1, sporadic 0.1 <= PZI < 0.5, discontinuous 0.5 <= PZI < 0.9, continuous 0.9 <= PZI) in 2012 (Coordinate System: WGS 84/ Pseudo-Mercator), b) Oil and natural gas well counts in each permafrost zone in 2012.

3.3.2.2. Oil and natural gas wells and land cover

Between 1984 and 1999, the number of OG wells drilled in the ABoVE domain was generally less than 500 per year. Most OG wells in the 1980s and 1990s were drilled in “Herbaceous”, “Sparsely Vegetated” and “Barren” classes. A continued increase in the number of annually drilled OG wells started in the early 2000s, with around 1,000 to 2,000 OG wells drilled per year in the previously mentioned land cover classes. Starting in 2006, annual OG well drilling in the “Evergreen Forest” class increased, overtaking “Barren” and “Sparsely Vegetated” classes. The “Deciduous Forest” class also underwent a significant increase in drilled OG wells from 2009 to 2014. We found a large increase in OG wells drilled between 1984 to 1999 and 2000 to 2014 in “Evergreen Forest” (+7274 or +204%), as well as in “Sparsely Vegetated” (+12347 or +253%) and “Barren” (+14156 or +349%) classes (Figure 3.4).

Since most OG wells in the ABoVE domain were located in the Boreal Plain and Taiga Plain ecoregions (97%), we performed a similar analysis of OG well drilling over the years focusing on these two North American Level II Ecoregions (U.S. EPA, 2010). In the ABoVE domain, 86% and 8% of OG wells were drilled are in the Boreal Plain and Taiga Plain ecoregions, respectively. Investigating the increase in OG wells drilled between 1984 and 2014 in these ecoregions, the most notable increases were seen in the “Evergreen Forest” (+304% and +194%), “Sparsely Vegetated” (+294% and +267%) and “Barren” (+398% and +420%) classes (Figure 3.4).

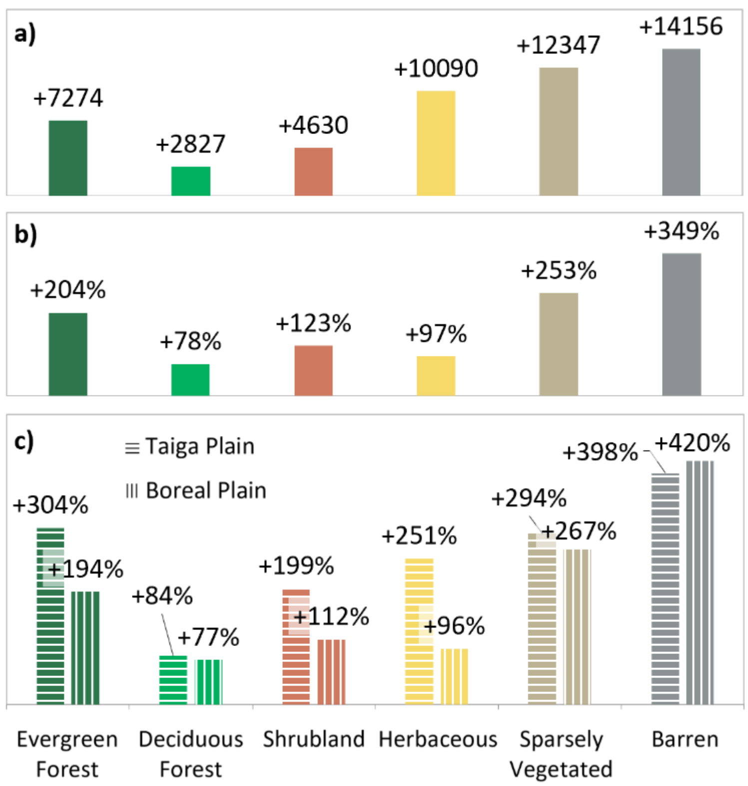

Figure 3.4 a) Increase in the number of oil and natural gas wells drilled across the ABoVE Core Domain, b) Percentage increase in oil and natural gas wells drilled across the ABoVE Core Domain, c) percentage increase in oil and natural gas wells drilled in the Taiga Plain and Boreal Plain Ecoregions between 1984-1999 and 2000-2014 by land cover class (“Evergreen Forest”, “Deciduous Forest”, “Shrubland”, “Herbaceous”, “Sparsely Vegetated” and “Barren”) after Wang *et al.* (2020).

3.3.3. Fugitive methane from emissions from oil and natural gas wells

Using published emission factors (Williams *et al.*, 2021), we found that abandoned OG well CH_4 emissions ranged from 0.003 Tg CH_4 (minimum emission factor, "method 1") to 0.018 Tg CH_4 (maximum emission factor, "method 2") in the ABoVE domain. Methane emissions from unplugged OG wells accounted for 60 to 65% of emission from all abandoned OG wells, even though unplugged OG wells represented only 20% of abandoned OG wells. Methane emission estimates from abandoned OG wells in the ABoVE domain alone corresponded to 32-183% of the Canadian nationwide estimate for abandoned OG wells in 2018 (0.01 Tg CH_4; ECCC, 2022) (Figure 3.5a).

Annual CH_4 emissions from all OG wells (active and inactive/ abandoned) in the ABoVE domain retrieved from a gridded emissions inventory for Canada (Scarpelli *et al.*, 2021) were 0.48 Tg CH_4, accounting for 13% of the total anthropogenic CH_4 emissions in Canada (Figure 3.5b). Abandoned OG well CH_4 emissions in the ABoVE domain were 0.00237 Tg CH_4 (Scarpelli *et al.*, 2021), which is 35-671% lower than the estimate of abandoned OG well CH_4 emissions in this study (0.003-0.018 Tg CH_4).

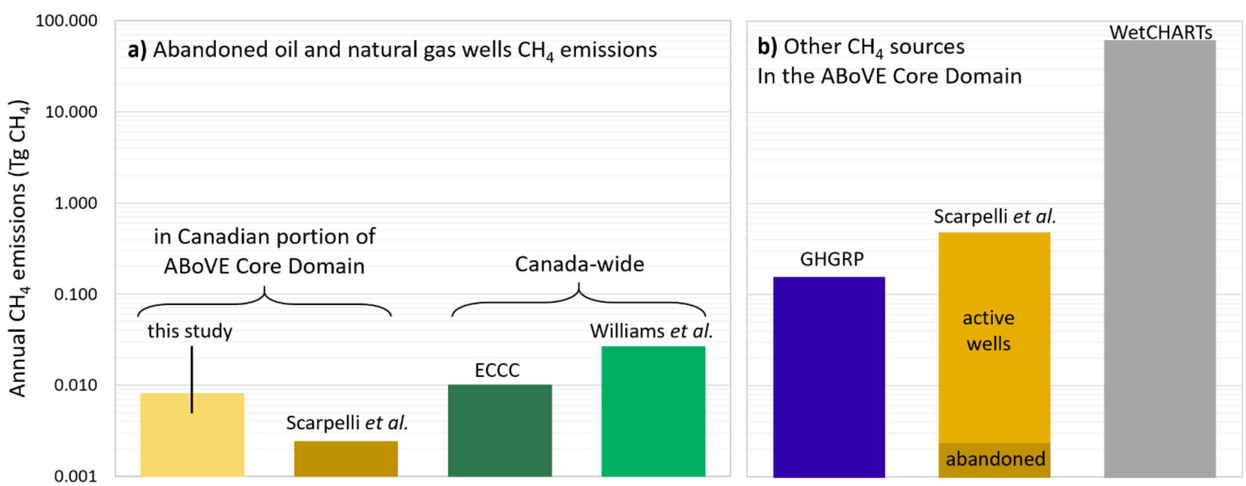

Figure 3.5 Annual methane (CH_4) emissions estimates from: a) Abandoned oil and natural gas wells (Scarpelli *et al.,* 2021; Environment and Climate Change (ECCC), 2019; Williams *et al.,* 2021) and b) Other sources inside the ABoVE Core Domain: facilities emitting more than 10kt $CO_{2\text{-eq}}$ (GHGRP), active and abandoned oil and natural gas wells (Scarpelli *et al.*, 2021) and wetlands (Bloom *et al.*, 2021).

Methane emissions from all OG wells in the ABoVE domain, retrieved from the Canadian gridded inventory (Scarpelli *et al.*, 2021) were 213% higher than the GHGRP reported emissions occurring inside the ABoVE domain, amounting to 0.153 Tg CH_4

(Figure 3.5b). In 2018, annual wetland CH_4 emissions (WetCHARTs) for the ABoVE domain were 61 Tg CH_4 (Figure 3.5b).

3.4. Discussion

3.4.1. Oil and natural gas well distribution across the ABoVE domain

We identified more than 242,007 OG wells drilled in the ABoVE domain as of 2018. The Boreal Plain and Taiga Plain ecoregions correspond approximately with the central and northern portions of the Western Canadian Sedimentary Basin, one of the world's largest OG-producing basins (MacKay and Pedersen, 2022). Oil and natural gas well drilling has been ongoing in the Western Canadian Sedimentary Basin since the early 1900s (Gray, 2005), and the rate of OG well drilling has increased each year, reaching up to 9,000 annually drilled OG wells in the early 2010s. From 2017 to 2020, approximately 4,000 to 5,000 wells were drilled annually in the ABoVE domain. It is important to note that our OG well database was developed based on publicly available well databases published by each state, province and territory. The databases include geographic coordinates but do not specify the precision and accuracy of these coordinates, which can become problematic when comparing OG well site location datasets to other spatial data products. Therefore, there is a need for field-based studies to verify site locations and improve OG well databases.

3.4.2. Impacts of oil and natural gas wells on ecosystems across Arctic-Boreal regions are understudied

The Arctic and boreal region of western North America is especially vulnerable to disturbances and is experiencing fundamental land cover changes (Carpino *et al.*, 2021; Wang *et al.*, 2020). Most OG wells were drilled in the "Evergreen Forest", "Sparsely Vegetated" and "Barren" classes (Figure 3.4). Wang *et al.* (2020) reported a significant loss of the "Evergreen Forest" class attributed mainly to the changing fire regimes, but the contribution of OG activities to this loss remains unclear. Moreover, 91% of the ABoVE domain is underlain by permafrost and 65,588 active and inactive/ abandoned OG wells were located in permafrost zones in 2012. Permafrost is thawing at rapid rates (Biskaborn *et al.*, 2019). The resulting landform and/ or land cover changes might affect active and abandoned OG well integrity, causing leakage of CH_4 and other contaminants to the surrounding soil, groundwater and atmosphere (Figure 3.1).

3.4.3. Methane emissions from oil and natural gas wells are often underestimated

Oil and natural gas wells emit non-negligible quantities of fugitive CH_4 emissions to the atmosphere (Zavala-Araiza *et al.*, 2018; Omara *et al.*, 2016; Kang *et al.*, 2021). Active and inactive/ abandoned OG well CH_4 emissions in the Canadian portion of the ABoVE domain accounted for 13% of the total anthropogenic CH_4 emissions in Canada in 2018. However, current fugitive CH_4 emission estimates from OG wells in national inventories do not consider the potential role of enhanced emissions from permafrost thaw leading to preferential migration and additional fugitive emissions from OG wells.

Moreover, 63% of all drilled OG wells in the ABoVE domain were abandoned in 2018 but may continue to emit CH_4. Plugged OG wells generally emit less CH_4 than unplugged OG wells (Kang *et al.*, 2016; Saint Vincent *et al.*, 2020); however, many abandoned OG wells remain unplugged, were plugged improperly or were abandoned before modern plugging technology and regulations became available (King and Valencia, 2014). To derive our estimate of CH_4 emissions from abandoned OG wells, we characterized the wells (e.g., well production type, status, drilling date) in the public well databases from a wide range of employed terminologies. However, a large proportion of OG wells in the ABoVE domain had unknown production type (60%). Improved record-keeping of OG well characteristics such as well production type, drilling date, abandonment date (when applicable) or geographical coordinates is necessary to derive accurate OG well CH_4 emission estimates and to understand the broader environmental impacts of these wells.

3.5. Conclusion

The southern portion ABoVE domain is a major OG producing region, with 242,007 OG wells drilled as of 2018. Most of the wells were drilled in “Evergreen Forest”, “Sparsely Vegetated” and “Barren” classes, suggesting that OG activities might be contributing to land cover changes in the ABoVE domain, particularly to “Evergreen Forest” class loss. We found that about 65,588 OG wells were drilled in permafrost in 2012, which covers 91% of the ABoVE domain. Potential interactions between OG wells and permafrost, such as the presence of a thawed zone or thermokarst formation in the direct surrounding of the OG well, can release heat or additional stress on OG wells. We found that fugitive CH_4 emissions from OG wells in the Canadian portion of the ABoVE domain accounted for 30% of the total anthropogenic CH_4 emissions in Canada and may be an important consideration in evaluating CH_4 emissions for all sources in the ABoVE region. This study provides evidence for an overlooked anthropogenic disturbance type that appears to exacerbate the rapid changes occurring across ecosystems in some portions of the Arctic and boreal region of western North America.

Data availability statement

The data supporting the findings of this work are available upon request to the athors

Ethics statement

This work does not contain any studies involving human or animal participants.

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4. Methane emissions from commercial and residential post-meter sources: testing in a controlled setting and field-based screening

4.1. Introduction

In 2021, Canada pledged to reduce its greenhouse gas (GHG) emissions by 40 to 45% below 2005 levels by 2030 (Environment and Climate Change Canada, 2022a). Although carbon dioxide (CO_2) is often at the forefront of global warming mitigation strategies, a recent report published by the Climate and Clean Air Coalition found that a 45% reduction in methane (CH_4) emissions by 2030 could avoid a 0.3°C increase in warming by 2040 (Ravishankara *et al.,* 2021). Methane is a short-lived but potent GHG with a global warming potential of 86−125 over a twenty-year period (Ravishankara *et al.,* 2021). Therefore, reductions in CH_4 emissions can contribute to limiting global warming, especially in the short term. As part of the Global Methane Pledge, Canada committed to reducing their oil and natural gas (OG) CH_4 emissions by at least 75% below 2012 levels by 2030 (Environment and Climate Change Canada, 2022a). The OG sector is a major source of CH_4 emissions, accounting for 45% and 22% of total anthropogenic CH_4 emissions in Canada and globally, respectively (Saunois *et al.*, 2020, Scarpelli *et al.,* 2021). Methane leaks can occur at every step of the OG supply chain, from production to processing, transmission, storage distribution and end use. Therefore, all OG CH_4 emission sources need to be identified, measured and quantified to develop and implement actionable emissions mitigation strategies.

The end-use segment of natural gas systems is a substantial contributor of CH_4 emissions but remains poorly quantified (Saint-Vincent and Pekney, 2020). Methane emissions can arise from incomplete combustion of the natural gas fuel, leading to some CH_4 remaining in the exhaust flue gas released through the exhaust vent of the appliances, or can occur prior to fuel combustion, from leaks in natural gas piping (including supporting infrastructure, e.g., regulators, fittings, valves) or natural gas appliances themselves. These latter emissions are referred to as fugitive post-meter emissions.

There are three published measurement studies focusing on CH_4 emissions from the end-use of natural gas in North America, all conducted in the U.S. and employing different methodologies to quantify emissions (Fischer *et al.*, 2018; Lebel *et al.* 2020; Merrin *et al.,* 2019). All three studies found similar emission trends but their estimates of annual CH_4 emissions differed widely. For example, Fischer *et al.* (2018) measured whole-house emissions while all natural gas appliances were turned off, using a mass balance approach and measured CH_4 and CO_2 concentrations in appliance exhaust gases during appliance operation. They found whole house emissions from single-family detached homes with at least two natural gas appliances ranging from 0 to 37 g/day CH_4, with a median value of 2.1 g/day. Most natural gas appliances exhibited no CH_4 enhancement during operation and CH_4 depletion was even measured due to consumption of ambient CH_4 as fuel by the appliance. Fischer *et al.* (2018) estimated California-wide residential CH_4 emissions at 35.7 Gg/yr, corresponding to 15% of natural gas related CH_4 emissions and 2% of total CH_4 emissions in California. The other studies measured CH_4 and CO_2 concentrations throughout the operational cycle of residential natural gas appliances, namely ignition, steady-state operation, extinguishment and steady-state off phases. To derive an emission rate, the measured CH_4 concentration was multiplied either by the high flow blower rate (Lebel *et al.,* 2020) or by an estimated exhaust flow rate based on the natural gas consumption of the individual appliances (Merrin *et al.*, 2019). Both studies found similar emission patterns, namely relatively low and steady emissions during operation and cool down phases and emission peaks during ignition and extinguishment of the appliance. All studies found differences in emission rates depending on the appliance type (boiler, furnace, storage water heater, tankless water heater, stoves), amplifying the importance of developing technology-specific emission factors. Combining the emission factors with natural gas consumption and appliance usage data, U.S. annual emissions were estimated by Lebel *et al.* (2020) and Merrin *et al.* (2019) at 29.5 Gg/yr (all natural gas appliances) and 82.3 Gg/yr (only gas water heaters), respectively. The high variability in the results of the U.S. studies indicate the need to compare methodologies and strategies for measuring natural gas appliance CH_4 emissions and to make measurements at additional sites to obtain a more representative sample of emission rates.

In previous studies (Fischer *et al.*, 2018; Merrin *et al.* 2019; Lebel *et al.* 2020; Saint-Vincent and Pekney, 2020), measurements were conducted on residential grade natural gas appliances in households. Even though commercial and residential natural gas appliances operate similarly, the size, heating capacity and natural gas consumption of the equipment can differ, which can translate to different emission regimes. Additionally, there are currently no published measurements of CH_4 emissions from post-meter CH_4 emissions in Canada. Given the differences in heating requirements and appliance use patterns between countries, there is a need to derive Canada-specific emission factors, in addition to technology- and infrastructure-specific emission factors for natural gas appliance emissions.

In this paper, we reviewed natural gas end-use CH_4 emission estimate methods in national greenhouse gas inventories and we developed and compared measurement strategies for these emission sources. First, we performed controlled releases of CH_4 to test the accuracy of the HETEK Flow Sampler (HETEK Solutions Inc., London, Ontario, Canada) at various CH_4 concentrations and CH_4 emission flow rates. The HETEK Flow Sampler is the most recent commercially available high flow sampling instrument. In the past, only the Bacharach Hi-Flow Sampler (Bacharach Inc., New Kensington, Pennsylvania, United States) was available, however a few studies have raised concerns about the efficiency of the Bacharach instrument (Connelly *et al.*, 2019; Ramon *et al.*, 2016; Howard *et al.*, 2015). Second, we performed direct measurements of CH_4 emissions on natural gas appliances, natural gas piping and appliance exhaust vents, employing three emission quantification methodologies, namely concentration screening, high flow sampling and the static chamber method. We conducted leak detection and site assessments in the boiler room of four McGill student residences and measured CH_4 emissions using concentration screening, high flow sampling, and chambers to evaluate emission rate patterns at 14 natural gas appliances and exhaust vents at the Ecole de Technologie Gazière (ETG). These measurements were used to evaluate the methods for measuring natural gas piping and appliance leaks (i.e., post-meter emissions), as well as incomplete combustion emissions occurring at the exhaust vents of the natural gas appliances. The results of our study provide the foundation for accurate measurements of CH_4 emissions from these sources in Canada and elsewhere.

4.2. Methods

4.2.1. Controlled release testing of the HETEK Flow Sampler

We performed controlled CH_4 releases at 10 CH_4 flow rates and four CH_4 concentrations to test the performance of the HETEK Flow Sampler. Even though natural gas is mainly comprised of CH_4, incomplete combustion emissions occurring at the exhaust vents of the natural gas appliances can be of various CH_4 concentrations. The instrument samples point sources at high flow rates (~11,808 g/hr or 300 slpm) to ensure the complete capture of the leak. The sensor measures CH_4 concentrations employing two modes, depending on the CH_4 concentration of the gas sample: catalytic oxidation for 0 to 5% by volume CH_4 or thermal conductivity for 5 to 100% by volume CH_4. The leak rate is derived by the instrument based on Equation 4.1, where Q_{leak} is the leak flow rate, Q_{blower} the blower flow rate of the instrument, C_{leak} the sample CH_4 concentration and C_{bkg} the background CH_4 concentration.

$$Q_{leak}\ [lpm] = Q_{blower}\ [lpm] * \left(C_{leak}\ [\%] - C_{bkg}\ [\%]\right) * 10^{-2} \qquad \text{(Eq. 4.1)}$$

The HETEK Flow Sampler has a lower detection limit of 18.3 g/hr (0.495 slpm), based on testing performed by the manufacturer (HETEK Solutions Inc., London, Ontario, Canada) and the Methane Emissions Technology Evaluation Center (METEC). To ensure the quality of the collected sample, the instrument performs a two-staged test, consisting of repeating the sampling at two different blower flow rates and comparing results. The maximum blower flow rate is 12,044 g/hr (306 slpm, at full battery charge) and the second blow rate is typically 70-80% of the first measurement and is selected automatically by the instrument. Equation 4.2 is used to derive the two-staged test accuracy ($2ST_{accuracy}$) of the measurement:

$$2ST_{accuracy}\ [\%] = \left|\frac{Q_{leak2} - Q_{leak1}}{Q_{leak2}}\right| * 100 \qquad \text{(Eq. 4.2)}$$

where Q_{leak1} and Q_{leak2} are the leak flow rates measured at the two blower flow rates. If the two-staged test accuracy is higher than 10%, the measurement is considered erroneous by the instrument.

Using a mass flow controller, we controlled the flow rate at which CH_4 gas standards with CH_4 concentrations ranging from 5 to 100% (Linde) were released. We tested two different CH_4 flow rate ranges, namely high flow rates (2,360 to 5,510 g/hr or 60 to 140 slpm of CH_4) and low flow rates (17.7 to 197 g/hr or 0.45 to 5 slpm of CH_4). During previous testing, the instrument exhibited low accuracy for flow rate above ~2,500 g/hr CH_4 (63.5 slpm). Because a correction was made to the firmware by the manufacturer since the previous testing, we tested these high flow rates after the correction. For the HETEK Flow Sampler to work, the total volumetric flow rate of the sample must be less than the blower flow rate. At the high flow rate ranges, we only released 50% and 100% CH_4 gases, at 120 to 280 slpm of 50% CH_4 gas and 60 to 140 slpm of 100% CH_4 gas. Using lower concentration gas requires very high volumetric flow rates (600 to 1400 slpm for 10% CH_4 gas and 1200 to 2800 for 5% CH_4 gas), which would exceed the HETEK Flow Sampler blower flow rate (maximum of 306 slpm). The low flow rates were selected based on the lower detection limit of the instrument provided by the manufacturer (18.3 g/hr or 0.465 slpm of CH_4) and CH_4 calibration standards with concentrations ranging from 5 to 100% CH_4. We calculated the absolute relative error of the controlled releases based on Equation 4.3, where the known flow rate is controlled by the mass flow controller and Q_{leak1} and Q_{leak2} are the leak flow rates measured by the HETEK Flow Sampler at the two blower flow rates.

$$Relative\ error\ [\%] = \frac{Known\ flow\ rate - \frac{Q_{leak1}+Q_{leak2}}{2}}{Known\ flow\ rate} \quad \text{(Eq. 4.3)}$$

To investigate how HETEK Flow Sampler accuracy related to the sample CH_4 concentration or flow rate, we derived mean absolute relative error by combining measurements performed at each concentration and flow rate. We calculated this mean by taking all the measurements into account (M1), as well as by excluding the measurements considered erroneous by the instrument (M2). By calculating both M1 and M2, we wanted to investigate the influence of erroneous measurements on the overall accuracy.

4.2.2. Leak detection and scoping visits at McGill student residences

We visited four McGill student residences in Downtown Montréal, Québec, Canada (Table 4.1), where we got access to the mechanical rooms as well as the exhaust vents of the natural gas appliances, located either on the roofs or outside facades of the buildings. We got access to nine water heaters (seven commercial and two residential grade) and three space heaters (one commercial boiler and two residential furnaces) (Table 4.2). First, we noted various attributes of the natural gas appliances (e.g., brand, model, appliance type and grade, heating capacity, size). We then screened the natural gas appliances, the surrounding natural gas piping components (e.g., flanges, fittings, regulators) and exhaust vents using the SENSIT Portable Methane Detector (SENSIT Technologies, Valparaiso, Indiana, United States) to identify potential leakage points and evaluate measurement approaches.

Table 4.1: McGill student residences specifications

Name of residence	Number of residents	NG Usage	Number of gas appliances in the mechanical room	Exhaust vent location
La Citadelle	286	68,153	4	No easy access
Carrefour Sherbrooke	346	125,459	3	Roof
Greenbriar	68	119,652	2	Roof
ECOLE	10	6,658	2	Front facade

4.2.3. Emission measurements at Ecole de Technologie Gazière

We measured CH_4 emissions from natural gas piping and appliance exhaust vents at ETG, a training center and laboratory run by Énergir, the main natural gas distribution company in Montreal, Quebec, Canada. They have a wide range of residential and commercial grade natural gas appliances that can be turned on and off on demand and a large section of their appliance room is dedicated to leak detection training, where leaks can be generated by a technician. The approximate magnitude of the leak can be controlled by loosening or tightening the pipe flanges. Therefore, ETG provides an ideal setting to develop field measurement methods that can be used at a wide range of natural gas appliances and infrastructure. All the natural gas appliances we measured at ETG were of residential grade (Table 4.2). The majority of natural gas appliances were boilers (n = 6), of which two were high efficiency (HE) appliances that have an annual fuel utilization efficiency larger than 90% (Matulka, 2013). At ETG, we tested two CH_4 measurement methods (chamber-based and high flow sampling) on two CH_4 emission sources (natural gas piping leaks and appliance exhaust vents emissions). For these tests, we used the HETEK DP-IR+ and the HETEK Flow Sampler (HETEK Solutions Inc., London, Ontario, Canada).

Table 4.2: Measured appliance specifications

Location	Brand	Model	Appliance type	Grade	Heating Capacity (BTU/h)
McGill student residence	Aerco	Aerco KC Gas Fired	Tankless water heater	Commercial	930,000
	RBI		Storage water heater	Commercial	892,500
	Laars		Storage water heater	Commercial	486,000
	Coleman		Furnace	Residential	123,500
	Bradford White		Storage water heater	Residential	76,000
	Cleaver Brooks	CFC-E	Boiler	Commercial	400,000 - 2,000,000
ETG	Buderus	Logamax plus GB 142-24	Boiler	Residential	75,200
	Lochinar	Knight	Boiler	Residential	97,000
	Weil McLain	Ultra 80 NG	Boiler	Residential	71,000
	Viessmann	Vitodens 222-F	Boiler	Residential	64,000
	Lincoln	DC90	Furnace	Residential	75,000
	York	Diamond 90	Furnace	Residential	130,000
	Goodman		Furnace	Residential	55,000
	Lennox		Furnace	Residential	90,000
	NTI	Trinity Tft85	HE boiler	Residential	78,000
	Navien	NCB-240	HE boiler	Residential	112,000

4.2.3.1. Chamber-based measurements

Using the static chamber, we derived 4 natural gas piping emission rates based on Equation 4.4, where $\frac{dC}{dt}$ is the slope of the linear regression trendline.

$$Q_{leak}\ \left[\frac{g}{min}\right] = V_{chamber}\ [L] * \frac{dC\ [ppm]}{dt\ [min]} * \frac{P\ [atm]}{R\left[\frac{L*atm}{mol*K}\right]*T\ [K]} * M\left[\frac{g}{mol}\right] * 10^{-6}\ \left[\frac{1}{ppm}\right] \qquad \text{(Eq. 4.4)}$$

To investigate the exhaust vent emissions, we placed the static chamber on the exhaust vents, as the natural gas appliances were turned on and off. A CH_4 emission rate of exhaust vents could not be derived using Equation 4.4, as the emissions were not constant during the time the chamber was placed on the source, mainly due to high emissions occurring during the ignition and extinguishment of the appliances. Therefore, we derived other metrics such as the maximum CH_4 concentration during ignition and extinguishment spikes and the duration of CH_4 concentration spikes to describe exhaust vent emissions. By plotting these metrics against the heating capacity of each appliance, we investigated potential linkage between appliance grade and CH_4 emissions.

4.2.3.2. High flow sampling measurements

Using the HETEK Flow Sampler, we performed high flow sampling measurements on leaking natural gas piping and appliance exhaust vents. natural gas piping leaks were generated by the ETG technician and we placed the HETEK Flow Sampler sampling bag over the leak, as per manufacturer's instructions (HETEK, 2022). To measure exhaust vents emission using the HETEK Flow Sampler, we turned each appliance on, waited for a few minutes for steady-state and placed the HETEK Flow Sampler sampling bag on top of the exhaust vent. The instrument sampled for two minutes at two different blower flow rates, which are default manufacturer settings.

4.2.4. National inventory reporting of natural gas end-use methane emissions

We investigated natural gas end-use emissions reporting in national GHG inventories, following Intergovernmental Panel on Climate Change (IPCC) guidelines and compiled IPCC default emission factors, as well as emission factors used in 7 publicly available national GHG inventories submitted annually to the United Nations Framework Convention on Climate Change (UNFCCC), namely the United States, Canada, the United Kingdom, France, Germany, Australia, Belgium and Switzerland (Environmental Protection Agency, 2022; Environment Climate Change Canada, 2022; Department for Business, Energy & Industrial Strategy, Science Research Programme, 2022; Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique, 2022; Federal Environment Agency, 2022; Australian Government Department of Industry, Science, Energy and Resources, 2022; Federal Public Service for Health, Food Chain Safety and the Environment, 2022; Federal Office for the Environment, 2022).

4.3. Results

4.3.1. Controlled release testing of the HETEK Flow Sampler

The controlled release testing showed that the HETEK Flow Sampler generally underestimated CH_4 flow rates, with largest relative errors appearing at lower CH_4 concentrations. For both high and low flow rates, the HETEK Flow Sampler underestimated the CH_4 flow rates by 1 to 86% (Figure 4.1). For a given CH_4 mass flow rate, the measured flow rates got closer to the actual value as the released CH_4 concentrations got higher and the total volumetric flow rates got lower. At the high CH_4 mass flow rates using the 50% and 100% CH_4 standards, the average relative error was 42% and 23%, respectively (M1, Table 4.3). At low flow rates the average relative error was 40% (M1, Table 4.3). We can see that the HETEK Flow Sampler strongly underestimated the flow rate for the 5 and 10% CH_4 releases, with average relative errors of 43% and 47% for releases of 5 and 10% CH_4 gas samples and of 39 and 30% for 50 and 100% CH_4. We saw a clear decreasing trend in the relative error of the HETEK Flow Sampler as the released CH_4 concentration increased (Figure 4.2). As for the influence of the flow rate on the HETEK Flow Sampler accuracy, no significant trend was detected. However, we can say that the instrument's accuracy and precision was significantly better at intermediate flow rates (40 to 197 g/hr), with relative errors ranging from 0 to 20%, compared to very low flow rates (17 to 30 g/hr).

Table 4.3: Average relative errors of high flow sampler measurements

Known gas concentration (%)	Number of measurements	Number of erroneous measurements	Average relative error (M1, %)	Average relative error (M1 > lower detection limit, %)	Average relative error (M2 > lower detection limit, %)
HIGH FLOW RATES					
50	12	4	41.6%	41.6%	42.3%
100	6	0	22.7%	22.7%	22.7%
Average			32.1%	32.1%	32.1%
LOW FLOW RATES					
5	10	3	42.8%	31.2%	31.0%
10	10	3	46.6%	35.5%	27.7%
50	10	2	38.7%	23.4%	23.7%
100	10	2	30.3%	12.9%	0.4%
Average			39.6%	25.7%	20.7%
Total	58	14			

Not accounting for measurements performed at CH_4 flow rates lower than the detection limit of the HETEK Flow Sampler or measurements considered erroneous by the instrument itself reduces the relative error. The lowest flow rate was 17.7 g/hr, which is just below the detection limit and the HETEK Flow Sampler did not pick up any CH_4 leak at this flow rate. Excluding the releases at flow rates below the detection limit determined by HETEK (18.3 g/hr or 0.465 slpm), the average relative error for low flow rates was 27%. Out of the 58 measurements we performed, 14 measurements (24%) were erroneous (>10% two-staged accuracy, see Methods). Excluding these measurements, we got average relative errors between the actual and measured flow rates of 33% and 21% for the high (2,360 to 5,510 g/hr) and low flow rates (18 to 197 g/hr), respectively (M2, Table 4.3). In comparison, the Bacharach Hi-Flow sampler (Heath Consultants Inc., www.heathus.com) showed an accuracy of 18% at 200 g/hr (Riddick *et al.,* 2019).

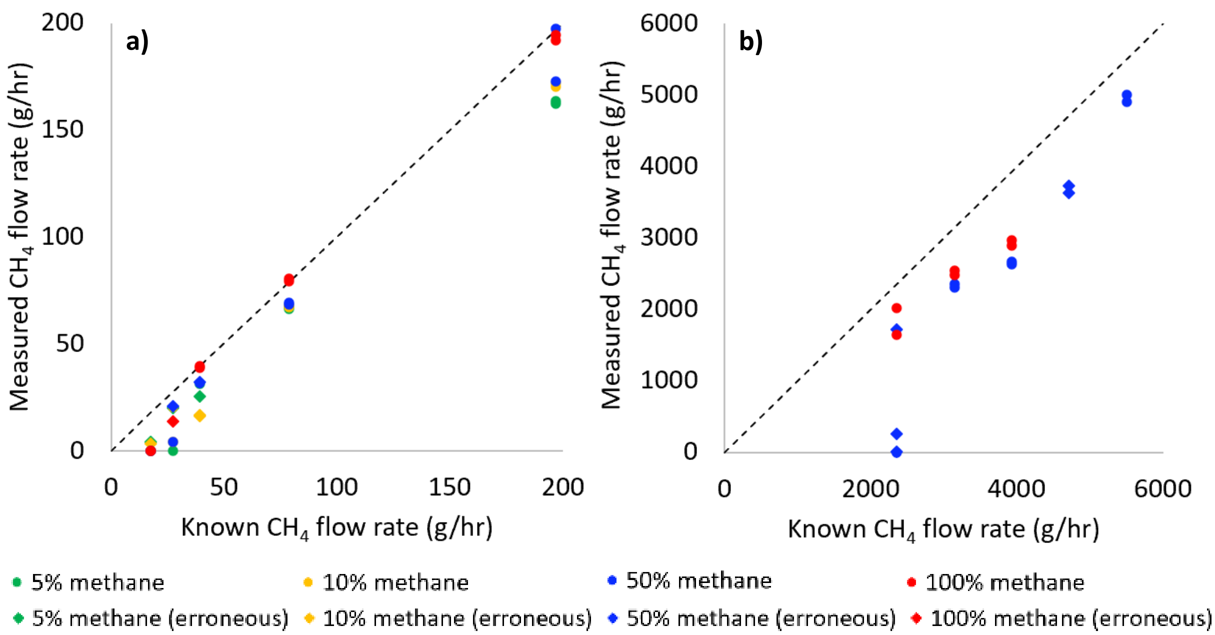

Figure 4.1: Comparison of the known methane flow rate and the flow rate measured by the HETEK Flow Sampler at a) low and b) high released methane flow rate

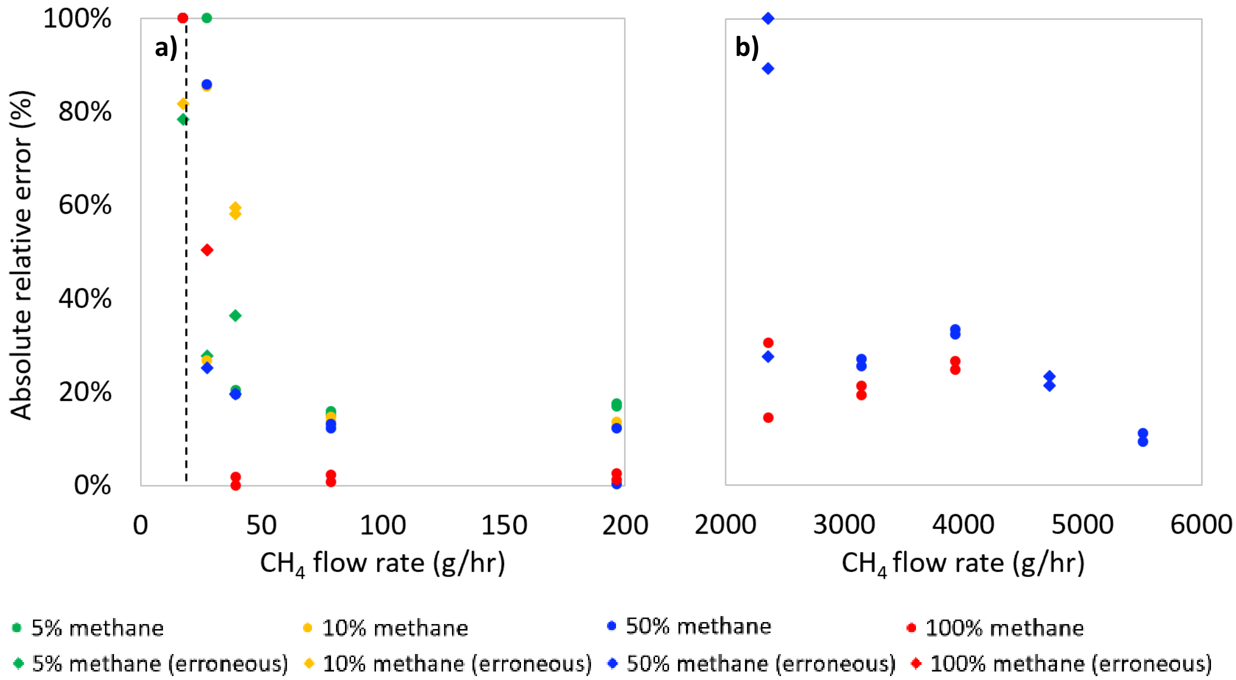

Figure 4.2: Relative error of the HETEK Flow Sampler when releasing various methane concentrations at a) low and b) high methane flow rate. The dotted line represents the lower detection limit of the instrument.

4.3.2. Leak detection and scoping visits at McGill student residences

We found CH_4 enhancements in each of the four mechanical rooms of the McGill student residences. The rooms all held three to four natural gas appliances of residential or commercial grade. Screening various natural gas appliance and natural gas piping components, we identified leaks ranging from 5 to 30 ppm. (Figure 4.3). Typical outdoor atmospheric CH_4 concentrations are around 1.9 ppm (Stein, 2022).

We observed a 150 ppm CH_4 concentration peak at an exhaust vent located on the roof of the Carrefour Sherbrooke residence. The other exhaust vents exhibited lower CH_4 emissions, ranging from 2 to 8 ppm, which were still above typical atmospheric CH_4 concentrations and indicated CH_4 leaks. The exhaust vent with the high CH_4 concentration peak was connected to four tankless water heaters, with only two of them running at the time. These appliances turn on/ off frequently. The two other exhaust vents were connected to storage water heaters, boilers and furnaces. We don't have information on the operational stage of the various natural gas appliances at the time of the screening measurement.

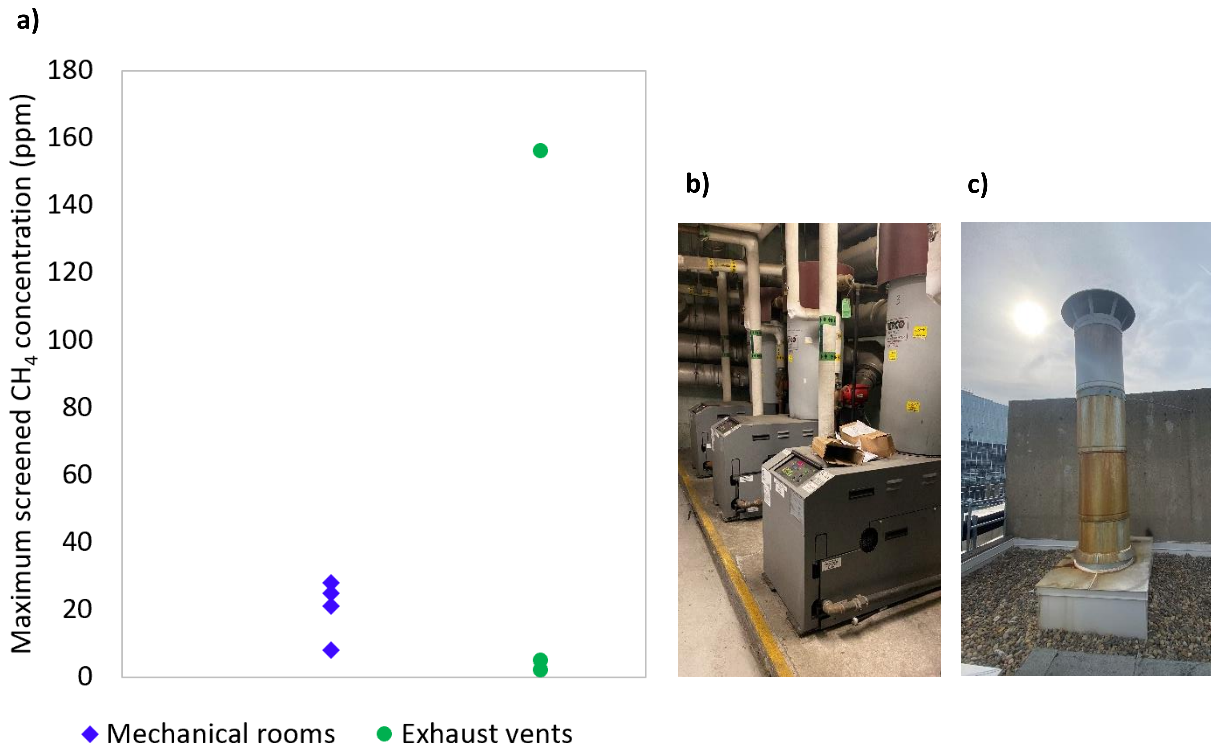

Figure 4.3: a) Maximum methane concentration (ppm) screened during the scoping visit in the mechanical rooms and exhaust vents of each McGill student residence visited during our scoping visit (Table 4.2) b) A mechanical room with four commercial grade storage water heaters c) An exhaust vent on the roof of Carrefour Sherbrooke

4.3.3. Emission measurements at Ecole de Technologie Gazière

For the natural gas piping leaks, we estimated emission rates ranging from 0.02 to 2.19 g/hr using the static chamber method (Figure 4.4). The HETEK Flow Sampler did not detect any of these leaks, as the lower detection limit of the HETEK Flow Sampler is 18.3 g/hr (HETEK, 2022), which was confirmed by our own testing of the instrument.

The exhaust vent emissions exhibited distinct emission patterns for each operational cycle of the appliance (ignition, steady state on, extinguishment, steady-state off). Using the chambers to isolate the natural gas appliance exhaust vents, we identified CH_4 concentration spikes during ignition and extinguishment of the natural gas appliances ranging from 45 to 2423 ppm. After these emission spikes, the CH_4 concentrations inside the chamber usually dropped rapidly back to concentrations around 3 to 40 ppm. After extinguishment and purging, during the steady-state off phase of the appliance, CH_4 concentrations were generally constant inside the chamber, ranging from 300 ppm at vents 1 and 8 to 40 ppm at vents 4 and 10. This indicated that only small amounts of CH_4 were emitted during the steady-state off phase.

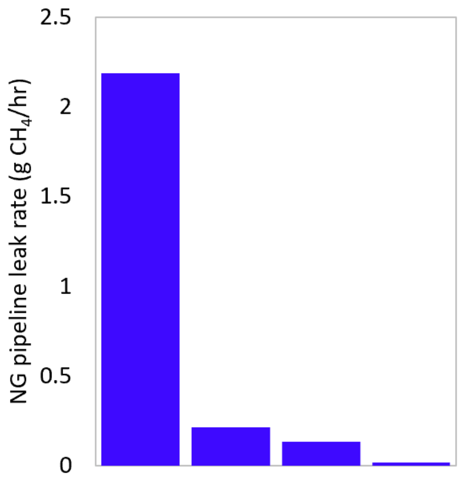

Figure 4.4: Natural gas piping leak emission rates (g/hr) derived using the static chamber method

Investigating the ignition and extinguishment CH_4 concentration spikes further, we found that the highest CH_4 concentration spikes were all attributed to furnaces, with maximum CH_4 concentrations of 2,423 ppm and 2,286 ppm reached at ignition and extinguishment, respectively (Figure 4.5.1). The lowest concentrations were attributed to high efficiency (HE) boilers, with maximum CH_4 concentration of 180 and 41 ppm during ignition and extinguishment, respectively (Figure 4.5.1). Natural gas appliances exhibited larger concentrations spikes during ignition than extinguishment. Investigating the correlation between the heating capacity of the natural gas appliance and the maximum CH_4 concentration reached at ignition and extinguishment of the appliance (Figure 4.5.1), we found that furnaces of higher heating capacity exhibited significantly higher CH_4 concentration inside the chamber at extinguishment (R^2=0.88 and p-value=0.018, Figure 4.5.1b). At the ignition stage, the large p-values indicate no significant correlation between appliance heating capacity and maximum CH_4 concentration (R^2=0.21 and p-value=0.5, Figure 4.5.1a). Focusing on the correlation between appliance heating capacity and CH_4 emission spike duration at ignition and extinguishment, we found no significant trend (Figure 4.5.2).

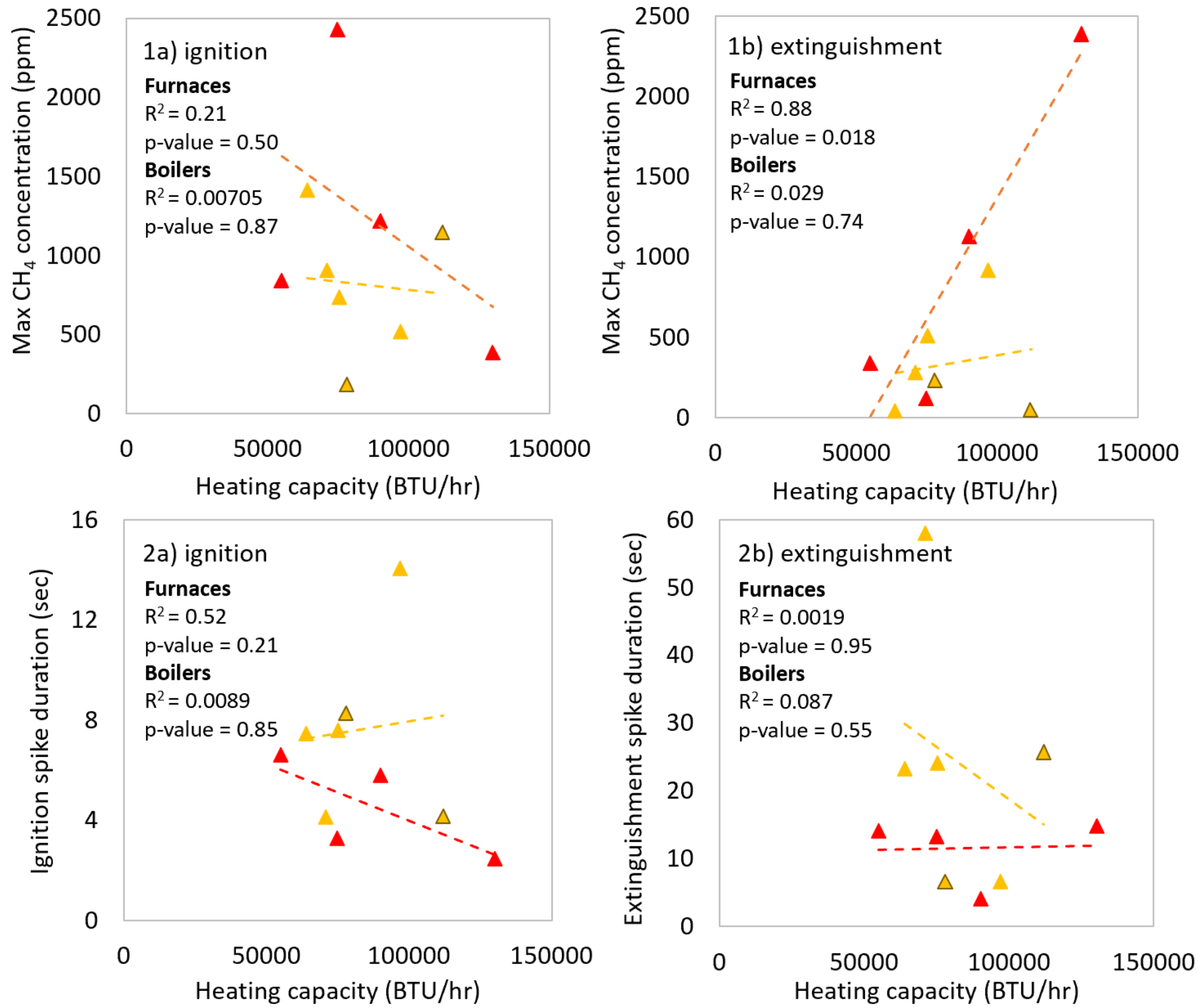

Figure 4.5: Methane emission spikes at exhaust vents of residential natural gas appliances (boiler, furnace and high efficiency (HE) boiler) of different heating capacities: maximum methane concentration at ignition (1a) and extinguishment (1b) and emission spike duration at ignition (2a) and extinguishment (2b).

4.3.4. National inventory reporting of natural gas end-use methane emissions

The IPCC provides guidelines to estimate GHG emissions by source, based on a bottom-up approach. Three estimation methods are detailed, depending on data availability. Tier 1 is employed when no technology- or country-specific emission factor is available. Tier 3 and 2 methods are considered higher tier methods, providing more accurate results. The IPCC recommends the inclusion of incomplete combustion emissions under the stationary combustion categories 1A4a (residential sector) and 1A4b (commercial/ institutional sector) (IPCC, 2006) and post-meter leaks under the fugitive emissions from natural gas systems (category 1B2b6) (IPCC, 2019). The default IPCC

Tier 1 emission factor for CH_4 from incomplete combustion of natural gas is 5 kg of CH_4 per TJ of natural gas on a net calorific basis (residential, commercial and institutional sectors; IPCC, 2006). As for post-meter fugitive CH_4 emissions from natural gas appliances, the IPCC provides a default emission factor of 4 kg of CH_4 per appliance per year (residential, commercial and institutional sectors; IPCC, 2019). All national GHG inventories include incomplete combustion emissions under the stationary combustion category, however most countries still use the IPCC Tier 1 default emission factor for incomplete combustion CH_4 emissions. As for post-meter emissions, they are not consistently included. For example, the U.S. reported them for the first time in 2022 as a separate post-meter subcategory (category 1B2b6) (Environmental Protection Agency, 2022), the U.K. and Switzerland reported post-meter emission under fugitive emissions from natural gas distribution systems (category 1B2b5) (Department for Business, Energy & Industrial Strategy, Science Research Programme, 2022; Federal Office for the Environment, 2022), Germany and Australia reported them under the “others” subcategory of the fugitive emissions from natural gas systems, also including emissions from abandoned natural gas wells (Federal Environment Agency, 2022; Australian Government Department of Industry, Science, Energy and Resources, 2022) and Canada, France and Belgium didn’t include post-meter emission (Environment Climate Change Canada, 2022; Centre Interprofessionnel Technique d’Etudes de la Pollution Atmosphérique, 2022; Federal Public Service for Health, Food Chain Safety and the Environment, 2022). Emission factors used in each national GHG inventory are compiled in Table 4.4.

Table 4.4: Emission factors used in national greenhouse gas inventories for natural gas appliances methane emissions.

National inventory	Incomplete combustion emissions	Post-meter leaks
United States	5 kg CH_4 / TJ	2.3 kg CH_4 / NG household (residential) 4 kg CH_4 / appliance (commercial)
Canada	0.037 g CH_4 / m^3	-
United Kingdom	5 kg CH_4 / TJ	1.93 kg CH_4 / TJ
France	5 kg CH_4 / TJ	-
Germany	3 kg CH_4 / TJ (residential) 0.16 kg CH_4 / TJ (commercial)	2 m^3 CH_4 / number of gas meters or fittings
Australia	0.9 MG CH_4 / PJ	0.022 kg CH_4 / appliance (furnaces) 0.77 kg CH_4 / appliance (residential storage water heater) 0.0012 kg CH_4 / appliance (residential tankless water heater) 0.0639 kg CH_4 /appliance (commercial water heater)
Belgium	5 kg CH_4 / TJ (Brussels and Wallonia Regions) 1 kg CH_4 / TJ (Flanders Region)	-
Switzerland	1 kg CH_4 / TJ (boilers)	0.000179 kg CH_4 / TJ (all natural gas distribution sources, not only post-meter)

4.4. Discussion

4.4.1. Implications on future measurements

The HETEK Flow Sampler controlled release testing showed a general underestimation of CH_4 flow rate (97% of measurements were underestimating the CH_4 flow rate) with average relative error rates of 33% and 21% for the high (2,360 to 5,510 g/hr) and low flow rates (18 to 197 g/hr), respectively. This strong negative bias introduced by the HETEK Flow Sampler needs to be considered when deriving emission factors from these measurements. However, the high flow sampling method proved not to be appropriate to capture exhaust vent emissions since emissions peaks all lasted for less than 30 seconds and the minimum sampling time required by the HETEK Flow Sampler is 30 seconds for the instrument's reading to stabilize (HETEK, 2022).

The CH_4 screening and chamber-based measurements both showed evidence of non-negligible CH_4 emissions associated with natural gas appliances, from both natural gas piping and appliance exhaust vents. Natural gas piping CH_4 leaks are usually due to loose fittings and when detected, can be easily fixed. The occurrence of natural gas distribution piping leaks might be correlated with piping material and age (Weller *et al.*, 2020). Using the chamber-based method (Equation 4.4), we estimated natural gas piping emission rates ranging from 0.02 to 2.19 g/hr. How natural gas piping leak rate relates to appliance operation is not clear and requires further investigation. As for exhaust vents emissions, we found that they are strongly linked with the operational stage of the natural gas appliance, with high emission spikes at ignition and extinguishment of the appliance and very low and steady emissions during the steady-state on and off stages. Since different appliance types operate differently (e.g., tankless water heaters turn on and off more often than storage water heaters, but for shorter periods of time), appliance exhaust vent emissions are strongly dependent on appliance type. The transient characteristic of exhaust vent emissions makes it difficult to measure emission rates using the static chamber and the high-flow sampling method, which are designed for constant emission rates.

At ETG, even though all measured natural gas appliances were of residential grade, their natural gas consumption differed widely. In other words, even within residential grade natural gas appliances, there is a large variation in heating capacity and natural gas consumption. We found a general increasing trend in CH_4 emissions with appliance heating capacity. As heating capacity is directly related to the natural gas appliance grade, this suggests that higher grade (including commercial natural gas appliances) probably emit more than residential natural gas appliances.

4.4.2. Post-meter methane emission estimates in national greenhouse gas inventories

The end-use of natural gas is associated with non-negligible CH_4 emissions that need to be quantified and reported in national GHG inventories. We identified two sources of emissions, namely CH_4 leaks from natural gas piping connecting the customer meter to the natural gas appliance (i.e., post-meter emissions) and incomplete combustion CH_4 emissions found at the exhaust vents of the appliances. These latter emissions are highly dependent on appliance type and grade, as well as operational cycle (e.g., ignition, steady state on, extinguishment, steady state off), which amplifies the importance of developing technology- and infrastructure specific emission factors to accurately estimate CH_4 emissions related to the end-use of natural gas in national GHG inventories. Following IPCC guidelines, incomplete combustion emissions should be reported under the stationary combustion category (1A4A and B) and the post-meter emissions should be reported under the fugitive emissions from natural gas systems category (1B2b6). Additional measurements from each reporting country are required to develop country-specific emission factors, taking into account the distribution of natural gas appliance of different type and grade, as well as heating requirements and usage patterns.

4.5. Conclusion

Methane emissions related to natural gas appliances generally occur from leaking natural gas piping components and at the exhaust vents of the appliances. Using a chamber method, we derived natural gas piping leak rates ranging from 0.02 to 2.19 g/hr. Exhaust vents exhibited high emission peaks (up to 2,500 ppm) upon appliance ignition and extinguishment and almost no emissions during steady state operation and when the appliance was off. The HETEK Flow Sampler did not pick up natural gas piping leaks or exhaust vents emissions, either due to low emission rates (<3 g/hr) or short emission times (<30 seconds). Considering the notable differences between emissions from natural gas appliances of different type and grade and the extent to which natural gas is used for space and water heating in Canada, conducting additional measurements of post-meter sources in Canada is necessary to develop accurate country- and technology-specific emission factors, allowing for inclusion of post-meter sources in national greenhouse gas inventories in Canada but also elsewhere.

Ethics statement

This work does not contain any studies involving human or animal participants.

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5. General discussion

5.1. Methane emissions from oil and natural gas systems

As society transitions away from carbon-intensive fuels, attention is drawn towards "cleaner" energy sources such as natural gas. Even though natural gas emits is less carbon-intensive than coal upon combustion, CH_4 being the primary constituent of natural gas, fugitive CH_4 emissions arise throughout the natural gas supply chain, from exploration, production and processing to distribution and end-use. Replacing coal-fired power plants with gas-fired plants becomes beneficial only when fugitive emissions remain less than 2.7% of total produced natural gas (Alvarez *et al.*, 2012). Therefore, accurately monitoring all emission sources across the supply chain of OG systems is necessary to guide the current energy transition and focus emission mitigation strategies where efforts are most needed.

GHG inventories, whether global, national, regional or sectoral, play a key role in understanding and monitoring emissions. National GHG inventories are required to be submitted to the United Nations Framework Convention on Climate Change (UNFCCC) from each Annex I Party country since 2002. The IPCC guidelines lay down the methodology for reporting, mostly based on a bottom-up approach (IPCC, 2019). The IPCC provides a default emission factor database; however, these generic emission factors are not necessarily representative of the current situation in all geographical regions and are often not technology specific. For example, the default IPCC emission factor for residential and commercial post-meter emissions (4 kg CH_4 per appliance per year), which is currently used in the U.S. GHG inventory to estimate commercial post-meter emissions, is not appliance specific and is based on a study by the International Gas Union conducted in the 2000s (IPCC, 2006; IPCC, 2019; EPA, 2022). Both our studies on CH_4 emissions from two segments the OG supply chains, namely OG production and natural gas end-use, highlight the importance of using accurate, up-to-date and specific emission factors, as well as to monitor activity data thoroughly.

In the case of OG well emissions, we found the availability of OG well characteristics to be a limiting factor. State, provincial and territorial OG well databases use a wide variety of terminologies to refer to well status and production type. Many OG wells are not attributed any production type or well drilling date and there is no information on the accuracy of the geographic coordinates. Focusing on abandoned OG wells, current IPCC default emission factors are based on studies conducted in the U.S. and only differentiate between plugged and unplugged abandoned OG wells, but not between different production types (oil vs. natural gas producing wells). We found that abandoned OG well emissions inside the ABoVE domain were underestimated by 69 to 533% in the gridded national inventory (Scarpelli *et al.*, 2021), which could be explained by the use of default IPCC emission factors or inaccurate or missing activity data.

As for natural gas appliance emissions, which are not included in all national GHG inventories today, our study showed that emissions vary widely between appliance type (e.g., boiler, furnace) and grade (commercial or residential). However, the current default IPCC emission factors for post-meter and incomplete combustion emissions don't distinguish between these appliance characteristics. Additionally, no emission measurements have been conducted on natural gas appliances in Canada, were heating requirement are generally higher than in the U.S. and where natural gas is extensively used for space and water heating. Here again, a major limiting element in accurately estimating emissions is the availability of accurate country- and source-specific emission factors, indicating a need to conduct more direct measurements on these natural gas system CH_4 emission sources.

5.2. Other impacts

In this study, we mostly focused on CH_4 emissions from OG systems; however, other impacts of OG systems, such as ecosystem impacts, air pollution and human health impacts also need be considered when discussing the transition to OG fuels.

The OG production sector is associated with many environmental impacts. With most OG reserves situated in remote and vulnerable regions of the world, such as the ABoVE domain, the local impacts of OG wells are especially important to consider. Permafrost temperatures in the ABoVE domain are rapidly rising causing land cover changes, deepening of the active layer and the development of thermokarst landforms such as thaw slumps and soil subsidence. Given the number of OG wells in the ABoVE domain, understanding interactions between OG wells and surrounding land cover and permafrost is important; however, studies on the subject are lacking. This is despite the fact that OG exploration and extraction activities are associated with vegetation clearing, soil compaction upon OG infrastructure construction. A land cover change study (Wang *et al.*, 2020) conducted in the ABR found a significant loss in Evergreen and Deciduous Forest land cover classes, mostly attributed to the changing fire regime but there was no mention on how OG activities might be exacerbating these changes.

Natural gas combustion from appliances emits air pollutants such as nitrous oxides (NO_x), carbon monoxide (CO) and formaldehyde (CH_2O). Most studies focus on gas stoves, as ventilation is generally less controlled than water heaters and furnace, where the appliance exhaust is located outside, directly affecting the indoor air quality and human health (Lebel *et al.*, 2022, Amirkhani Ardeh *et al.,* 2020, Singer *et al.*, 2017, Logue *et al.,* 2014). A few studies also discuss air pollution from water and space heaters (Zhou *et al.*, 2021, Choudhury *et al.*, 2020). NO_x and CH_2O gases can cause respiratory issues, including asthma, breathing difficulty and coughing. CH_2O is classified as a carcinogen and mutagen by the European Commission. CO exposure affects the ability of blood to carry oxygen to our organs, causing headaches, fatigue and dizziness. Additionally, the global warming potential of NO_x and CO gases is non-negligible. Both gases are chemically reactive gases, contributing to the formation of tropospheric ozone (O_3), a very potent GHG with a short lifetime.

5.3. Steps forward

We highlighted the importance of accurate GHG inventories to monitor emissions from all emitting sectors and understand their relative importance. This is critical to guide policy decisions and emission mitigation strategies. In addition to conducting more measurement studies to develop specific emission factors, a thorough recording of activity data is needed. Depending on the CH_4 emissions source type, this corresponds to the number of wells by well type and status (production), the volume of transported OG by transportation type (e.g., pipeline, truck, ship) (transport), the volume of OG refined and processed (refining and processing), the length of distribution pipeline by pipeline characteristics (e.g., pipeline material) (distribution), the volume of natural gas consumed by the end-user and number of appliances by type and grade (post-meter), to name a few.

Finally, after understanding and monitoring CH_4 emission sources, mitigation strategies can be implemented to reduce these emissions. They can be implemented either through policies regulating activities or by replacing the current infrastructure with more efficient systems following technological advances. In the case of OG wells, implementing efficient well integrity monitoring practices of active and abandoned wells could allow the detection of well integrity failures and OG well leakage, as well as increasing our understanding OG well leakage processes. Currently, regulations require the plugging of abandoned OG wells; however, regulations vary across states, provinces and territories and there is no requirement to monitor integrity of plugged wells (Kang *et al.,* 2021). Conducting more studies on the impacts of OG well plugging on ecosystems, groundwater, air and human health is necessary. As for gas appliance emissions, the subject of injecting hydrogen (H_2) into the natural gas distribution network has been getting a lot of attention recently. H_2 is a carbon-free energy source that is formed through water hydrolysis and provides many advantages over other fuels, such as near-zero GHG emissions upon combustion or easy storage and transport. Many studies have been conducted on the effects of H_2-enriched natural gas on appliance performance and associated emissions (Sun *et al.*, 2022, Jones *et al.*, 2018, Leicher *et al.*, 2022). Important aspects to consider when implementing such changes are the differences in calorific content and density of both gases, as well the combustion velocity (or flame speed) of the fuel mixture. For example, Sun *et al.* (2022) found that a H_2-natural gas mixture with less than 23 vol% of H_2 guarantees safety and increased thermal efficiency of appliances, with decreased air pollutant emissions. Leicher *et al.* (2022) discusses some concerns that may arise with the implementation of H_2-enriched natural gas fuels, such as the higher combustion temperatures that may lead to overheating of the appliance components, increased NO_x emissions or the higher combustion velocity of a H_2-natural gas mixture compared to natural gas, which can affect the flame stability and cause safety issues. Many research organizations are currently investigating this topic (e.g., Testing Hydrogen for Gas Appliances (THyGA) in the EU or HyBlend in the U.S.). Additionally, implementing more regulations on Leak Detection and Repair programs could reduce CH_4 leaks from natural gas piping and increase our understanding on factors affecting natural gas piping leaks.

6. General conclusion

6.1. Summary of results

In this work, we studied CH_4 emissions and environmental impacts of two segments of the OG supply chain, where we identified knowledge gaps in terms of direct measurements of CH_4 emissions and understanding complex regional and global interactions between these activities and environmental systems (e.g., atmosphere, hydrosphere, cryosphere, biosphere and geosphere): the OG production and end-use sectors.

We constructed an OG well database for the ABR of Western North America and mapped OG wells, land cover and permafrost. We found more 242,007 OG wells drilled as of 2018, with 65,588 in permafrost areas in 2012. OG well drilling has increased significantly from 400-700 annually drilled wells in the 1980s and 1990s to 2000-7000 in recent years. Upon OG well drilling, subsurface pathways are created which can release trapped CH_4 gas to the atmosphere. These CH_4 emissions in the ABR contribute non-negligibly to Canadian anthropogenic CH_4 emissions. Moreover, 63% of OG well in the ABR are no longer producing, but continue to emit CH_4. Large uncertainties remain in OG well emissions reported in GHG inventories, due to incomplete OG well databases or the use of generic and inaccurate emission factors. Moreover, we reveal the need for more studies on how OG wells impact their surrounding environment, including land cover and permafrost.

Natural gas appliance emissions were investigated using various qualitative (concentration screening) and quantitative (high flow sampling and chamber-based) methods. By screening various elements, we identified two main CH_4 emission sources, namely natural gas piping and the natural gas appliance exhaust vents. The natural gas piping leaks ranged from 0.02 to 2 g/hr CH_4. The exhaust vents emissions exhibited transient emissions, with high emission peaks (up to 2,500 ppm) upon ignition and extinguishment and very low emissions while the appliances were running or turned off. We identified non-negligible differences in emissions between appliances of different types (e.g., boilers, furnaces) and natural gas consumption, which is linked to appliance grade (residential or commercial).

6.2. Limitations and recommendations

This study provides a review of the current state of research on OG systems impacts and identifies two understudied segments of the OG supply chain. Therefore, our work mostly contains preliminary findings necessary to guide further research. The following section provides limitations of our work and recommendations for future research opportunities.

Our study on the impacts of OG extraction activities was based on publicly available data recorded by provinces, states and territories. The public databases didn't provide any information on the accuracy and precision of their data (e.g., geographic coordinate of the wells or drilling data) and many well records had missing information, mostly on the well production type or well drilling data. Conducting additional research on available data and merging multiple datasets, or even developing our own independent dataset would be valuable. Additional research opportunities lie in studying the thermal interactions between OG well and permafrost, as well as permafrost thaw in the vicinity of OG wells.

Additional sampling campaigns on post-meter natural gas piping leaks and incomplete combustion emissions are required, measuring a wider sample set of appliances and including a variety of appliance types (e.g., tankless water heaters, storage water heaters, boilers, furnaces, stoves, barbecues) and grades (residential and commercial). Measuring emissions from other co-emitted gases, such as CO, NO_x and CH_2O would be valuable. Moreover, analyzing emissions from natural gas appliances supplied with H_2-enriched natural gas could provide insight into this new topic of interest.

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Annex: Oil and natural gas wells across the NASA ABoVE domain: fugitive methane emissions and broader environmental impacts - Supplementary Information

SI-1 Well type classification

Oil and natural gas (OG) wells with no recent production (i.e., about 6-12 months), which were designated as “Abandoned”, “Junked”, “Shut in”, “Suspended”, and “Plugged” were used in the various state, provincial and territorial databases, were defined as abandoned. We assigned a drilling date to each OG well in the study domain, based on information provided in the databases (Table S2, SI-4). For example, we used the spud date in well databases from Alaska, the Northwest Territories and Saskatchewan, corresponding to the start of the drilling process, and the well licensing date in Alberta and the “status effective date” in British Columbia and Manitoba, corresponding to the end of the drilling process. The Yukon only provides an abandonment date but no date corresponding to the drilling process. Therefore, Yukon OG wells were not included in our temporal analysis of OG well drilling, but were included in our abandoned OG wells fugitive methane (CH_4) emissions estimate.

SI-2 Fugitive methane emissions estimation method

We estimated CH_4 emissions from abandoned oil and natural gas (OG) wells in the Canadian portion of the NASA Artic Boreal Vulnerability Experiment (ABoVE) Core Domain using published emission factors (emission factors) developed for abandoned OG wells (Williams *et al.*, 2021). Williams *et al.* (2021) reported nationwide and regional emission factors for each well production type (gas producing, OG producing or unknown production type) and plugging status (plugged or unplugged). We provide some indication of uncertainty in our OG well CH_4 emission estimate by considering the minimum and maximum emission factors for Canada reported in Williams *et al.* (2021) (Table S4, SI-4). Second, since 61% of the abandoned OG wells in our database did not have a reported production type, we computed two estimates with and without production type information. The first method ("method 1") consisted of calculating the ratio of oil and gas producing to gas producing wells, from the proportion of wells having this information reported in each province/ state/ territory well database inside the ABoVE Core Domain. We applied the ratio to characterize the remaining wells of unknown type into gas or OG producing wells. In the second method ("method 2"), we used a specific emission factor for wells of unknown production type ("all unplugged" and "all plugged" in Table S4, SI-4), following the methodology employed by Williams *et al.*, 2021). These emission factors were calculated based on the ratio of gas to OG producing wells reported by the Canadian Association of Petroleum Producers and the Energy Information Agency. Since we used three emission factors (nationwide, minimum and maximum) and made two estimates with/ without production type, we obtained six CH_4 emission estimates for abandoned OG wells in the ABoVE domain.

SI-3 Well reporting spike in Alberta's well database

About 18,000 OG wells in Alberta's well database had the same licensing date, namely 1998. This is due to a change in reporting regulations in Alberta, causing a lot of OG wells to be included in the database that year. OG wells reported in 1998 might have been drilled years before 1998.

SI-4 Supplementary Tables

Table S1 Data source links to each province/ state/ territory well database.

Province/ state/ territory	Source	URL
Alaska	Alaska Oil & Gas Conservation Commission	https://www.commerce.alaska.gov/web/aogcc/Data.aspx
Alberta	Alberta Energy Regulator	https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st37
British Columbia	BC Oil & Gas Commission	https://www.bcogc.ca/data-reports/data-centre/?format=geographic
Manitoba	Manitoba Regulatory Services (Oil and Gas)	https://www.manitoba.ca/iem/petroleum/gis/index.html
North Western Territories	NWT Office of the Regulator of Oil and Gas Operations	https://www.orogo.gov.nt.ca/en/resources?f%5B0%5D=field_resource_type%3A74
Saskatchewan	Saskatchewan Ministry of Energy and Resources	https://gisappl.saskatchewan.ca/Html5Ext/index.html?viewer=GeoAtlas
Yukon	GeoYukon, Government of Yukon	https://mapservices.gov.yk.ca/GeoYukon/index.html?layerTheme=9

Table S2 Available dates in each province/ state/ territory oil and natural gas well database, in orange: the date used as well "spud date" in our study.

Province/ State/Territory	Dates Available & Well count not dated									
Alaska	SpudDate	707	CompletionDate	664	ReleaseDate	900	LastStatusChange	70		
Alberta	LicDate	0	FDDate	3300	StatDate	0				
BC	STATUS_EFF	0	WAG_DATE	0						
Manitoba	STATUS_DAT	0								
NWT	First SPUD year	0	Latest SPUD or Start Date	0	Latest Rig Release or End Date	0				
Saskat-chewan	WELLLICENCEISSUEDATE	0	WELLOFFCONFIDENTIALDATE	0	WELLDERIVEDSPUDDATE	0	WELLFINISHDRILLDATE	0	WELLBORECOMPSTATUS_FROMDATE	0	WELLBORECOMPTYPE_FROMDATE	0
Yukon	ABANDON	42								

Table S3 Land cover classification (Wang *et al.*, 2020).

ID	Detailed label	Aggregated label	Description
1	Evergreen Forest	Evergreen Forest	Area dominated by tall woody vegetation (> 3m tall) and over 60% canopy coverage with primarily (>75%) evergreen phenological habit (canopy maintains green foliage year-round).
2	Deciduous Forest	Deciduous Forest	Area dominated by tall woody vegetation (> 3m tall) and over 60% canopy coverage with primarily (>75%) deciduous phenological habit (annual cycle of leaf-on and leaf-off periods).
3	Mixed Forest		Area dominated by tall woody vegetation (> 3m tall) and over 60% canopy coverage with neither forest type (deciduous or evergreen) exceeding over 60% of the area.
4	Woodland	Evergreen Forest	Area dominated by tall woody vegetation (> 3m tall) with between 30-60% canopy coverage. Frequently co-exists with peatlands and typically, but not always, evergreen in phenological habit.
5	Low Shrub	Shrubland	Area dominated by dense hemi-prostrate to low-erect shrubs (5-30cm in height) with >60% area coverage. Analogous to "prostrate dwarfshrub" and primarily occurring in tundra areas.
6	Tall Shrub		Area dominated by woody vegetation between 50cm and 3m tall and shrub canopy coverage >60% coverage. Typically, but not always, deciduous phenological habit.
7	Open Shrubs		Area with woody vegetation less than 3m tall and between 30-60% canopy coverage. Shrubs typically underlain by herbaceous or barren land cover.
8	Herbaceous	Herbaceous	Area dominated by herbaceous land cover greater than 60% land cover and tree/shrub cover less than 10%.
9	Tussock Tundra		Tundra-specific herbaceous land dominated by Eriophorum vaginatum and other tussock-forming herbaceous species, coverage over 60%.
10	Sparsely Vegetated	Sparsely Vegetated	10-30% canopy coverage, any vegetation but typically herbaceous/bryophyte, with rock underneath
11	Fen	Fen	Hydrologically connected, sedge/grass dominated wetland
12	Bog	Bog	Ombrotrophic, peat and shrub dominated wetland
13	Shallows/littoral	Shallows/littoral	Lakes <1m deep with some vegetation or shoreline mixed with water/land
14	Barren	Barren	<10% vegetation, mostly rock
15	Water	Water	Oceans, lakes, and rivers, either salt-water or freshwater.

Table S4 Emission factors (emission factor) for fugitive CH_4 emissions from abandoned unplugged/plugged gas or oil and natural gas (OG) producing wells (Williams *et al.*, 2021). "All unplugged" and "all plugged" correspond to the emission factor used for wells with unknown production type in "method 2".

EF (g CH_4 / hr)		unplugged			plugged		
		O&G	gas	all unplugged	O&G	gas	all plugged
nationwide	CA	12	22	10	4.6×10^{-2}	4.8	1.5
	U.S.	13	23	11	5.1×10^{-2}	4.8	1.6
min	CA	12	15	0.15	4.6×10^{-2}	4.8	1.8×10^{-3}
	U.S.	12	17	3.2	5.1×10^{-2}	4.1×10^{-3}	1.8×10^{-3}
max	CA	14	28	12	1.2×10^{-1}	18	2.5
	U.S.	14	48	21	1.7×10^{-1}	18	9.6

Tables S5 Oil and natural gas (OG) well counts in each state/ province/ territory in the ABoVE Core Domain as of 2018. *OG wells in Alaska are not included in the abandoned OG well CH_4 emissions estimate done in this study; **Manitoba is inside the ABoVE Core Domain but there are no OG wells drilled in the ABoVE Core Domain portion of Manitoba.

Province/ state/ territory	All OG wells					
	All			Gas producing	Oil and natural gas producing	Unknown production type
Alaska*	6,778.00			97.00	6,259.00	422.00
Alberta	204,496.00			48,841.00	30,098.00	125,557.00
BC	29,502.00			12,396.00	2,119.00	14,987.00
Manitoba**						
NWT	654.00					654.00
Saskatchewan	501.00				80.00	421.00
Yukon	76.00					76.00
Total	242,007.00			61,334.00	38,556.00	142,117.00
Province/ state/ territory	Active OG wells					
	All			Gas producing	Oil and natural gas producing	Unknown production type
Alaska*	3,912			38	3,602	272
Alberta	67,374			16,773	11,721	38,880
BC	10,123			7,720	812	1,591
Manitoba**						
NWT						
Saskatchewan						
Yukon						
Total	81,409			24,531	16,135	40,743
Province/ state/ territory	Abandoned OG wells					
	All	Plugged	Unplugged	Gas producing	Oil and natural gas producing	Unknown production type
Alaska*	2,816	2,282	534	59	2,622	135
Alberta	136,817	111,469	25,348	31,965	18,292	86,560
BC	11,997	8,374	3,623	4,676	1,307	6,014
Manitoba**						
NWT	654	589				654
Saskatchewan	430	430			37	393
Yukon	76	64				76
Total	152,790	123,208	29,582	36,700	22,258	93,832

SI-5 Supplementary Figures

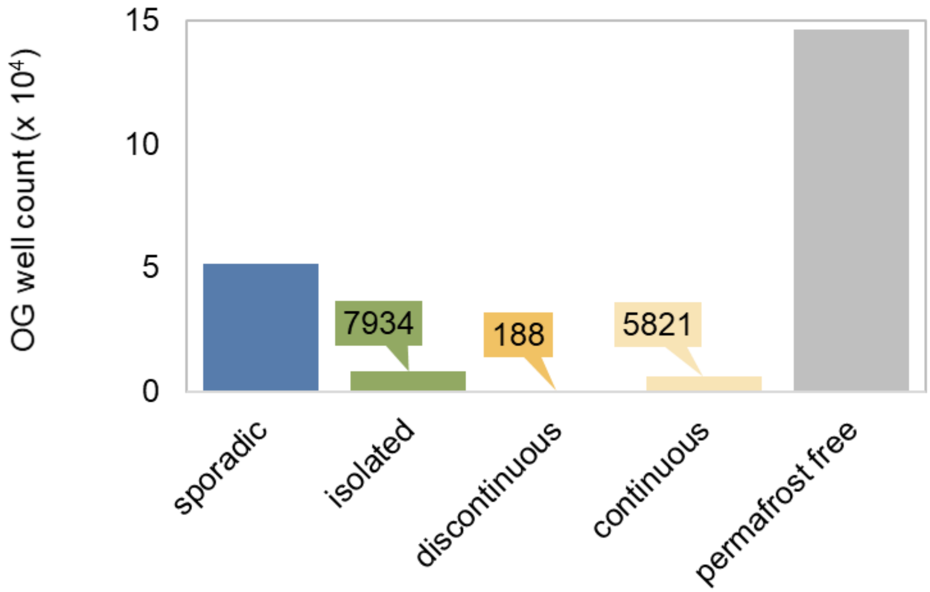
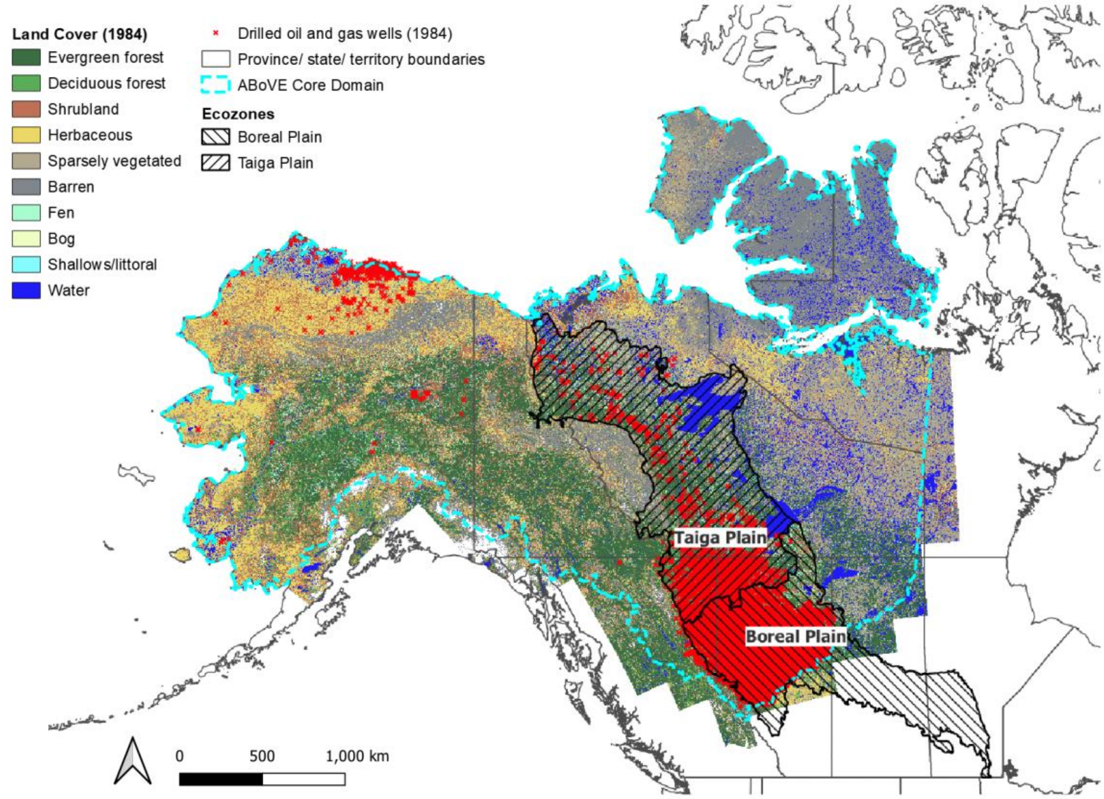


Figure S1 Oil and natural gas (OG) well counts in different permafrost zones (including permafrost free regions) in the ABoVE Core Domain.

a)



b)

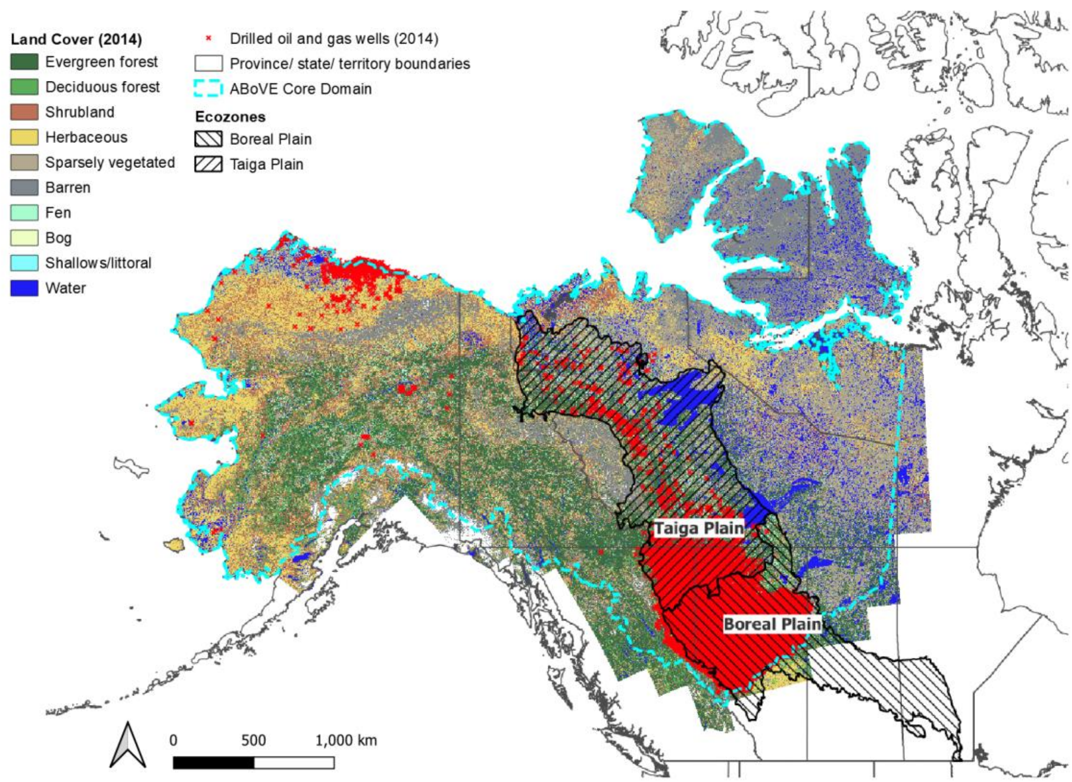


Figure S2 a) 1984 land cover map (Wang *et al.,* 2020) and oil and natural gas wells drilled in and before 1984, b) 2014 land cover map (Wang *et al.,* 2020) and oil and natural gas wells drilled in and before 2014.

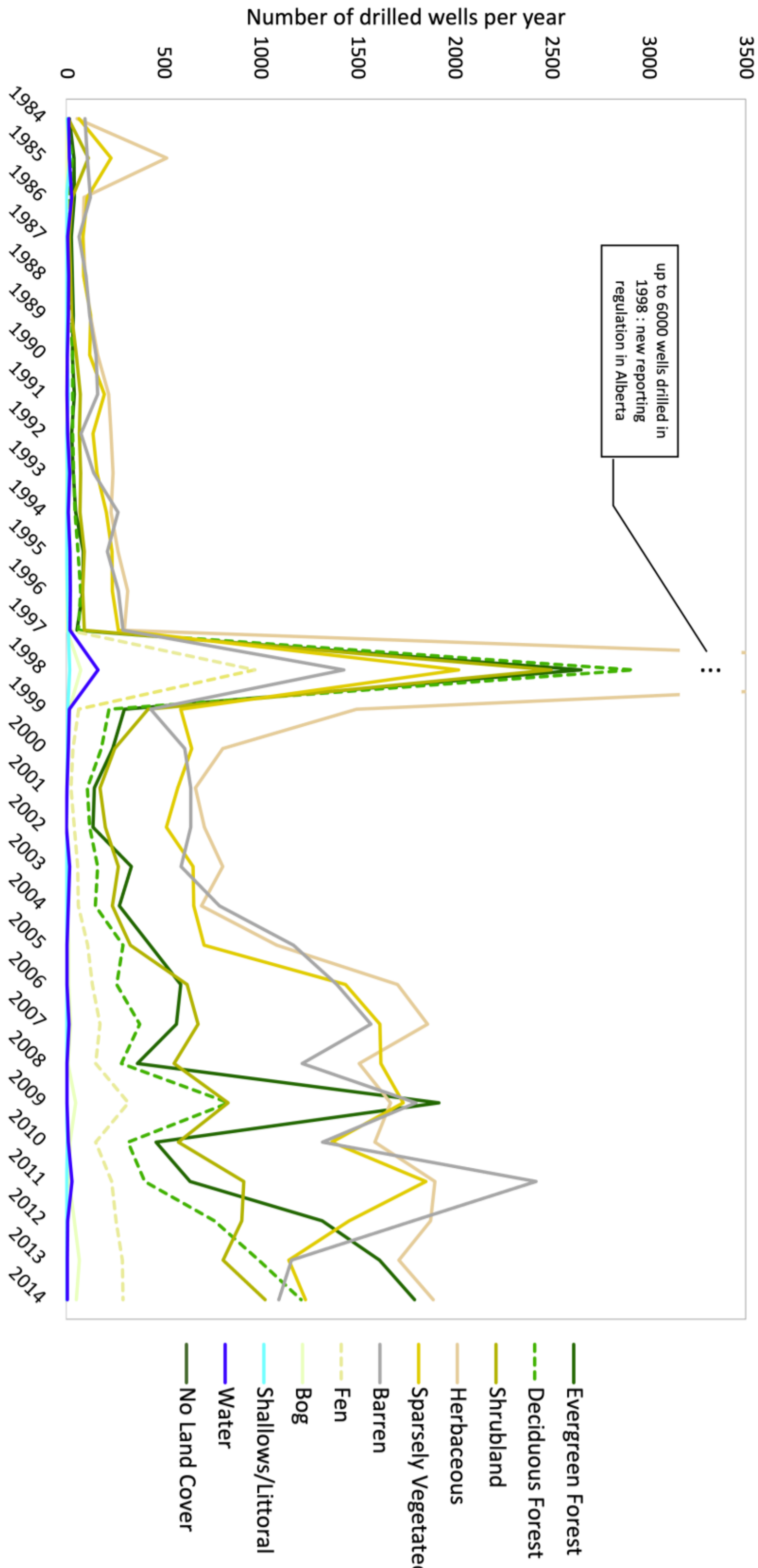


Figure S3 Spudded oil and natural gas wells in each land cover class (Wang *et al.,* 2020) throughout the study period (1984-2014).

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