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Identifying, Characterizing and Addressing Soil and Groundwater Issues related to SCVF and other types of natural gas migration.

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Kirk Osadetz

Corresponding author:

Kirk Osadetz,

CMC Research Institutes Inc.,

3535 Research Road N.W., Calgary AB T2L 2K8

E: kirk.osadetz@cmcghg.com

T: 403-210-7108; F: 403-210-9398; C: 403- 919-4492

W: www.cmcghg.com

1 ABSTRACT

Natural and anthropogenic methane emissions are ubiquitous in sedimentary basins. Some human activities like the petroleum and coal based energy systems, agriculture and municipal solid waste disposal are human sources of these emissions. There are multiple potential sources that generate methane, but the impacts are similar regardless of their source. Unsaturated soils provide the major methane sink due to microbial methane oxidation, which reduces the net atmospheric methane flux from subsurface sources that migrate through the soil.

Most methane sources are not explicitly measured or monitored, but inferred using rational methods that are based on limited sampling and monitoring datasets. The 2010 Environment Canada national inventory, inferred Alberta upstream petroleum activities contributed emissions of 987.8 kt methane/yr, including “Accidental and Equipment Failure” methane emissions of 192.5 kt methane/year (19.5%) of which 78% (150.2 kt methane) is inferred attributed to surface casing vent lows and gas migration (SCVF/GM) from wells.

SCVF/GM is also measured annually and centrally compiled by some Provincial regulatory agencies such as the AER and BCOGC. Many leaking wells have been remediated, especially wells >300 m^3/day. Currently, (2016/06/02) the Alberta annual SCVF/GM emission rate is about 84.4×10^6 m^3, (~56.5 kt methane). The 2010 Alberta SCVF/GM methane emissions data was 63.5 kt methane or only about 42% of the 2010 National Inventory value. Measured and monitored SCVF/GM emissions have decreased progressively since 2008 and they are currently 11% less than the 2010 measured value, but 62% lower than the 2010 Alberta National Inventory estimates, an unexplained difference. Existing literature and reports do not portray wellbore SCVF/GM leakage accurately, primarily due to the reduction of these emissions with time, but also because some previous studies contain errors in fact.

The Upstream petroleum industry methane emission situation in in Canada is inferred different from that in the United States, where atmospheric methane emission increases are attributed to increased upstream petroleum activities. Canadian air quality studies find methane concentrations like the global atmospheric average and associated anomalies in heavier volatile organic carbon compounds are attributed to transportation emissions primarily.

Methane emissions effect: Public Safety and Human and Plant Health – although typically indirectly, as well as the climate. Impacts are similar regardless of the source of the methane and whether it is an emission of natural or anthropogenic origin. Rarely are significant specific impacts associated with Canadian upstream petroleum activities including SCVF/GM wellbore issues. Impacts from wellbores occur in the immediate vicinity of some wells, but similar effects at a distance may have other natural or anthropogenic sources, most which are not well characterized or documented. Cases of demonstrated or inferred contamination by leaking petroleum wellbores is commonly based on isotopic hydrocarbon composition and the

assumption, probably incorrect, that light hydrocarbon compositional components are stratigraphically immobile generally.

There is also an unsubstantiated perception that other potential sources of methane emissions such as water wells are not significant sources of wellbore leakage and atmospheric emissions, although these are not carefully monitored and they were not generally constructed with comparable regard for wellbore integrity. Leaking petroleum wellbores are identified, regularly monitored and serious leaks are remediated. The success of the monitoring and reporting strategy is illustrated by the declining SCVF/GM emissions with time, despite the increase in the number of petroleum wells. Whether other potential sources of natural and anthropogenic methane emissions, such as water wells, agricultural activities, landfills, or the agricultural degradation of the soil methane sink should be subject to similar monitoring and remediation strategies is outside the scope of this report, but it appears that SCVF/GM methane emissions were incorrectly inventoried in 2010 and that, despite their being the best characterized and most comprehensively and regularly monitored methane emission sources they have also been one of the targets of the earliest emissions reductions strategies. This emphasis on wellbore SCVF/GM does not reflect the relative importance of their emissions contributions.

Wellbore SCVF/GM leakages are clearly the most comprehensively monitored, reported and the most aggressively remediated sources of Canadian methane emissions. Other sources should emulate the monitoring and remediation example provided by SCVF/GM monitoring and remediation actions. A uniformly described Canadian methane leakage sources database from both natural and anthropogenic sources would be useful and informative for both GHG mitigation and policy formulation.

2 EXECUTIVE SUMMARY

Methane emissions, both natural and anthropogenic are a ubiquitous feature of sedimentary basins globally. These basins, which are also the focus of fossil fuel extraction activities are clearly the site of natural petroleum (hydrocarbons, including methane, and associated non-hydrocarbon compounds) seepages into the atmosphere. Total mass and rate of these geosourced petroleum seepages is not well understood, but it must be immense, based on studies of select processes, such as the volume of secondary biogenic methane that was produced by anaerobic bacteria responsible for the degradation that produced the Western Canadian bitumen and heavy oil accumulations from the Athabasca region alone (>4991 trillion cubic feet or 141.3 X 10^{14} m^3 Huang, 2015) practically all of which has been lost to the atmosphere, probably since mid-Eocene time.

Some human activities like the petroleum and coal based energy systems, agriculture and municipal solid waste disposal also result in atmospheric methane emissions. The petroleum well-based emissions and similar activities, like water wells, are distinguished from industrial and societal emissions because they facilitate the emission of methane that is currently naturally sequestered, or stored, with the Earth's crust, while in contrast, the agricultural and societal emissions are new sources of methane produced by organisms, particularly methanogenic microbes. Thus there are multiple potential sources for the generation of methane, some of which can be distinguished by isotopic compositional traits and association with other compounds. In contrast, the only significant natural sink for methane is unsaturated soils in which methane is microbially oxidized. As a result, the actual methane emissions from all but surface sources, such as animal waste, are commonly impacted by microbial activity in the soil sink, that tends to reduce the net atmospheric flux.

In general, for most sources, methane emissions are not explicitly measured and monitored, but rather they are inferred using worksheet calculations, based on specific previous studies of emissions rates from studies of places, machines and animals. The 2010 Environment Canada national inventory, an important reference date for methane emissions reductions targets, inferred that upstream petroleum activities in Alberta contributed emissions of 987.8 kt methane/yr, that included "Accidental and Equipment Failure" methane emissions of 192.5 kt methane/year, which constitute 19.5% of the upstream petroleum industry methane emissions, of which about 78% (150.2 kt methane) was attributed to surface casing vent lows and gas migration (SCVF/GM) from wells.

In contrast to many of the natural and anthropogenic methane sources wellbore SCVF/GM are measured annually, centrally compiled by some Provincial regulatory agencies such as the AER and BCOGC. Many leaking wells are remediated and their leakage rates reduced or terminated, especially at seriously leaking wells (>300 m^3/day). Currently, as of June 2, 2016, the Alberta average daily natural gas emission rate from well surface casing vent flows and gas migration is 22.4 m^3/day and the estimated annual natural gas emission rate for 2016 is inferred to be about 84.4×10^6 m^3 for 2016, (56.5 kt methane). In contrast to the 2010 National Inventory from SCVF/GM sources, the 2010 Alberta SCVF/GM methane emissions data was 63.5 kt methane or about 42% of the National Inventory value.

In spite of the annually increasing number of wells drilled in Alberta the total SCVF/GM emissions have been decreasing generally since 2008. Compared to the 2010 SCVF/GM data, wellbore leakage methane emissions have declined by 11% since 2010 and they are 62% lower than the 2010 Alberta SCVF/GM National Inventory estimates. It is not yet clear why the 2010 National Inventory estimate of upstream petroleum industry methane emissions overestimates significantly the measured SCVF/GM data that has been analyzed retrospectively. Available peer-reviewed and unreviewed literature and reports also do not accurately portray wellbore SCVF/GM leakage accurately, primarily due to the progressive reduction of these emissions with time, but also because some of those studies, including peer-reviewed publications contain significant errors in fact. Provincial databases are recommended as the preferred source of this data, its rates and volumes should always be cited identifying the source and date.

The wellbore leakage situation in Canada is inferred to differ from that recently inferred in the United States. Current and historical studies of Canadian air quality generally find methane concentrations like the global atmospheric averages and some studies suggest that anomalies in heavier volatile hydrocarbon compounds are attributable to transportation emissions not upstream petroleum activities.

Methane emissions, regardless of source, can effect: Public Safety and Human and Plant Health – although typically indirectly, and the Climate. Public safety is addressed by the petroleum regulators and industry using setbacks from structures. The impacts on plant health are well understood and clearly recognizable, but they depend on many factors and proscriptive leakage limits are not available, nor would they be easily determined considering the complex interactions between plant species, the microbial methanotrophs in soils and the physical and chemical role that soil properties exert on the process.

Only in specific situations and only uncommonly are significant detrimental impacts reported in association with Canadian upstream petroleum activities, and these are most commonly associated with ground and surface water impacts attributed, sometimes incorrectly, to gas migration in aquifers, but also including SCVF/GM wellbore issues in the immediate vicinity of the wells. Impacts from wellbores are typically immediately manifest in the vicinity of the well. Similar effects at a distance from a petroleum well have been sometimes shown due to other sources of methane and other gases, most which are not well characterized.

The attribution of contamination by leakage from petroleum wells is a topic of considerable regulatory, public and media concern. Arguments based on isotopic hydrocarbon compound alone assume, apparently often erroneously, that naturally occurring methane and other light hydrocarbons are generally stratigraphically immobile in the Western Canada Sedimentary Basin. The error of this assumption is illustrated by several features including, the loss to the atmosphere of immense volumes of petroleum including secondary biogenic gas generated during the microbial biodegradation of crude oil across the entire Mesozoic succession, the association of methane and other gases with bacterial contamination attributable to human and animal wastes and the fact that water wells, like petroleum wells, are potential conduits for wellbore leakage and atmospheric emissions. Few water wells are constructed with similar regard to wellbore integrity as that common to petroleum wells. Chemical tracer studies that are the most dependable method for demonstrating migration and contamination are exceedingly rare.

It is true that some petroleum wellbores leak and emit methane to the atmosphere. These are clearly identified, regularly monitored and required to be remediated when serious. As a result, the amount of petroleum wellbore SCVF/GM emissions have been declining despite the increase in the number of such wells. Such wellbore leakage is a significant source of atmospheric methane emissions, which is comparable to other inventory-assessed sources of atmospheric methane that are not regularly monitored, although recently British Columbia has required the monitoring and remediation of landfill methane emissions.

Upstream petroleum industry methane emission targets have, in the case of SCVF/GM already been technically achieved, primarily because the benchmark 2010 estimated emissions were significantly overestimated, but also because monitoring and remediation have resulted in a real and monitored 11% reduction of these emission since 2010 despite the significantly larger numbers of wells. Whether other potential sources of natural and anthropogenic methane emissions, such as water wells, agriculture, landfills, or the agricultural degradation of the soil methane sink should be subject to similar monitoring and remediation is outside the scope of this report, but it does appear that SCVF/GM methane emissions are the object of the earliest emissions reductions actions despite both being a relatively small part of the inventory and being the best characterized and most regularly monitored source of anthropogenic methane emissions.

Wellbore SCVF/GM leakages are clearly the most comprehensively monitored, reported and the most aggressively remediated source of Canadian methane emissions. Other sources should emulate the monitoring and remediation example provided by SCVF/GM actions. Other methane emitters should move from IPCC worksheet calculations of inferred methane sources to real, monitoring based studies that consider the role of all natural and anthropogenic sources and sinks, especially those that consider the local role of specific soils and their microbial communities. Top-down and bottom up technologies for methane flux characterization need to reconciled, which is both a knowledge and technology gap. Development of uniformly described databases of Canadian methane leakage sources from all anthropogenic sources into the atmosphere and into the shallow subsurface, should be based on measured and monitored values using appropriate combinations of top-down and bottom-up approaches that specifically cross-validate survey results.

3 STUDY GOAL, SCOPE AND SOURCES

GOAL, SCOPE AND PHASES

This study attempts to improving the understanding of the magnitude and impacts of SCVF and gas migration, the key types of gaseous wellbore leakage, by:

- Identifying gas migration paths to surface.
- Identifying and capturing all current relevant research regarding the magnitude wellbore leakage.
- Identifying and capturing all current relevant research regarding the impacts of wellbore leakage, particularly with respect to the shallow subsurface

Wellbore leakage is the unintended migration and release of gas and other formation fluids from any type of wells to the atmosphere, soils or subsurface strata. Such leakage may contribute to greenhouse gas emissions or the contamination of other resources, especially groundwater and soils. Concerns regarding contamination and has inhibited or delayed petroleum development in some regions, especially where those developments involve the use of horizontal drilling and reservoir stimulation by multiple induced hydraulic fracturing stages.

While the issue is not new, it has received considerable public attention recently due to news articles, journal publications and various reports, including the Council of Canadian Academies (CCA) (Cherry and others, 2014) and Canadian Water Networks (CWN) (Gagnon and others, 2015) reports on the environmental and subsurface impacts of shale gas development and hydraulic fracturing.

We note, from the outset that that there is a major distinction between hydraulic fracturing activities and wellbore gas leakage. Where petroleum activities that employ hydraulic fracturing contain the introduction and injection of water dominated substances that contain other chemical additives (Vidic et al., 2013) that have been the subject of societal concern, as described in the CCA (2014) and CWN (2015) reports, the leakage from wellbores has both safety and non-safety impacts. Where there are safety concerns they are addressed immediately. Where there are non-safety concerns – many of them potentially serious, we must consider that we are dealing with migrations of naturally occurring substances, the impacts of which are well understood because of their common appearance in the environment, and the need to address analogous migration issues and impacts in other settings and uses, most notably natural gas transportation, waste management and coal mining. This report draws heavily on the available data and impact studies of analogous studies of gas migration in the shallow subsurface and into the atmosphere, where much previous work informs gas migration from wellbores. Most importantly, we note that methane also has biological sources, including human sources, and that methane in potable water is not addressed or limited in either the Canadian or World Health Organization drinking water guidelines (e.g. Alberta Environment, Methane and Groundwater, http://environment.gov.ab.ca/info/library/8079.pdf and URL's therein).

The various studies done on the subject of wellbore and other sources of gas leakage and the public concern over the issue, emphasize the need to better understand wellbore leakage, including how it can be reduced and what its potential range of environmental impacts are. This study component focuses on improving our understanding of the magnitude and the impacts of wellbore leakage, as compared to other leakage, and its impacts, particularly with respect to the shallow subsurface and atmosphere. We discuss identify gas migration paths to surface. We identify and capture all current key relevant research on the subject to answer the following questions:

- What is the magnitude of methane emissions from leaky wells to the atmosphere and to the subsurface, and how does it compare to other sources?
- What is the impact of methane leakage on the environment: impact on groundwater quality and soil, and attendant impacts to biota?
- What, if any, is an acceptable leakage rate? And, if we don't have the answer, or complete answer, to the above questions, then:
    1. What currently existing or ongoing studies, knowledge, technology, or regulatory changes could be applied to help answer the questions?
    2. What knowledge and technology gaps remain?
    3. What R&D will help address these gaps?

SOURCES AND CONSULTATIONS

This study included a phase of consultations and inquiries that provided perspectives, data and interpretation that were especially beneficial for the preparation of this report. The most significant issue encountered in this study was not the estimation of SCVF and GM methane emission volumes, but rather the analysis and determination why essentially all the prior reports of SCVF and GM methane emission volumes were, as a group contradictory – even when they used identical data sources of identical vintage. In the end, as discussed below, we infer that the Alberta and British Columbia regulatory data sets, which are themselves dynamic and time varying, should be considered the only reliable source of SCVF and GM data. This is discussed extensively below.

Consultations related to this study can be classified as belong to the following group:

1. Consultations, data and information exchanges with regulatory agencies;
2. Consultations, data and information exchanges with individuals, corporations and associations that are predominantly composed of petroleum industry corporate members.
3. Consultations and data sharing of third party data with individuals in consulting firms and academia with a special emphasis on contributors to both the peer-reviewed and non-peer-reviewed journal and report literature on the subjects addressed.

REGULATORY AGENCIES:

The authors are most indebted to the staff of both the AER and the BCOGC for their open and willing sharing of their reports, some of which were in draft form. Information, slide decks and discussions with Gerry Boyer, Senior Advisor, Industry Operations AER Anita Lewis of the AER Closure and Liability, petroleum group were essential for the provision of key data and reports and slide decks that discuss the data and interpretation of SCVF and GM volumes in Alberta. John Nurkowski of the BCOGC provided similarly valuable information and insight from a British Columbia perspective. The AER’s Climate Policy Assurance Team, led by Mark Taylor, shared key draft documents including a reports on the history and current state of Alberta SCVF and GM volumes and characteristics (AER, 2016a) that is the most important data within this report. The CPAT also provided a draft background report (AER 2016b) that included AER perspectives on the 2010 reference level upstream petroleum industry methane emission inventory in Alberta. It is interesting that these two documents indicate significantly different perspectives on contribution of SCVF and GM to the 2010 Alberta reference level upstream petroleum industry methane emissions as stated in the Environment Canada National Inventory (2014) that was prepared by Clearstone Engineering (Environment Canada, 2014; AER 2016b) and the 2010 Alberta reference level of these emissions that is calculated from the AER SCVF and GM reporting data (AER 2016a). This difference remains to resolved and discussions with the AER will continue. This difference, while simply noted in this report could have significance for policy and regulation, specifically as it applies to the question of the targeted 45% reduction of upstream petroleum industry methane emissions because it appears that the 2010 Alberta inventory methane emissions were significantly overstated (Environment Canada, 2014; AER 2016b). As a result, it would appear that the inferred 2016 SCVF and GM emissions (Table 2 in AER, 2016a) are only about 37% of the reported 2010 Alberta methane emissions inventory (Environment Canada, 2014; AER 2016b), which technically exceeds the 45% reduction target without any action being required, whereas the actual reduction of Alberta methane SCVF and GM emissions is only reduced about 11% compared to the 2010 emission volumes determined using the measured data source (Table 2 in AER, 2016a).

INDUSTRIAL CONSULTATIONS:

The data compiled by regulatory agencies is measured by and submitted by upstream petroleum companies their employees and consultants. We are especially grateful for the discussions and information provided by employees and consultants that provides individual and corporate perspectives on SCVF and GM occurrences with a strong focus on their remediation, which was not a specific focus of this study, but which was important background information. More important is the diligent and professional reporting of SCVF and GM data by individuals and corporations to the AER and the BCOGC which serve to populate the regulatory databases from which the comprehensive, measurements and other data regarding SCVF and GM wellbore leakage are derived. Most specifically, we appreciated discussions and data transfers from individual members of the Canadian Society of Gas Migration (CSGM), especially Mr. Jay Williams, President, who in his corporate role as an employee of Weatherford Inc. provided a copy of the April 2016 AER SCVF and GM dataset to us for analysis and incorporation in this report, although most of the key SCVF and GM statistics cited are actually based on the June 2016 extraction from that same database (2016). John Slofstra, a CSGM Director, was a key source of non-peer reviewed literature and reports related to this topic. We are also appreciative of the perspectives and priorities that Ms. Teresa Watson provided on this topic.

The essence of the industrial discussions are also captured and reflected in the Summary Report of the March 12, 2015 CSGM workshop (AITF, 2015), the CSGM special session at the 2016 Geoconvention in Calgary, Tuesday March 8th, 2016, (http://www.geoconvention.com/delegatebook/) and the CSGM Technology Roadmap Workshop in Calgary, June 28, 2016.

CONSULTATIONS RELATED TO THE REPORTING AND ANAYLSIS OF THIRD-PARTY DATA:

Typically, one relies on peer-reviewed publications as the authoritative sources of information regarding both data and interpretation. Unfortunately, that is not the case for this study and much of the effort in this study was spent trying to reconcile aspects, particular emissions volumes, in the peer-reviewed literature on the subject of wellbore integrity, SCVF and GM in Alberta and British Columbia with, other peer-reviewed publications against both non-peer reviewed publications and reports. Details of the inconsistencies in the data and its interpretation are discussed below in additional detail. The source of most inconsistencies were resolved to be a combinations, key among which are the temporally varying nature of the emissions data due to, the continued addition of wells to the SCVF and gas migration database, the significant and on-going attempts of industry to remediate wells, especially the "serious" wells that are the source of the largest emissions, and errors in fact in all types of published and non-published literature and reports, most of which are resolved herein and through correspondence with the authors. We are especially appreciative of the frank and open correspondence with Richard E. Jackson of Geofirma and Ali Nomamooz of Laval University. We also wish to express our appreciation to Mr. Larry Taerum, recently of Chevron Canada, who was instrumental in the reformatting of historical AER SCVF and GM well data that was employed in several of the conflicting reports, which helped to both identify and address the data issues in these publications and papers. As stated above, the regarding the apparent overstatement of Alberta SCVF and GM methane emissions reported in national inventories (Clearstone Engineering, 2004a; Environment Canada, 2014; AER, 2016b) as compared to the emissions inferred from the well data reports (AER, 2106a) remains to be resolved.

As a result of these consultations we recommend that emissions volumes should always be referred to the vintage and sources of data from which they were extracted, that provincial regulatory data compilations should be employed as the best and most comprehensive source of data and the no future employment of Alberta SCVF and GM data in essentially previous publications, all of which significantly and erroneously overstate either emissions volume and well integrity issue rates, some of which are widely sited and that have been used to establish policy and emissions reduction targets should be abandoned and disregarded, except for their mention in historical context or as they have been adopted for policy and regulatory reasons. Below we employ the SCVF and GM data from the AER (2016a, retrieved June 2, 2016, except where otherwise stated)

4 SOURCES OF METHANE

Petroleum, both crude oil and natural gas that is composed predominantly of hydrocarbon compounds, but which may also contain significant non-hydrocarbon gases, is a ubiquitous feature of both sedimentary basins and the natural near surface environment (Tissot and Welte, 1984; Hunt, 1979). There are three primary mechanisms for the generation of petroleum (Schoell, 1988), including:

- thermocatalytic generation from kerogen,
- biogenic generation from organic matter, kerogen and petroleum alteration, both of which are important for the consideration of Canadian petroleum leakage.
- inorganic carbon reduction at high temperatures, an unimportant contribution volumetrically that is neglected hereafter.

Petroleum can also be manufactured industrially (Hamper, 2006), commonly from either coals or kerogen and these processes are mentioned here because the of the historical, engineering and scientific importance of manufactured gas for understanding of the impacts of petroleum on safety, soils and plants.

Thermocatalytic generation of petroleum has ceased in Canadian onshore sedimentary basins, because of the cooling of source rock kerogens associated with the pervasive uplift and erosion that affects all onshore Canadian sedimentary basins since about mid-Eocene time (55-45 mya). Biogenic petroleum generation, particularly light hydrocarbons, predominantly methane, from “primary” biogenic generation is inferred to continue currently in some settings and environments, as indicated by contaminated water wells (Cheung and Mayer, 2009; Jones et al., 2011), landfills (Themelis and Ulloa, 2007), wetlands (Conrad, 1996) and soil gas generation (Le Mer and Roger, 2001). Secondary biogenic methane and other hydrocarbons result primarily from the anaerobic biodegradation of crude oils by microbes (e.g. Huang, 2015).

5 PATHWAYS FOR GAS MIGRATION AND FLOWS FROM THE SUBSURFACE

PETROLEUM SEEPS FROM NATURAL FEATURES AND ANTHROPOGENIC CONSTRUCTIONS:

Commercially produced petroleum from the Western Canada Sedimentary Basin (WCSB) and other Canadian onshore sedimentary basins (e.g. Michigan Basin, St. Lawrence Lowlands, Appalachians) can have either thermocatalytic, biogenic or mixed origins. Therefore, it is essential to understand that anthropogenically induced leakages from petroleum and water wellbores, mines, landfills and other anthropogenically engineered structures is a facilitation and acceleration of the natural process of the general and eventual migration of all petroleum to the surface over time, either as hydrocarbons, or as carbon dioxide, if the petroleum is biologically degraded prior to reaching the surface. A clear indication of this is the general stratigraphic distribution of petroleum resources in conventional (i.e. secondarily migrated) petroleum pools which shows a distribution strongly weighted toward occurrence in geologically younger parts of the stratigraphic succession (Figure 1).

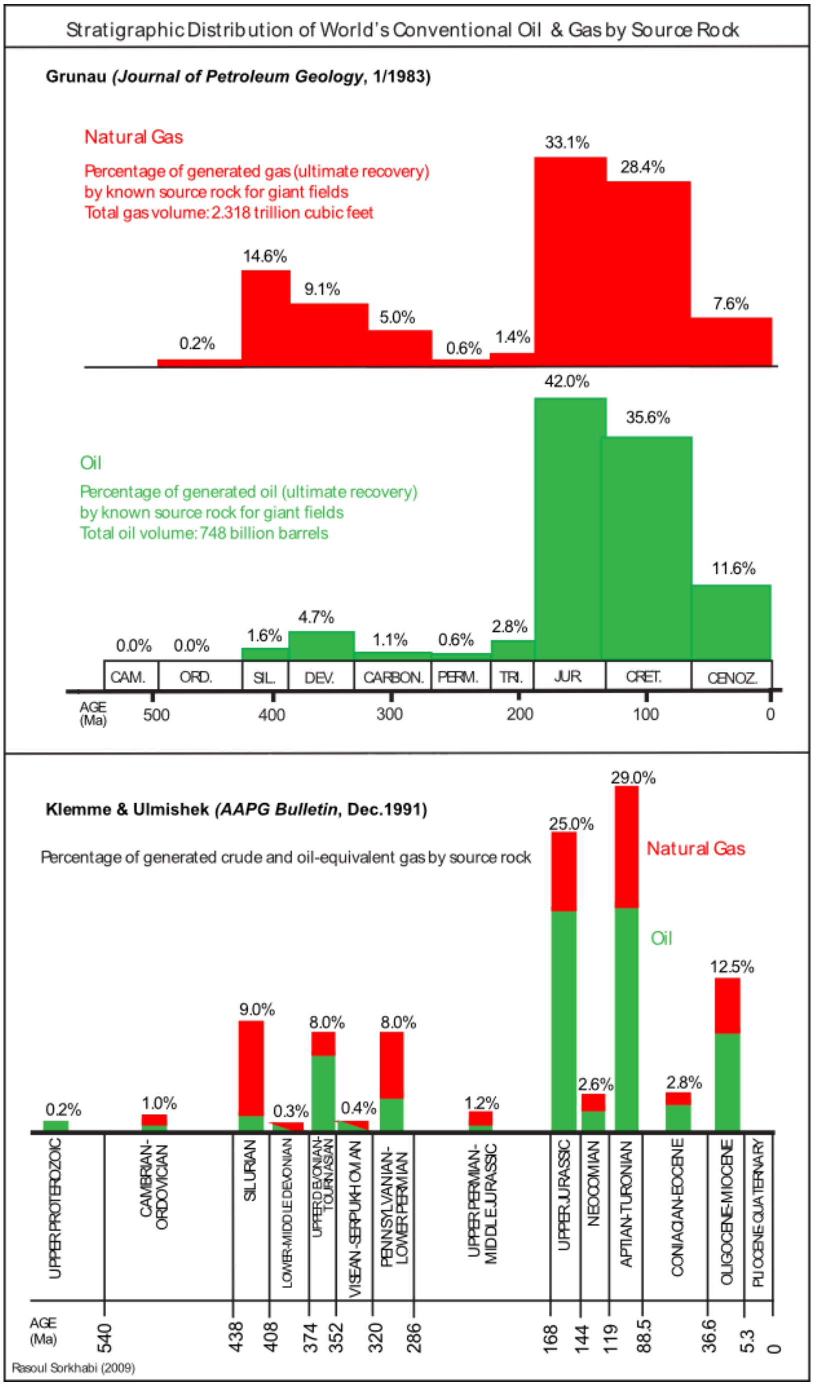

Figure 1: The stratigraphic importance of geological age relative to petroleum system productivity. There is little reason to infer that any given period is more or less productive than any other, even in the presence of anomalous geological and biological events, such that the disproportionate weighting of petroleum resources to occur in younger strata suggests primarily a greater preservation potential and less time for both biological degradation and physical loss of the petroleum generated (sources from the literature, diagram from R. Sorhkabi, 2016).

The role of microbes is of key importance since microbial communities comprise mixtures of methanogenic and both aerobic and anaerobic petroleum-trophs, especially methanotrophs.

Methanogenic bacteria, operating predominantly in strongly reducing and oxygen deplete environments, can be a source of methane (other bacteria are also known to generate lesser ethane, but less commonly) that augments or is the sole source of a gas leakage. Petroleum-trophs can either contribute to gas sources, as in the significant generation of secondary biogenic gas attributed to the anaerobic biodegradation of petroleum or they can consume and oxidize petroleum such that leakages are either reduced or completely dissipated (see reviews by Conrad, 1996; Le Mer and Roger, 2001).

It is also important to distinguish leakages from contamination. Where leakage is can be either naturally or anthropogenically facilitated, contamination implies that the appearance of methane at one location, potentially a well for any purpose, has its origin at another place, ultimately from a natural source, but perhaps facilitated by another engineer structure, potentially a different well, as discussed in more detail below.

METHANE LEAKAGE IN THE UPSTREAM PETROLEUM SYSTEM: THE UNITED STATES EXAMPLE

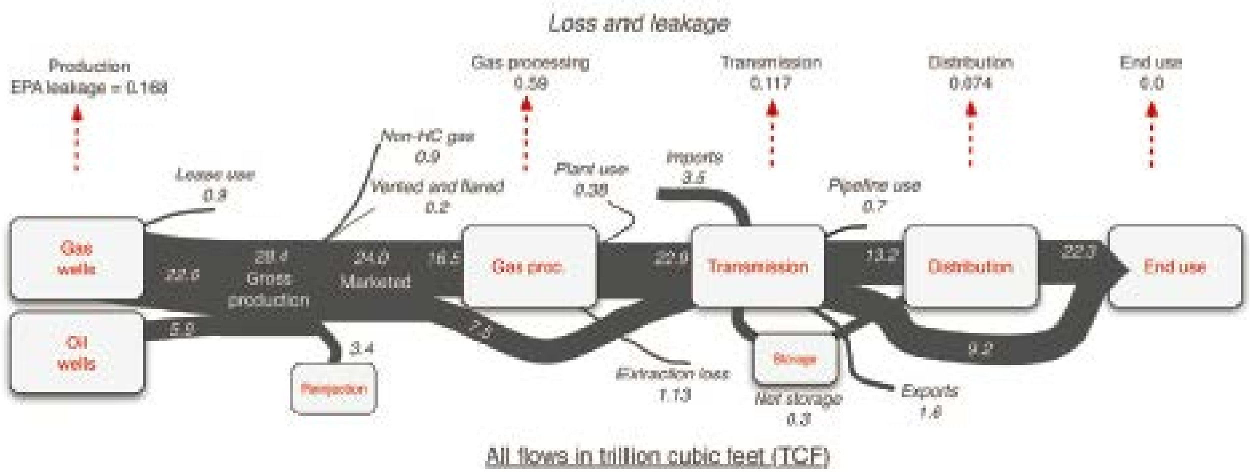

Figure 2: Flows and leakage in the US natural gas system (from Brandt and Petron, 2015 their Figure 1) showing estimated flows and leakages from the US gas system.

Brandt and Petron (2015) illustrated the estimated flows and leakages from the US gas system (Figure 2). They employed data from both the United States Environmental Protection Agency inventory (2015) and various sources of US Energy Information Administration data. The inferred leakage at various stages of the system are:

- Production facilities (~wells) is 0.168 TCF (10.4%),
- Gas Processing is 0.59 TCF (36.5%),
- Gas Transportation (~pipelines) is 0.117, TCF ((7.2%)
- Gas Distribution is 0.74 TCF (45.8%), and
- End Use is 0.0 TCF (0%).

Kort et al (2008) used COBRA-NA atmospheric observations to estimate of the combined Canadian and American natural gas leakage and obtained a result that was consistent, within the uncertainty of their estimate, with the EPA inventory for the USA alone (Kort et al. (2008) shown as reference 5 in Brandt et al., 2014, their Figure 1). Their result suggests that Canadian atmospheric methane emissions are small compared to American emissions measurements and inventories. A Canadian model similar to Figure 2 is not available, but the proportional contributions along the system can be inferred similar due to the technological similarities of the two systems, which are integrated. Data from Canadian wellbore presented below confirms this inference.

Figure 3 illustrated the two primary methods by which atmospheric methane emissions are either monitored or inferred. Top down methods are represented by actual air samples. While these methods typically detect total emissions over large area and are characterized by higher methane concentrations they can affected by weather conditions at the time of the survey and there are both more removed from and less certain of the source of the measured values. In contrast the more commonly performed and more extensive data set from bottom-up studies, while more expensive and subject to inferred sampling bias are more clearly and unambiguously associated with sources of emissions and they are capable of indicating flux rates into the atmosphere, which the top-down methods are not similarly capable of performing. In general, where both measurements exist the total emission from top-down methods often are larger, sometimes significantly, than those obtained by bottom-up methods, as discussed below.

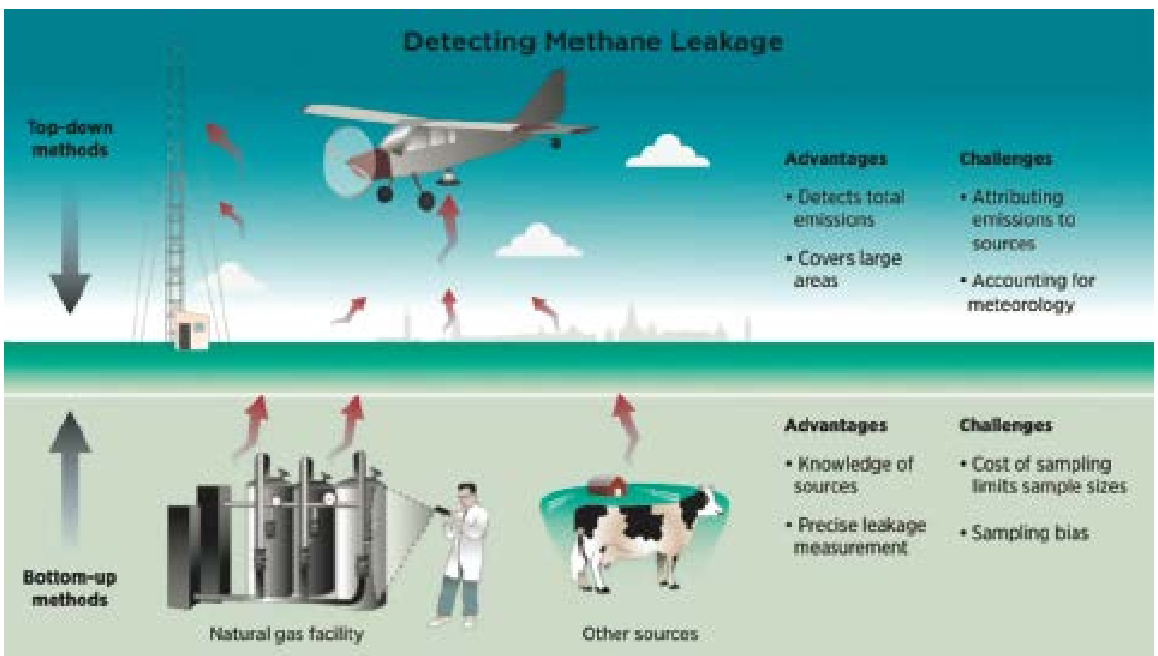

Figure 3: *Illustration of top-down and bottom-up methods for detecting methane leakages. The advantages and disadvantages of the methods are complementary, suggesting important information to be gained from using both methods" (Figure and caption from Brandt and Petron,*

2015, their Figure 2 that includes acknowledgement for the illustration from John Bellamy, Stanford University).

METHANE LEAKAGE IN THE UPSTREAM PETROLEUM SYSTEM IN ALBERTA AS ESTIMATED IN THE 2010 CANADIAN EMISSIONS INVENTORY

2010 Alberta methane upstream petroleum industry emissions (Environment Canada, 2014; AER 2016b) for the base case against which methane emission reduction targets will be compared (Table 1). Note that wellbore leakage attributable to SCVF/GM are included in Accidents and Equipment Failures where they account for about 78% of that class of methane emissions. On this discounted basis the 2010 inventory appears to significantly overstate the SCVF/GM methane emission that were retrospectively obtained from well monitoring data (AER, 2016a), as discussed below.

Table 1: 2010 Alberta methane emission inventory for upstream petroleum activities (AER, 2016b).

Methane Emissions by Sector and Source, 2010			
Sector	**Source**	**Total (kt/y)**	**% Share of Total**
Natural Gas Production	Unreported Venting	209.179	21.2%
Accidents and Equipment Failures	Surface Casing Vent Flow and Gas Migration	192.464	19.5%
Heavy Crude Oil Cold Production	Reported Venting	158.285	16.0%
Light/Medium Crude Oil Production	Unreported Venting	82.115	8.3%
Natural Gas Production	Fugitive Equipment Leaks	80.79	8.2%
Light/Medium Crude Oil Production	Reported Venting	52.829	5.3%
Light/Medium Crude Oil Production	Fugitive Equipment Leaks	34.648	3.5%
Gas Transportation	Fugitive Equipment Leaks	26.542	2.7%
Natural Gas Production	Fuel Combustion	22.479	2.3%
Heavy Crude Oil Cold Production	Fugitive Equipment Leaks	22.078	2.2%
TOTAL		**987.742**	**100%**

In contrast to the poorly quantified natural petroleum seepage into soils and the atmosphere, the flux attributable to wellbore surface casing vent flows, migration and other leakage pathways (Figure 4) are much better understood and characterized due to considerable industrial effort (e.g. Jocksch, 1993; Erno and Schmitz, 1994; Szatkowski et al., 2002; Watson and

Bachu, 2009; King and King, 2013; Jackson and Dusseault, 2014; Davis et al., 2014; see also the resources at: http://www.wellintegrity.net/ and a general review of well integrity reinterpreted with respect to CO2 injection and storage by Zhang and Bachu, 2011).

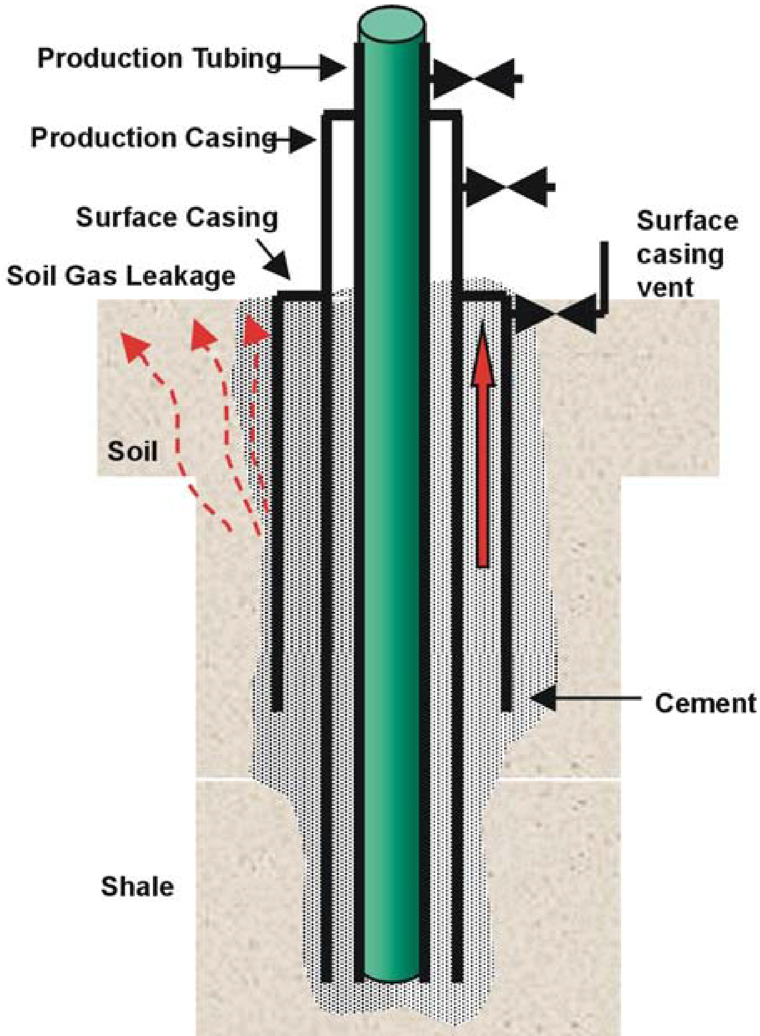

Figure 4: Conceptual and Diagrammatic illustration of methane migration pathways into, in the shallow surface and from there into the atmosphere. Other more complicated diagrams have been proposed (e.g. Jackson and Dusseault, 2014), but these often contain speculations regarding the migrations pathways, such as the role of fractures in the rock succession, that are in general conjectural as discussed in the text below.

A recent and detailed report (Ingraffea et al., 2014) studied casing and cement impairment using 75,505 compliance reports for 41,381 conventional and unconventional petroleum wells in Pennsylvania drilled from January 1, 2000–December 31, 2012, to determine the statistics of casing and cement issues that impact wellbore integrity. The data indicated a higher incidence of cement and/or casing issues for shale gas wells that was six times higher than that of conventional wells. A similar risk is not apparent in Alberta as discussed below. They employed a "Cox proportional hazards model" that identified both temporal and geographic differences in risk, such that post-2009 unconventional gas wells had an integrity risk for cement or casing 1.57

that of a conventional well drilled within the same time period. They also found that unconventional gas wells in northeastern Pennsylvania had integrity issues that were 2.7 times higher relative to the conventional wells in the same area and that the cumulative risk for all wells (unconventional and conventional) in that part of Pennsylvania is 8.5 times greater than for wells drilled in the rest of Pennsylvania. The methods and results of this analysis, while generally similar to the approach of Watson and Bachu (2009) set a potential standard for understanding well risk.

Beaubien et al. (2013) monitored soil gas and CO_2 flux around the Weyburn oil field from 2001–2005 and in 2011 to determine baseline values and distributions, and to monitor for surface leaks, above a pilot CO_2-Enhanced Oil Recovery (CO_2-EOR) project in southern Saskatchewan. Results show no sign of leakage of the injected CO_2 and the spatial and seasonal trends and measured values from discrete sampling of soil gas CO_2, O_2, Ar, N_2, $\delta^{13}C$-CO_2, He, Rn, and CH_4, and the continuous monitoring of soil CO_2 and Rn, as well as from discrete sampling of CO_2 flux were attributed to near-surface biochemical processes, seasonal environmental conditions, and soil properties. They also found other light hydrocarbon gases, like C_2H_4 and C_2H_6, to be generally near or below detection limits.

Sponja (1995) and Watson (2004) provide decision trees and summaries regarding the identification and repair of wellbore leakage problems. Vishwanathan et al. (2008) provided a method for the assessment of wellbore leakage, while Tao et al., (2013) developed a method to infer the effective permeability of leaking petroleum gas wells and Newell and Carey (2013) performed an experimental evaluation of wellbore Integrity along a cement-rock boundary. They found that the permeability of leakage pathway decreased during their experiment due to chemical reactions with the CO_2-rich fluid they employed. The observed reduction in the leakage permeability is not a general characteristic of such studies.

Wellbore casing pressure, surface casing vent and gas migration issues (wellbore leakage) cannot be considered in isolation. Depending on the migration pathways there are multiple opportunities for:

- Capillary trapping in lithic and soil pore space,
- Adsorption onto coal and other mineral surfaces,
- Solution storage in pore space and soil waters (although due to the low solubility of petroleum gases in waters this is not a key factor), and
- Biological interactions with soil microbial communities that will either augment or diminish the migrating gas volume due to either methanogenesis and methanotropy. Especially in soils (Le Mer and Roger, 2001).

There is a common, but probably inappropriate, use of or appeal to surface fractures as analogs for naturally fractured reservoirs at depth. Especially important is the depth to which joints and fractures seen at the surface penetrate downward to provide discontinuities along which migration and leakage can occur. The fact that this pathway is not well understood is indicated by both the lack of migration information related to claims of contamination, which is discussed below in the context of migration, leakage and contamination.

While fracture migration pathways can be present at any depth within the brittle Earth, it is increasingly rare to find open fractures with increasing depth and it is extremely unlikely that the fracturing and joint patterns in the subsurface resemble those in the subsurface. This occurs because of the stress state changes with increase of lithostatic/hydrostatic pressure ratios with increasing depth, such that fractures observed at the surface are highly unlikely to extend downward significantly.

Rutquist (2015) summarized the rock mechanics of fracture permeability, finding a general decrease in permeability with depth that also showed up to six orders of magnitude variations of permeability with depth in specific instances. In general, many fractured crystalline rock sites exhibit a more pronounced depth dependency on fracture occurrences. Fractures are more commonly found in the upper 100–300 m of the bedrock, like that observed at the URL Pinawa. The more pronounced depth dependency at shallow depths is attributed to nonlinear normal stress-aperture relationship of extension joints that was also observed by Snow (1968), who studied numerous dam foundations. In addition, open subsurface fractures become the site for mineralization and cementation, as attested to the common appearance of filled than open fractures in petroleum and mining cores. Studies in underground mines and test facilities such as the Underground Research Laboratory in Pinawa, Manitoba, show that almost all surficial joints and fractures and iron-oxidation effects end at a few tens of metres below the ground surface (Martin, C.D. and N.A. Chandler, 1994; Everitt et al., 1998). This suggests that pervasive fracture networks such as those suggested by Jackson and Dusseault (2014, Fig. 1, p. 2) to occur to depths of ~500 m are unlikely geomechanically, although it is possible that individual sites could contain rare open fractures to these of deeper depths, especially where diastrophic and non-diastrophic process such as endogenic karst, such as salt dissolution processes have occurred.

As such the actual migration pathways (Figure 4) both in wellbores, their annulus and the adjacent rock mass are largely conjectural and poorly documented. One important corroborating indicator for the sparsity of natural open fractures in rocks is clearly apparent by the success of induced hydraulic fracturing. Pre-existing open and even mechanically closed fractures are always more easily dilated as compared to the process of forming new fractures. The simple observation that induced hydraulic fracturing "works" and typically produces neoformed fractures is a clear indication of the subsurface, even at moderate depth is not commonly fractured. This is also confirmed by the sparsity and rarity of open fractures in recovered petroleum cores. Meissner (1978), among others, proposed that the volume increase accompanying petroleum generation resulted in a pervasive natural hydraulic fracturing of petroleum source rock successions, especially with reference to the Bakken shales. Early horizontal wells drilled prior to induced hydraulic fracturing indicted that his inferences were unsupported by observation and well performance.

6 METHANE EMISSIONS FROM WELLBORES: SURFACE CASING VENTS AND GAS MIGRATION.

PREVIOUS STUDIES AND ESTIMATES OF SCVF AND GM IN ALBERTA AND ENVIRONS:

Typically, one relies on peer-reviewed publications as the most reliable source of information. One also hopes that key industrial reports, some of which are used in the formulation of national inventories and policies will be comparably reliable. Unfortunately, this is not the case for the topic of SCVF and GM studies for several reasons:

1. The emissions rates are subject to both natural variations, with a general tendency for declining emissions with time, and engineering interventions to reduce emissions that are performed directly to mitigate the leakage from serious wells and at the time of abandonment to mitigate the leakage from non-serious wells. In addition, it is clear that historical efforts to improve well construction and develop improved materials has resulted in a decline in the number of leaking wells and their SCVF and GM issues. As a result, the current emissions rates are subject to change temporally, with a clear trend downward to lower total emitted gas volumes.
2. Peer reviewed and non-peer reviewed literature also contain significant, typically inexplicable errors and inconsistencies that are reconcilable with the available data (e.g. R. Jackson pers. comm., and discussion below), and finally,
3. Some of the earliest studies of well integrity issues dealt with wellbore gas leakage and gas migration more broadly, including leaks related to wellhead assemblies that would not currently be included in SCVF and GM emissions estimates.

The result is that the data and interpretations in the peer-reviewed and some of the non-peer-reviewed literature should be discounted as either superseded and incorrect or both. However, we present a brief review of these studies and some analysis of their contents. There are several published studies of SCVF and gas migration characteristics in Canadian settings including, some of which were mentioned previously.

Among the earliest studies is a restricted Saskatchewan study by Erno and Schmitz (1996) that looked at well integrity failure SCVF and GM. In 1999 and 2005 Clearstone Engineering (1999, 2005a) performed comprehensive studies of Upstream Petroleum industry GHG emissions, including methane. The 2005 report explicitly identifies Surface Casing Vent Flow and Gas Migration contributions in the year 2000 as 3217 and 42 ktCO_{2eq}., which is the equivalent to approximately 130.36 kt of methane, and that these constituted about 78% of the emissions attributed to “Accidents and Equipment Failures” (Clearstone, 2005a, Table A). Subsequently the estimate of emissions attributed to “Accidents and Equipment Failures” increased to 192.464 kt of methane (AER, 2016b attributed to Environment Canada, 2014) suggesting that SCVF and GM emissions were in the neighborhood of 150 kt methane, if the proportion of emissions in the “Accidents and Equipment Failures” category remained unchanged.

A benchmark study was performed by Watson and Bach (2007 reprinted in 2009) who considered the integrity SCVF and GM of Alberta wells drilled between 1910-2004. However, they provide no estimate of the cumulative wellbore leakage volume, either from the wells or into the atmosphere. Their study is, and remains, the most comprehensive and best documented discussion to SCVF and GM and its association with well construction features and other factors. Key among their finds was the observation that: wellbore leakage issues declined from peaks of about 10% of wells spudded prior to the revision of Alberta well cementing guidelines, around 1980, to less than 2% of wells spudded in 2004, when their study concluded. They found that: well location, deviation, whether the well was cased prior to abandonment, the abandonment method, the presence of uncemented well annulus and the regulatory and business environment were major factors associated with wellbore leakage; that the well operator, depth of surface casing, total well depth, geographic well density and topography were less strongly associated with wellbore leakage; and that well age and current status, the completion interval and the presence of acid gas components were not associated with well leakage.

Bachu and Watson (2009) subsequently discussed the issues related to only acid gas injection wells. They concluded that wells posed a greater risk for leakage than geological features such as faults and fractures. Focusing on the risks of potential CO2 storage in geological media they employed 31 wells used for CO2 injection and 48 wells used for the disposal of produced acid gas from sour gas plants, of which 22 wells were drilled specifically for acid gas disposal to study a variety of well integrity issues including surface casing vent flow, casing failure, tubing failure, packer failure, and zonal isolation failure. They demonstrated that well failure was lower for wells constructed specifically for acid gas injection and disposal than for other wells that were converted to injectors. They found that injection was not primary cause of well integrity issues, but that well construction and completion factors were more important, especially if wells were constructed prior to 1994. They found that rates of well failure in acid gas injectors were comparable to those in the general, petroleum production, population, but noting that purpose built acid gas injector wells had a lower failure rate and they concluded that wells constructed in a properly regulated environment should result in few anticipated well failures. Their work is widely cited and we note that Celia et al (2009) elaborated on their analysis of well depth as a risk factor, while Fabbri et al. (2012) proposed a revision to the risk management framework proposed by Watson and Bachu, 2007, where the later used an inappropriate method for the treatment of missing data.

In a peer-reviewed literature contribution Jackson and Dusseault (2014) stated that 14% of post-1971 “energy” wells had serious SCVFs exceeding 300 m^3/day and shut-in pressures > 11 kPa times the surface casing depth. They cite Vidic’s et al. 2013 statistics for enforcement orders in Pennsylvania. Neither Jackson and Dusseault (2014) nor Dusseault et al. (2014) explicitly stated a total gas flux for either British Columbia or Alberta, but is possible to infer flux estimates from a graphical analysis of their Figures. Unfortunately, this study contains errors in fact and any stated or inferred statistics related to rates of well failures or emissions rates should be disregarded (R. E. Jackson, pers. comm.).

A thesis-based study by Checkai et al (2013) of wellbore leakage in British Columbia used BCOGC 2011 SCVF data to infer the effective permeability of leaking wells that was also reported by (Tao et al., 2013). Davies et al., (2014) included the benchmark Alberta and Saskatchewan studies in a global study of well integrity. Boothroyd et al. (2015) provide one of the few studies that specifically considers fugitive emissions from abandoned wells, which are not commonly studied or sampled.

There are also individual well studies including wells in other provinces, specifically an abandoned shale gas well in Quebec (Nowamooz et al., 2015) and a single heavy oil well in Saskatchewan (Szatkowski et al.). The Alberta data cited by Nowamooz et al., was obtained from Jackson and Dusseault (2014). There are notable contradictory differences between the reporting of SCVF and GM data in these two papers even though they both employ the same SCVF and GM data file from the AER and BCOGC regulatory databases. This work should be treated as dated and superseded.

HISTORICAL AND CURRENT SCVF AND GM EMISSIONS IN ALBERTA FROM THE AER (JUNE 2, 2016).

Of primary importance is the apparent historical decline of wellbore leakage issues as a percentage of wells drilled since the early 1980's (Watson and Bachu, 2007, their figure 9), even at the total number of wells being spudded increased (Watson and Bachu, 2007, their figure 8a). Jackson and Dusseault (2104) suggested that this trend had reversed, but the AER data and its analysis, as discussed below indicate that this is not the case.

In Alberta (AER 2016a), wells with methane predominant surface casing vent flows (SCVF) has increased over time, generally because of the annually increasing number well and the much fewer well abandonments. 1980s, The Energy Resources Conservation Board (ERCB) Drilling and Completions Committee, which had noticed these emissions as early as the beginning of the 1980, was the lead agency in the development of ERCB issued Interim Directive 95-01: Surface Casing Vent Flow / Gas Migration Requirements that instituted required reporting/monitoring, categorization, and repair schedules, in part to provide industry with guidelines for well integrity remediation. Beginning in 2003 electronic SCVF / gas migration (GM) electronically statistic reporting began using the AER's Digital Data Submission (DDS) system. In conjunction with the switch to digital reporting previous hard-copy reports were entered into the DDS system. As a result, the historical tracking of all SCVF/gas migration statistics can be inferred:

- almost comprehensive, but possibly under reported for non-serious wells and possibly over reported for serious wells (see below);
- measured and accurate generally where reported;
- time dependent and up-to-date; and

considering the year over year increase in the number of completed well and new opportunities for SCVF and GM well problems to arise, the reported number of wells, by classification (Figure 5) indicative of active industrial remediation efforts to reduce the number of serious wells and to mitigate the volume of such methane emissions (Figure 5).

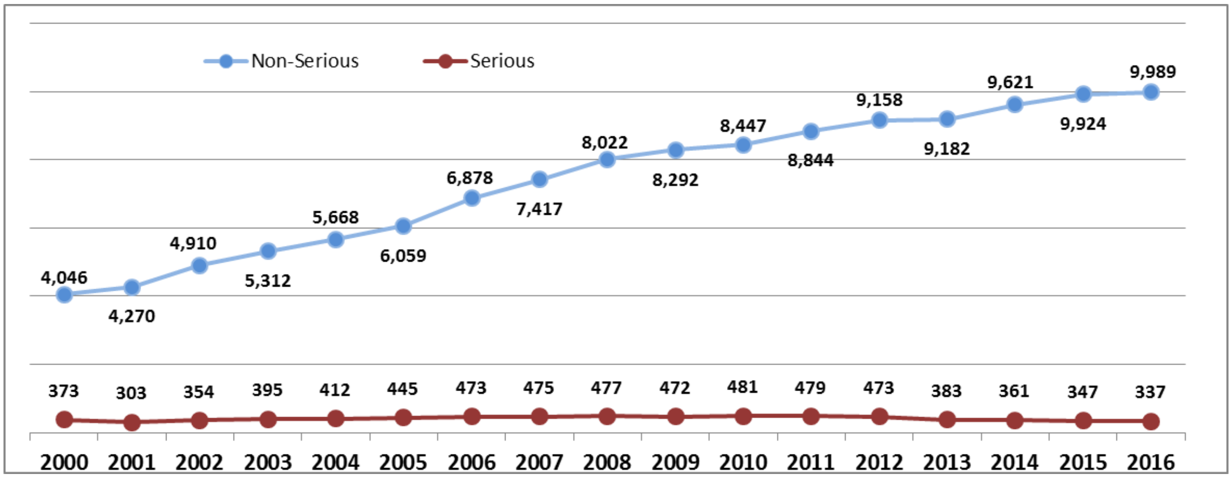

Figure 5. *Natural gas SCVF/GM well counts June 2, 2016 (from AER 2016a)*

In total, since reporting began around 25 000 wells have reported either SCVF or GM at some point in their history. The majority of reports for new drill, active, and inactive wells (Table 2), among which 79% report natural gas as a released substance, 6% indicate other substances, primarily water are being released and 15% of the reports do not indicate the released substance.

About 89% of leaking wells report a SCVF, 10% report a gas migration issue and 1% report both. Reporting requires both flow rate and pressure leaking SCVs. Among non-serious SCVF wells 69% of wells report a measured gas rate and 31% report gas rate as too small to measure (TSTM). Individual well SCVF natural gas flow rates are observed to be intermittent, variable and sometimes reducing or disappearing over time. Gas composition is not typically reported, but the AER estimates that SCVF gases are between 95% to 99% methane. This introduces some uncertainties into the extrapolation of annual and cumulative gas emissions. GM flow rates and cumulative emissions, which form a minor component of emissions are much less well characterized because the flow is typically dispersed within the soil, where it can be captured in either soil probe or closed canister sample devices, or from the air directly in the vicinity of the seepage and these are typically reported as concentrations that are in units of either parts per million or as a percentage of the lower explosive limit of methane. The statistics for abandoned and reclaimed wells do not include wells that were abandoned prior to the establishment of the reporting requirements, that general status of which is unknown.

Table 2: Well life-cycle status, number of wells reporting SCVF and GM issues and the percentage of wells with this life-cycle status that report SCVF and GM issues (from AER, 2016a).

Life-cycle status	# SCVF/GM	Percentage
New drill	37	3.3%
Active	9 462	5.2%
Inactive	8 723	10.3%
Abandoned	4 833	7.0%

Reclaimed	2 092	2.0%
Total	**25 247**	

Of the approximately 10,000 natural gas SCVF/GM wells reported the vast majority, 97%, are non-serious (AER Interim Directive 2003-01), Non-serious wells are monitored for five-years period and must be repaired at the time of abandonment. Only 3% of well are serious,300m3/day, currently (June 2nd, 2016) and these are required to be repaired within 90 days (AER Interim Directive 2003-01). Most serious wells are currently under repaired or are being monitored subsequent to a repair activity. Among serious wells about half report “die-out” in the monitoring period as the final repair type. The AER suggests that the emissions contribution may be serious, as many companies do not change their reported flow rates until the well is deemed non-serious, sometimes after several repair attempts. because licensees do not typically update the flow rates for serious SCVF after a repair attempt unless they reclassify it as non-serious well, and because in some instances serious vent flows are produced into the gathering system and do not emit to the atmosphere. With the assistance of Weatherford staff (Jay Williams, pers. Comm., June 29, 2016) the licensees of the 34 current serious wells in Alberta as of April, 2016 are (Table 3):

Table 3: Licensees of Alberta Wells with Serious SCVF or GM leakages during April, 2016. (J. Williams, pers. comm.)

Operator	Number of >300m3/day wells
Canadian Natural Resources Limited (0HE9)	10
Pine Cliff Energy Ltd. (A1GR)	4
Just Freehold Energy Corp. (A2N1)	3
Ember Resources Inc. (A1H9)	2
Husky Oil Operations Limited (0R46)	2
Omers Energy Inc. (A08E)	2
Alexander Oilfield Services Ltd. (0MK6)	1
Cardinal Energy Ltd. (A6A7)	1
Enerplus Corporation (A5RD)	1
Enhance Energy Inc. (A216)	1
Ouro Preto Resources Inc. (A5HR)	1
Pengrowth Energy Corporation (A5R5)	1
Petrus Resources Corp. (A632)	1
Predator Oil Ltd. (A6CG)	1

Striker Exploration Corp. (A0GT)	1
TAQA North Ltd. (A2TG)	1
Tourmaline Oil Corp. (A573)	1

The AER has inferred the natural gas emission rates from the current inventory of unrepaired SCVF/GM from measured flow rate data assuming: that reports of TSTM are assumed to be 1 m3/day, even though licensees can measure flows ~0.1 m3/day; that where not reported, the well emits at the average reported natural gas emission rate; that repaired and "died out" wells are no longer emitting.

The average daily natural gas flow rates from SCVF for serious and non-serious vent flows are historically variable (Figures 6 and 7). The average daily natural gas emission rates for non-serious vent flows appear to have been decreasing over the last 15 years. The rate for the last four years has stabilized at about 13 m3/day. There can be several reasons for this; however, one large contributor would be better drilling practices used by licensees (e.g., better primary cementing of the casing), which can reduce the likelihood of SCVF and the rates if it occurs.

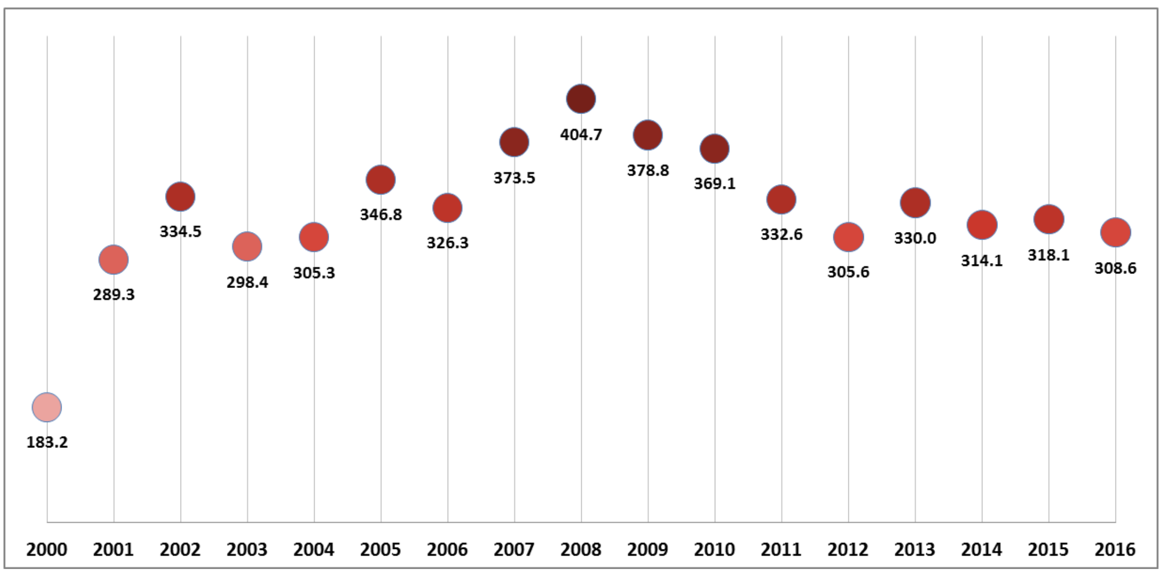

Figure 6: *Average daily natural gas emission rate for serious SCVF/GM (m3/day), June 2, 2016 (from AER 2016a)*

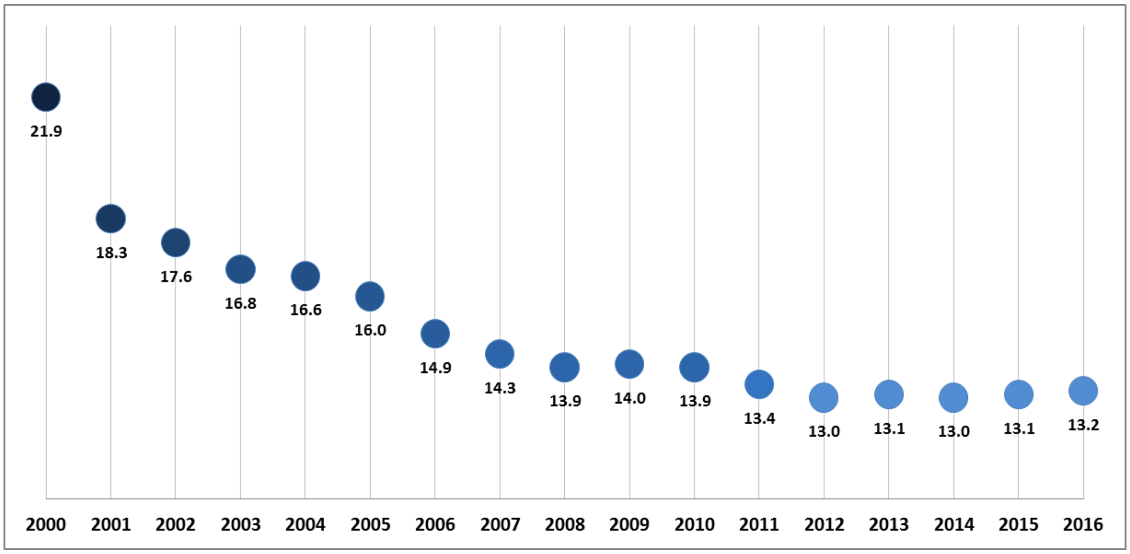

Figure 7: Average daily natural gas emission rate for non-serious SCVF (m^3/day, June 2, 2016) (from AER 2016a)

Table 4 displays the inferred history of average daily natural gas emission rate and an annual natural gas emission rate since 2000. Currently, as of June 2, 2016, the Alberta well average daily natural gas emission rate is 22.4 m^3/day and the estimated annual natural gas emission rate for 2016 is extrapolated to be 84.4×10^6 m^3 for 2016.

Table 4: Daily and annual natural-gas emission rate with 2016 emission extrapolated from the currently reported daily emissions rate (from AER 2016a).

Year	Well count	Average daily natural gas emission (m^3/day)	Annual natural gas emission (10^6 m^3)
2016	10 326	22.4	84.4*
2015	10 247	22.8	85.6
2014	9 982	23.1	84.2
2013	9 624	25.3	89.4
2012	9 563	25.1	87.6
2011	9 318	26.9	92.0
2010	8 926	29.0	95.1
2009	8 762	30.5	98.1
2008	8 495	33.4	104.3
2007	7 880	34.4	100.2
2006	7 337	34.6	95.3
2005	6 479	38.1	93.5

2004	6 052	37.3	85.8
2003	5 663	37.2	84.2
2002	5 197	33.7	69.8
2001	4 557	31.9	54.9
2000	4 404	32.1	53.1

The relative importance of estimated annual emissions from serious and non-serious SCVF/GM wells has varied historically During some years much smaller population of serious wells has contributed about half of the total emissions (Figure 6). In spite of the annually increasing number of wells drilled in Alberta, which increase the potential for well integrity issues the total SCVF emissions have been decreasing generally since 2008, when they had reached a maximum of 104 X 10^6 m^3 natural gas. As well the relative contribution from serious wells has declined from almost half of the total emissions to just less than 30% of the total emissions (Figure 10).

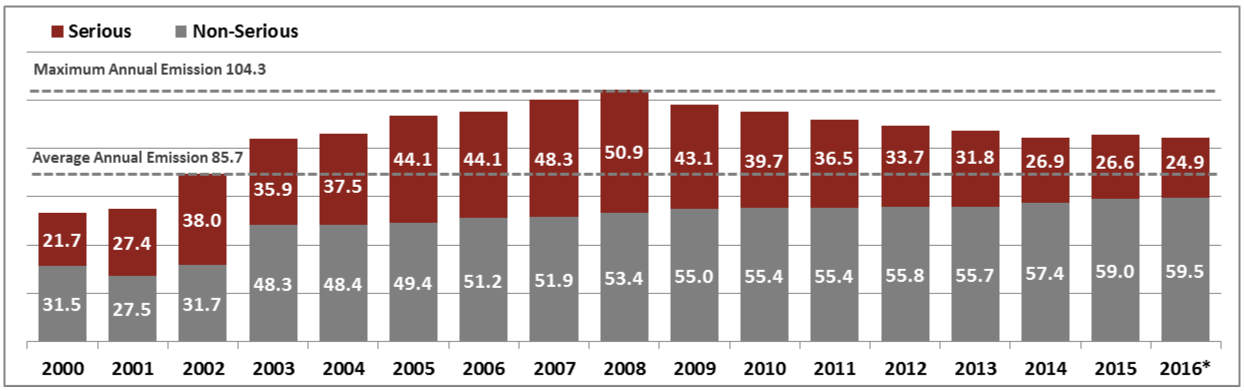

Figure 10: *Annual natural gas emissions for SCVF/GM (106 m3) as of June 2, 2016 with 2016 emission extrapolated from the currently reported daily emissions rate (from AER, 2016a).*

DIFFERENCES BETWEEN MEASURED AND INVENTORY ESTIMATES FOR SCVF AND GM METHANE EMISSIONS FROM PETROLEUM WELLS

We recommend that the AER (2016a) data are preferred and well justified estimates of SCVF and GM annual estimates of SCVF and Gm that are based on the best available data and the fewest and most rational assumptions. The 2010 SCVF and GM well data based methane emissions estimate is 95.1 X10^6 m^3 natural gas (Table 1). Assuming this to be predominantly, if not nearly exclusively composed of methane the resulting emissions would be 63.5 kt methane (assuming a 0.668 kg/m^3 density at normal conditions http://www.engineeringtoolbox.com/gas-density-d_158.html).

The National Inventory methane emissions assigned to "Accidents and Equipment Failures are predominantly SCVF and GM emissions (Clearstone Engineering, 2005a; Environment Canada, 2014). SCVF and GM constitute ~78% of the of 192.5 kt methane emissions attributed to "Accidents and Equipment Failures" (Environment Canada, 2014) which is similar to the proportion of SCVF and GM emission in “Accidents and Equipment Failures” reported earlier (Clearstone, 2005a). The AER Climate Policy Assurance Team (2016b) employs the 2010 Alberta methane SCVF and GM emissions, of 150.2 kt methane, in the National Inventory report as the reference level for these emissions. The Alberta Climate Policy Assurance Team attribute the 2010 “Accidents and Equipment Failures” methane emissions to “Upstream Petroleum CH4 Emission Inventory by Clearstone Engineering” without a specific reference, but which is clearly the Environment Canada National Inventory report (Environment Canada, 2014). As a result, the 2010 and AER (2016a) data-based estimate of SCVF and GM emissions of about 63.5 kt methane are about 42% of the SCVF and GM Alberta methane emissions currently described for 2010 in the Canadian National Inventory (Environment Canada, 2014).

The current estimated 2016 SCVF and GM annual methane emissions of 84.4 $X10^6$ m^3 natural gas (AER, 2016a, Table 4), is equivalent to approximately 56.4 kt methane, which is 37% of the 2010 reference emissions of 150.2 kt methane. Thus we can conclude that measured and reported petroleum well data for SCVF and GM emissions has declined over time from about 63.5 kt methane in 2010 to about 56.4 kt methane in 2016. **The 2016 Alberta SCVF and GM emissions (AER 2016a) are currently 11.2% lower than the same data sources indicated for 2010 and that they are 62% lower than the Alberta SCVF and GM values reported in the national inventory for 2010.**

The fact that the National Inventory of Alberta “Accident and Equipment Failure” estimates are significantly larger than the measured well data based emissions estimates has important implications for both the perception of the “methane emissions” issue and its management. Above we indicated that the US EPA suggests that wellbore leakage constitutes about 10.4% of the methane emissions from the for American natural gas system. The AER Climate Policy Assurance Team indicates that Alberta “Accident and Equipment Failure” emissions constitute about 19.5% of the 2010 Alberta upstream petroleum industry emissions. However, the more recent analysis (AER, 2016a) suggests that SCVF and GM methane emissions were about 63.5 kt methane in 2010, or about 7%, rather an about 15% of the total 2010 Alberta upstream petroleum industry methane emissions inventory, assuming that other components of the 2010 inventory are correctly estimated.

The AER (2016a) well data based methane emission estimates of appear to be consistent with the Alberta Environment Air Quality surveys that find Alberta atmospheric methane concentrations (http://aep.alberta.ca/air/reports-data/air-quality-reports-and-surveys.aspx), are typically similar to global averages (Dlugokencky, 2003). Bottenheim and Shepherd (1995) measured C2-C6 hydrocarbons at four rural Canadian localities, although none of which was located in the Interior Platform Geological Province or the Cordillera east of the continental divide, but two of which were well removed from urban sources. They measured low molecular weight hydrocarbons measured over a single year (1991) and concluded that the major sources of C2-C6 hydrocarbons were anthropogenic. They compared their data with continental data and concluded that the background distribution of hydrocarbons above North America was effectively homogeneous. Their measurements showed seasonal and other trends, including weekday-weekend trends at two sites that correlated with a limited set of CO observations at one site suggesting that the C2-C6 hydrocarbons had transportation related sources.

It is difficult to compare SCVF/GM to other methane emitters, such as landfills, since the emissions of from other anthropogenic sources are not typically measured but inferred from more easily obtained parameters like mass of solid waste following IPCC worksheets. Actual studies of other emitters commonly exhibit large variations and there is a generally similar relationship between top-down and bottom-up monitoring results where the larger estimates are provided by to-down methods. It is uncertain which of the two possible sources, natural geosourced gas, petroleum upstream wellbore leakage, petroleum transportation and processing, coal mines, or landfills is the largest source of atmospheric emissions.

7 OTHER SELECT ANTHROPOGENIC METHANE LEAKAGE AND EMISSION SOURCES

METHANE LEAKAGE FROM ALBERTA WATER WELLS:

The migration of these same natural gases can be facilitated by engineering interventions, primarily wells of all types, not just petroleum wells. Methane in Alberta groundwater is monitored by the Alberta Groundwater Observation Well Network (GOWN; http://esrd.alberta.ca/water/programs-and-services/groundwater/groundwater-observation-well-network/default.aspx) following well established sampling and characterization practices (Hirsche and Mayer, 2007; Cheung and Mayer, 2009; Jones et al., 2011), including a detailed and repetitive baseline studies of one well over an 8-year period lead by the University of Calgary (Humez et al., 2015). Methane emissions from water wells are typically not measured or monitored, even though methane is a common constituent of water wells and many well waters are saturated, or nearly so, with respect to methane.

METHANE LEAKAGE FROM PETROLEUM TRANSPORTATION SYSTEMS (PIPELINES)

The 2010 Alberta Upstream Methane Emissions inventory does not estimate that interregional petroleum transportation by pipelines is a significant source of methane emissions (AER, 2016b). Similarly, the inventory of American upstream petroleum emissions does not infer that pipeline transportation is a significant source of methane emissions. However, the majority of these estimates are inventory based. In specific instances, as detailed surveys of urban natural gas distribution systems in select American cities found numerous leaks that were studied after impacts on vegetation, specifically tree mortality was used as an indication of potentially significant gas migration from leaking pipelines. The significance, magnitude and surprisingly large number of these leaks were identified by state-of-the art fugitive gas emission studies, as outlined in the following studies.

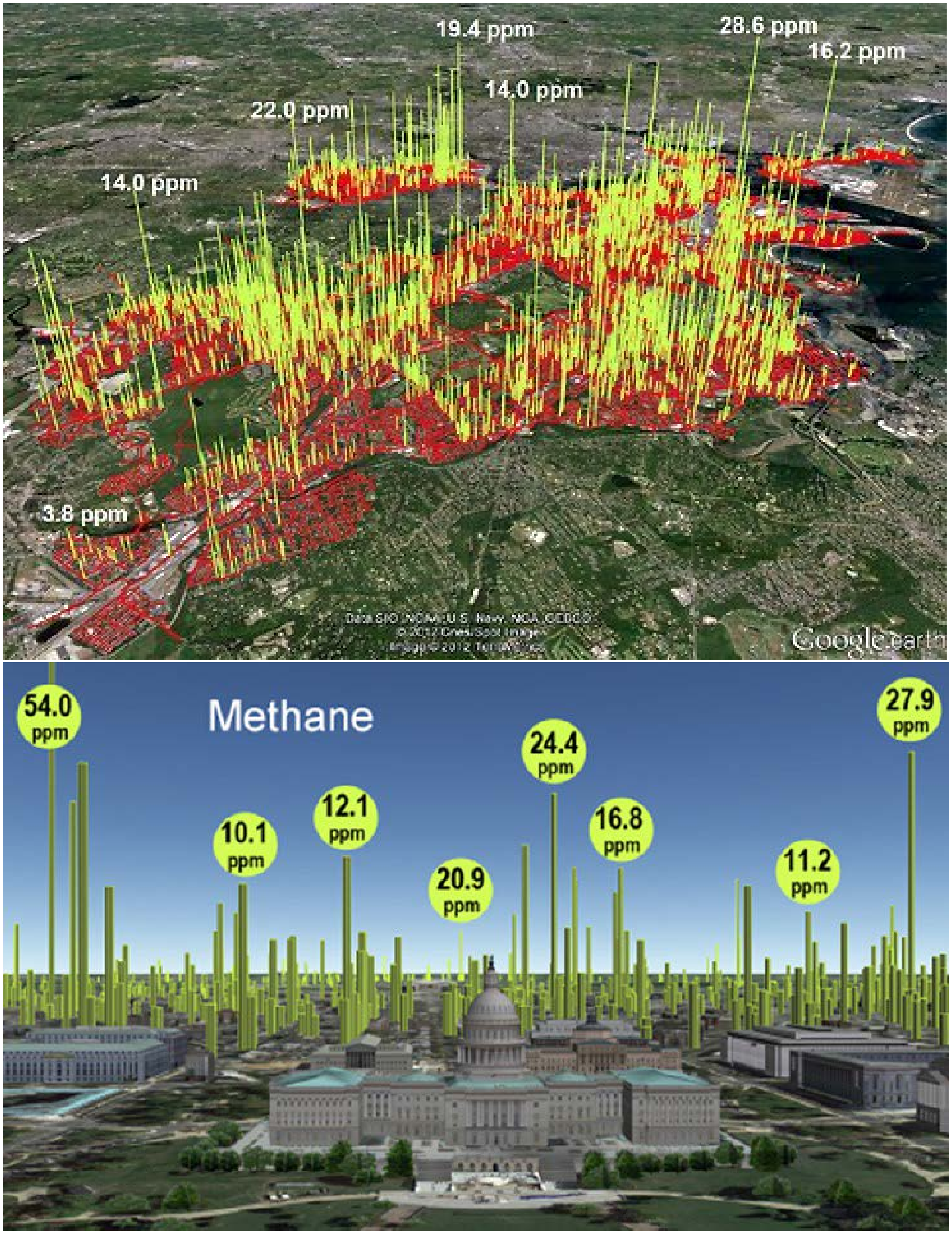

Figure 9: *a) Boston gas pipeline leak survey results from Phillips et al (2013). Above the 3356 inferred leaks (> 2.5 ppm CH4) and b) Washington survey results (Jackson et al., 2014).*

Phillips et al. (2013) assessed methane pipeline leaks across Boston along 785 miles of streets using a mobile cavity-ring-down mobile CH4 analyzer (Figure 9). They identifying 3356 methane leaks some exceeding 15 times the global background. They also measured d13CH4 isotopic signatures from a subset of these obtaining isotopic confirmation that that most of the leaks were from a fossil fuel source, as opposed to other sources. Boston leaks were associated primarily with cast iron mains that were sometimes over a century old. The leak frequency was linearly related to number of miles of cast iron mains, but only marginally to miles of non-cast-iron piping. A similar response was obtained in Washington (Jackson et al., 2014, Figure 9). While these studies are important because they inform potential survey methods and they illustrate the nature of distribution system leakages where cast iron pipes and oakum joints are still in use they are more important for this study because they illustrate the linkage between impacts on vegetation and methane leakage into soils. Unfortunately, none of the studies provides any guidance on rates of methane leakage, either into the soil or at surface and its relationship to plant mortality.

The above studies were not conducted in frozen soils and the effects of freeze-thaw cycles as might be expected in Canada. However, in the study of a single well (Van Stempvoort et al., 2005) inferred that bacterial sulfate reduction may play a major role in "bioattenuation" of fugitive natural gas in western Canada. They found evidence indicating anaerobic methane oxidation by bacterial sulfate reduction in a shallow aquifer near Lloydminster. Evidence included spatial and temporal groundwater methane and sulfate concentration associations with bicarbonate and sulfide. They found ^{34}S and ^{18}O enriched sulfate at low concentrations that was matched by elevated depleted ^{13}C bicarbonate close to the well they studied as well as a strong correlation between sulfate concentrations and the $d^{13}C$ values of bicarbonate. d34S was depleted in sulfide compared to sulfate, from which they inferred that bacterial sulfate reduction occurred near the well and that the increased, ^{13}C-depleted bicarbonate formed from a methane oxidization and sulfate reduction reaction that was probably microbially mediated.

COAL MINE EMISSIONS:

Coal mines are another significant source of methane emissions (Karcan et al., 2011). These emissions should be considered in two parts. "Coal Mine Methane" results from the combination of gas production and mining activities that are well studied, although primarily estimated and reported as inventories rather than monitored volumes. Coal Mine Methane production and emissions constitute anthropogenic emissions which could be compared to SCVF emission estimates. Biblier et al. (1998) estimated that underground coal mines worldwide liberate an estimated 29–41 10^9 m^3 of methane annually, of which less than 2.3 10^9 m^3 are used as fuel. Thakur et al. (1996) estimated global methane emissions from the world coal industry at 25 million tonnes per year. About 4.3 million tonnes (17%) of which was recovered, but only 2.0 million tonnes (8%) of which were used. Their estimates, although now dated are among the most quantitative available. They contain a mixture of specific, but incomplete Coal Mine Methane data combined with inventory estimates. Neither study included Canadian emissions estimates and Takur et al. (1996), purposefully omitted surface coal mining operations from their inventory, even though such mines are the primary type of operational coal mines in Canada. There are also coal-based natural background emissions associated with coal measures, that are less well studied and reported, although these emissions less well described.

One might presume that quantitative data related to the methane management and atmospheric emission from coal mines would be both abundant and easily accessible, in part because it was from coal mine degassing activities that the concept of coal-bed or coal-seam gas resources were identified and commercialized (Fassett, 1989; Flores, 1998), in a manner similar to landfill gas recovery projects. Unfortunately, this is not the case, and although some venting data is available, with a few exceptions (Saghafi et al., 1997; Thielemann et al., 2001) Coal Mine Methane data are typically qualitative (Karcan et al., 2011). Saghafi et al. (1997) found a positive but poor correlation between the product of coal in situ gas content and coal production with mine emissions for a small number of Australian mines (Figure 10). Unlike land fill gas studies the measured volumes of recovered and emitted Coal Mine Methane is not accessible, although one presumes such data exists. Karacan et al. (2011), who reviewed Coal Mine Methane state, "Accurate estimation of the rate of methane emissions from mines, i.e., specific emissions, can be challenging due to the large number of variables involved with mine operations". Hence, like landfill gas and other anthropogenic methane sources discussed above we find that the quality of data describing emissions is inferior to that for SCVF emissions, to the point of not being able to perform a comparison of the relative importance of different methane sources using monitored emissions data.

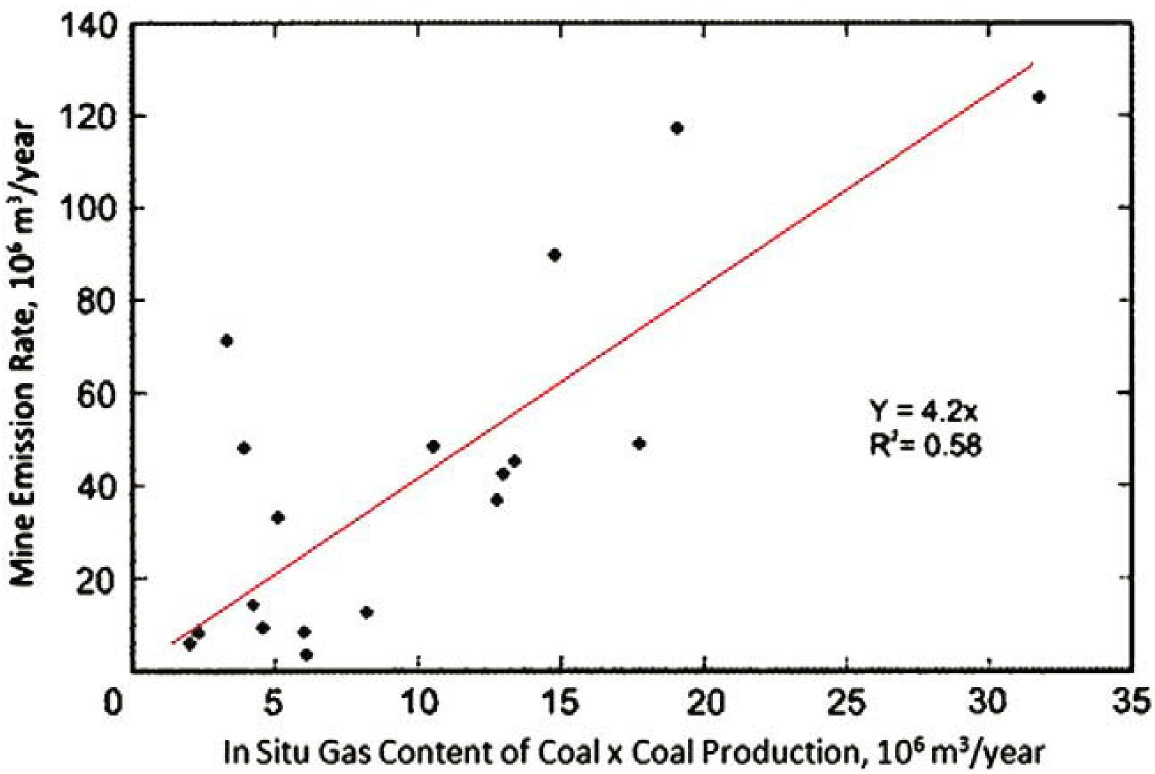

Figure 10: *The relationship between the product of coal in situ gas content and annual production with the annual mine emission (from Saghafi et al., 1997).*

Marshall et al. (2011) reviewed methane emission management opportunities associated with surface coal mines from several nations, although not including Canada. Western Canadian coal mines belong to this group and their data, as well as the US EPA studies of methane emissions from surface mines are of this type (USEPA, 2005; 2008; 2014).

Table 5: Recommended gas contents for United States surface mined coals (USEPA, 2005).

Coal Basin	Inventory Code	Major Coal Rank Mined	2003 Revised Gas Content (cf/t)	Recommended New Gas Contents (cf/t)	Comments
Northern App	NAB	Bituminous	59.5	59.5	Data compiled from USBM report
Central App	CAB	Bituminous	24.9	24.9	Data compiled from USBM and MRCP reports
Warrior	WRB	Bituminous	30.7	30.7	Data compiled from USBM report
Illinois	ILB	Bituminous	34.3	34.3	Data compiled from USBM and MRCP reports
S.West/Rockies	WTB	Bituminous			
S.West (NM, AZ, CA)		Bituminous	7.3	7.3	Data compiled from USBM and MRCP reports
Rockies (CO)		Bituminous	33.1	33.1	Data compiled from USBM and MRCP reports
Rockies (UT)		Bituminous	16.0	16.0	Data compiled from USBM and MRCP reports
N.Great Plains	NGP	Lignite	5.6	5.6	North Dakota mines lignite coal
Northern Rockies (MT,WY)	WYM	Sub-bituminous	5.6	20.0	Data compiled from USGS, and private sector
West Interior	WIN				
Forest City, Cherokee		Bituminous	34.3	34.3	Arkansas, Missouri, Kansas, Iowa coals similar to Illinois Basin
Arkoma (OK)		Bituminous	74.5	74.5	Data compiled from USBM and MRCP reports
TX, LA		Sub-bituminous	33.1	11.0	Texas & Louisiana mine borderline sub-bituminous coal
Northwest	NWB	Sub-bituminous	5.6	16.0	Washington, Alaska coals similar to Powder River Basin

Surface coal mine emissions can be inferred to be direct atmospheric contributions. Coal mining Canadian coal mines produce about 6.9 X 10^7 T of coal of various ranks annually. Canada's Emission Trends estimate that coal mining results in about ~4 X 10^6 TCO2e annually (Environment Canada, 2013, Table 15) or about 6.18 X 10^7 m^3 methane. This is essentially similar to the estimate that would obtained using the average USEPA surface coal emission values (Table 5) for annual Canadian coal production (~6.0 X10^7 m^3 methane), assuming that environment Canada used a methane global warming potential of 36. This suggests that the daily methane emissions from Canadian coal mines is ~1.70 X 10^5 m^3, again assuming a methane global warming potential of 36, but possibly as high as 2.18 X 10^5 m^3 methane daily if the methane global warming potential is assumed to be 28, as is more common practice. Therefore, the daily methane emissions from Canadian coal mining operations are roughly comparable to total SCVF emissions estimated above, and significantly higher than the non-serious SCVF emission from petroleum wells which are not required to be remediated directly.

It would of significant interest to understand the relationship between the Coal Mine Methane volumes, as discussed immediately above, and the natural methane emission rates into both soils and the atmosphere overlying bedrock coal measures, especially where they underlie soils. One study of Ruhr Basin surface methane emissions overlying underground mines was identified. That study also contained reference to shaft emissions. (Thielemann et al., 2001). Similar data for American underground mines was provided by (Kirchgessner et al., 2000). There is a clear association of high methane in groundwater associated with subcropping coal seams (Cheung and Mayer, 2009; Jones et al., 2011), but these associations are not typically expressed as rates of methane or ethane flux into either soils or the atmosphere. A recent study (Mayer et al., 2015) of cuttings and mud gas from shallow bedrock samples indicates that the gas content of coals is large in the Alberta plains even at very shallow (<50 m depths), but its mobility and influence on emissions into soils and the atmosphere are uncertain.

LANDFILLS:

Oonk (2010) reviewed landfill methane generation, oxidation and emissions using global data from a European perspective. He concluded that there was general uncertainty in the estimates of methane generation, oxidation and emissions from landfills due to a large number of factors, that he reviewed in detail and against which he made practical recommendations for improvements in both modelling and monitoring. Those uncertainties, as they apply to Canadian American landfill emissions are mirrored in the discussion below.

The Canadian Biogas Association (2013) and the Canadian Gas Association (Abboud et al., 2010) reports that there are over 10,000 Canadian landfills and dumps, including about 800 active engineered landfills as of 2001. Cumulatively, they are inferred to be the third largest anthropogenic methane source nationally (Table 6). Landfill gas inventories, based primarily on their intake masses are inferred to contribute 3% of Canada's GHG emissions due to fugitive methane emissions, about 7 Mt eCO2 of which are captured and combusted. The Canadian Gas Association (2010) estimated that Canadian landfills emit 2.034 X 10^9 m^3 CH_4/yr of which an estimated 21% is captured.

Table 6: Canadian landfill gas methane recovery projects in 2005 by province, from Canadian Biogas Association (2013).

	Methane Generation 2005[38]	GHG Generation 2005[39]	Methane Captured 2005	Methane Emitted 2005[40]	GHG Emitted 2005	LFG projects 2012
	(kt CH_4/yr)	(kt CO_2 eq/yr)	(kt CH_4/yr)	(kt CH_4/yr)	(kt CO_2 eq/yr)	Number
NL	38.57	810	0.00	38.57	810	0
PE	6.69	141	0.00	6.69	141	0
NS	39.66	833	5.39	34.28	720	2
NB	43.34	910	0.00	43.34	910	3
QC	469.46	9,859	143.97	325.50	6,835	8
ON	465.17	9,769	126.09	339.08	7,121	29
MB	44.10	926	0.00	44.10	926	0
SK	43.71	918	0.00	43.71	918	1
AB	103.55	2,175	5.39	98.16	2,061	5
BC	189.60	3,982	27.89	161.71	3,396	16
NT	2.34	49	0.00	2.34	49	0
NU			0.00			0
YK	1.15	24	0.00	1.15	24	0
Canada	**1,447.35**	**30,394**	**308.74**	**1,138.62**	**23,911**	**64**

Although there were 68 active landfills in Canada involved in capturing landfill gas in 2009 the Canadian Biogas Association (2013) provides data for the 64 projects operating in 2005. Among these projects only 53% of the captured landfill gas at projects was converted to heat or electricity the rest flared. The number of landfill gas management projects is increasing, in part due to Ontario's and BC's requirement for LFG gas management regimes and programs.

Alberta requires the monitoring of landfills, including methane (http://environment.gov.ab.ca/info/library/7316.pdf see also, http://www.qp.alberta.ca/documents/codes/LANDFILL.PDF). In that document the Province called for detection, interception, venting, or recovery of landfill gas (Section 7(2)(e)), but not its monitoring. In 1999 Alberta issued guidance regarding landfill gas issues (http://environment.gov.ab.ca/info/library/5847.pdf) for the purpose of providing the Province and Municipalities as well as land developers, with guidance concerning the management of methane gas around landfills, which was prepared for information purposes, as a review of policies, guidelines, and regulations in other jurisdictions throughout North America, including the technical aspects of methane migration and its impacts. They also listed pertinent legislative and regulatory requirements related to landfill gases in a table (Table 7):

Table 7: Legislation relating to the management of methane in Canadian and other landfills from (http://environment.gov.ab.ca/info/library/5847.pdf)

TABLE 2-1
LEGISLATION RELATING TO MANAGEMENT OF METHANE GAS FROM LANDFILLS

Jurisdiction	Regulation/Guideline
Canada	
Ontario	Guidance Manual for Landfill Sites Receiving Municipal Waste (November, 1993)
	Guideline D-4, "Land Use On or Near Landfills and Dumps" (April 1994)
	New Standards for Landfill Sites, Proposed Regulatory Standards for New Landfilling Sites Accepting Non-Hazardous Waste (June, 1996)
British Columbia	Landfill Criteria for Municipal Solid Waste (June, 1993)
Quebec	Projet de reglement sur les dechets solides, version technique (March 1994)
United States	
US EPA	Resource Conservation and Recovery Act (RCRA), Subtitle D (October, 1991)
	Clean Air Act, Proposed New Source Performance Standards and Emission Guidelines (NSPS), 40 CFR, Part 60
New Jersey	Solid and Hazardous Waste Management Regulations, Title 7
California (SCQAMD[1])	Control of Gaseous Emissions from Active and Inactive Landfills (Regulation XI)
Pennsylvania	Municipal Waste Management Regulations, Title 25, Chap. 288, C
Illinois	Solid Special Waste Management Regulations, Title 35, Subtitle G
Alabama	Solid Waste Management Regulations, Dept. 355, Div. 13, Chap. 4

(1) South Coast Air Quality Management District

Focused primarily on the explosive limit, the guidance document provided criteria and recommended limits for soil methane concentrations adjacent to buildings. It recommended that measurements include both the soil gas pressure and the concentration of methane. As the soil gas pressure affects the rate methane could migrate into adjacent buildings, and because a measurable soil gas pressures adjacent to a building was inferred to indicate a significant flow of gas through the soil from the adjacent landfill. They adopted soil gas pressure of less than 0.249 kPa as the limit at which gas flows become significant.

Alberta municipalities report on landfill activities and monitoring results annually, but the reporting of monitoring results is not standardized, focused on safety limits for methane, when the word "methane" even appears in the annual report and the Province appears not to compile landfill gas monitoring rates or compositions. For example, in 2012 Lloydminster reports landfill monitoring activities, but they state that no hydrocarbon monitoring was performed as their practice is to monitor hydrocarbons during odd-numbered years (http://www.lloydminster.ca/DocumentCenter/Home/View/7). In contrast the 2012 report by Wetaskiwin (http://wetaskiwin.ca/DocumentCenter/View/590) identifies 18 landfill gas sampling points including 11 dedicated landfill gas monitoring wells. They conclude that "high methane" in some wells indicates anaerobic methanogenesis, but they neither municipalities report rates of methane flow either in observation wells, through the soil cap or at the active depositional sites.

There are several landfill gas utilization projects in Canada (Canadian Biogas Association, 2013). An example is the Edmonton landfill gas and electric power generation project at its Cloverbar Landfill site (http://www.edmonton.ca/programs_services/garbage_waste/landfill-gas-recovery.aspx). That project, the only of its kind in Alberta, began in 1992, and it recovers landfill gas that is about 50% methane and 50% carbon dioxide. They infer that the each tonne of organic waste produces ~125 cubic metres of methane. 101 gas wells have been drilled into the landfill and there are currently 60 wells operating at an average depth of ~25 m. The wells are connected by pipeline a Landfill Gas Recovery Plant and since 2005 EPCOR has generated electricity at the landfill site. More than 5.0 X 10^4 m^3 of gas, is consumed daily at the generating station to produce 4.6 megawatts of electricity daily. Between 1992-2013, 3.70 X 10^8 m^3 of landfill gas have been recovered in total for giving annualized average recovery of 1.76 X 10^7 m^3/yr or 4.83 X10^4 m^3/day, which is comparable to the current daily consumption at the electrical generation plant. The exact daily rates are not provided, but should be obtainable. Neither is the fate of the co-produced CO2 specified, nor are any associated soil fluxes of landfill gas specified.

British Columbia requires assessment of landfill gas generation, which may require the construction and monitoring of landfill gas management system and including the measurement and of the gas collected and flared (http://www.env.gov.bc.ca/epd/codes/landfill_gas/pdf/lg-reg-12-08.pdf), although no rates of either recovered methane or emitted CO2 easily obtainable. While the recovered landfill gas volumes and compositions help to inform us regarding the landfill methane emissions they do specifically constrain the rate of leakage into the soil caps and the atmospheric emissions. A study of the Vancouver-Delta landfill found methane to be about 51% of the recovered landfill gas and the volume of methane recovered to average 18.86 X 10^6 m^3/yr over a two-year period (CH2MHILL, 2013), which is comparable to the annualized average recovery at Edmonton, Cloverbar. The Village Farms landfill gas utilization project in British Columbia is described at, https://fuelcellsworks.com/archives/2014/03/24/village-farms-international-inc-in-collaboration-with-quadrogen-power-systems-inc-and-fuelcell-energy-inc-announces-the-first-ever-7-5-million-quad-generation-energy-project/

Thompson and her colleagues (Thompson et al., 2006; 2007, 2009) have been attempting to improve the reconciliation of methane recovery from Canadian landfills with inventory based methane generation models. They optimistically infer that 80% of the landfill methane is recovered, which is much higher than the 34% recovery used in a major California study (Themelis and Ulloa, 2007). Therefore, we must infer that, methane, sometimes in significant volumes, is a product of some Canadian landfills although the quantities and rates, at both recovery and monitoring wells or through soil caps are not well established.

Where actually monitored, landfill emissions are extraordinarily variable and effectively uncertain. Most landfill emissions are estimated using IPCC worksheets that use mass of waste as the key input. Bogner and Scott (1995) found landfill emissions, primarily measured using closed chamber tests, vary over six orders of magnitude, from 0.003 to more than 3000 g methane m^{-2} day^{-1}, the highest rate being equivalent to 4.41 m^3 CH_4 m^{-2} day^{-1}. Soil caps are employed commonly to reduce or in rare cases eliminate landfill emissions from landfills (Bogner et al., 1995), but their relative efficiency is both variable and uncertain due to a number of factors, including whether or not landfill gas recovery is present, the characteristics of soil cap, the landfill environment and the rate of indigenous microbial methane oxidation. Park and Shin (2001) observed seasonal variation and Galle et al (2001) noted differences in monitored landfill emission between top-down atmospheric geophysical assays and bottom-up soil gas capture methods. In general, the methane emissions are spatial and temporally discontinuous and the bottom-up (closed chamber) approaches significantly underestimate the results from top-down (atmospheric monitoring) approaches, especially where both are cross-validated at a single landfill (Galle et al., 2001).

Table 8: California landfills subject to gas recovery program (Themelis and Ulloa, 2007, their Table 5).

Landfill name	MSW (Tonnes/yr)	Captured CH_4 (Nm3/yr)	Captured CH_4 (Nm^3/t MSW)	Assumed generation (Nm^3/t MSW)	Estimated loss CH_4 (Nm^3/ t MSW)
Altamont	1,157,312	24,001,656	21	122	101
Scholl Canyon	412,429	50,237,893	122	122	
Azusa	157,445	17,056,769	108	122	14
Puente Hills #6	3,377,867	200,549,669	59	122	63
Bradley Avenue West	418,341	40,190,314	96	122	26
Crazy Horse	151,258	4,822,838	32	122	90
Monterey Peninsula	197,797	3,351,872	17	122	105
Prima Deshecha	703,051	11,253,288	16	122	106
Olinda Alpha	1,877,620	17,862,362	10	122	112
Frank Bowerman	1,991,666	20,095,157	10	122	112
Sacramento Co (Kiefer)	615,702	16,076,126	26	122	96
Colton Refuse Disposal Site	305,682	13,664,707	45	122	77
San Timoteo	158,405	2,154,647	14	122	108
Otay Annex	1,267,641	11,164,869	9	122	113
Miramar	1,289,295	28,334,172	22	122	100
Sycamore	817,255	6,695,706	8	122	114
Tajiguas	200,084	9,766,246	49	122	73
Newby Island	592,877	17,683,738	30	122	92
Kirby Canyon	246,902	3,633,204	15	122	107
Guadalupe Disposal Site	166,915	8,038,063	48	122	74
Santa Cruz City	51,191	3,351,872	65	122	57
Buena Vista Disposal Site	131,775	4,420,935	34	122	88
Woodville Disposal Site	61,368	4,822,838	79	122	43
Visalia Disposal Site	108,327	8,038,063	74	122	48
Yolo County Central	163,841	10,449,482	64	122	58
Average			43		82

Due to EPA concerns about water quality and contamination since 1988 the number of American landfills has decreased, although active landfills have become larger generally. A study of 25 California landfills with active methane recovery programs (Themelis and Ulloa, 2007, Table 8) indicated that methane capture at these landfills was, on average, 43 m^3/t of municipal solid waste (MSW), but it also provided an excellent review of landfill biogas projects in the United States. They inferred, assuming a constant generation rate of 122 m^3 CH_4 /t MSW and that around 82 m^3 CH_4 /t MSW were "lost". Among the 25 landfills they studied the average total methane generated was 1.2 X 10^5 m^3/day. The largest California Landfill studied was inferred to generate 1.6 X10^6 m^3 methane per day of which slightly more than one third was captured but, of which about <1.1 X10^6 m^3 might be emitted daily. What proportion of this "lost" methane might have been remediated soil caps was uncertain, but it is obvious that the inferred methane emissions at the California sites were much higher than those typically monitored at the surface elsewhere.

The California study has important implications for Canadian landfill, wellbore leakage and natural methane fluxes in Alberta. First it underscores several important characteristics of landfill studies including:

- The specific lack of monitored estimates of gas generation in landfill, as illustrated by the assumed methane production rate per tonne of municipal solid waste (MSW), which they employ in spite of their own discussion of discrepancies between recovered landfill gas and bioreactor generation rates (Themelis and Ulloa, 2007).
- The ability to easily quantify recovered landfill gas volumes and compositions, also evident in the Canadian studies.
- The general lack of agreement on the efficiency of landfill gas recovery, as indicated by the large difference between the estimates of Thompson et al. (2009) who infers 80% recovery and Themelis and Ulloa (2007) who suggested 34% recovery.
- The inference that landfill emissions equal the difference between inferred gas produced and measured gas recovered, even though the potential role of soil caps affecting surface methane emissions rates is well established and sometimes much more effective than inferred by the IPCC (Bogner at al., 1995; Boeckx et al., 1996; Oonk, 2010; Wangyao et al., 2011).

The California study implies, acknowledging uncertainties, that a single, albeit the very large California landfill, which is inferred to capture about one third of its methane emissions could have daily atmospheric methane emissions (Table 8, Puente Hills #6 = 1.05 X10^6 m^3/day) of an order of magnitude comparable to all Alberta and British Columbia wellbore SCVF estimates**.** More importantly, the efforts to both monitor and infer landfill methane emission rates provide examples of the challenges that will be faced if natural background methane fluxes are to be measured and compared to wellbore leakages in Canada.

AGRICULTURAL FERTILIZER AND AGRICULTURAL AND DOMESTIC WASTE (MANURE AND SLURRY) IMPACTS ON THE SOIL METHANE SINK:

Agricultural practices have a large impact on the global methane budget and provide a major target for methane reduction globally (Wollenberg et al., 2016). Agricultural practice and agricultural and domestic liquid waste management are considered together and distinguished from municipal solid or landfill waste, discussed above, although some of the impacts are similar.

While some natural and anthropogenic methane emissions are input directly to the atmosphere others pass through the soil, which is a methane sink. Soil hosted microbial methantrophy is the largest global sink for atmospheric methane (Levine et al., 2011, Figure 14). Aerobic methanotrophic communities in soils are estimated to consume ~30 Tg/year of atmospheric CH4 and forest soils were identified as the most efficient sinks (Dalal and Allen, 2008). Conrad (1996) reviewed the microbial, enzymatic and chemical soil processes that affect trace atmospheric gas components. He (ibid.) pointed out that the abundance of soil microbes in an agricultural soil occurred at levels of billions per g of soil and that they constituted a biomass of approximately 500 kg of C per ha (250), which he equated to one sheep per 100 m^2 of terrain. Soil microbial methanotrophy and plant impacts due to natural gas transportation leaks was discussed above. He we discuss the impact of soil methanotropy specifically as it pertains to agricultural practice, because, it is appropriate to evaluate the anthropogenic impact on global methane sinks just as it is to consider anthropogenic sources.

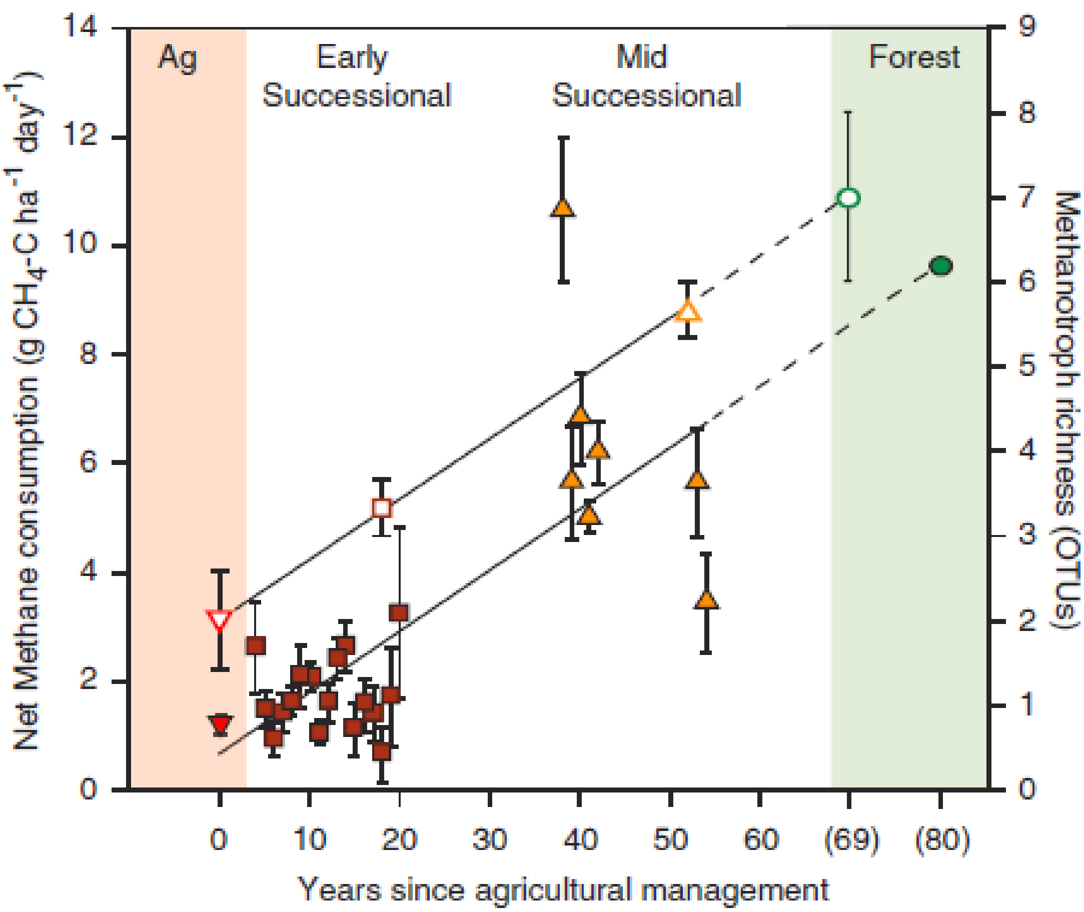

Figure 11: *From Levine et al. (2011, Their Figure 4 and its caption). "The recovery [impact] of methanotroph diversity and CH4 consumption at Kellogg Biological Station Long Term Ecological*

Research site following row-crop agriculture. Increase in methanotroph diversity (open symbols) and CH4 consumption (closed symbols) as a function of time since cessation of agriculture."

Six factors control the effectiveness of the soil microbial community, as mentioned above in the discussion of soil methane impacts on plants. Seghers et al. (2003) concluded that the function and molecular and chemical composition of the methanotrophic community are altered in soil fertilized with mineral fertilizer. Maxfield et al. (2008) studied the impact of agricultural practice on these processes in situ by exposing mineral soils to atmospherically about 2 ppmv $^{13}CH_4$ and ^{13}C phospholipid fatty acids to conduct an isotopically based assessment of the methanotrophic processes in soils. They found that soils treated with inorganic fertilizers at the site of a protracted agricultural demonstration exhibited a >70%, reduction of methanotrophic microbes and that the associated reduction of methane consumption was even lower, although slightly, than the reduction in microbial population. They concluded that the impacts on the methanotrophic community was directly indicated by the reduction of methane oxidation and that common agricultural practices have significant detrimental impacts on soil microbial diversity that reduce interactions with atmospheric gases. Crossman et al. (2004) applied a similar method to landfills but did not explicitly state impacts on methane fluxes, although they inferred that the microbial community in the landfill soil was specifically dependent on the higher methane flux provided by the landfill, which distinguished it from a normal soil population. Levine et al. (2011) illustrated a strong correlation between land use impacts and methane consumption. Although Levine et al. (2011) did not extrapolate their results geographically, it is clear that agricultural practices significantly impair the soil microbial methane sink. Therefore, it should be possible to make estimates of the cumulative effects of that impairment using agricultural landscape use data, although such an estimate could not be identified.

Agricultural waste includes both managed, i.e. high intensity farming with collection of manure in holding tanks, and unmanaged waste deposited directly on soil (http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/cl10038/$file/GHGBulletinNo11Manuremanagement.pdf?OpenElement). The emissions and impacts of manage waste are more easily studies. Kaharabata et al (1995) estimated CH_4 emissions from Canadian swine and dairy slurry outdoor holding tanks at 0.71 Tg CH4/yr ($\pm$ 40%) and 0.24 Tg CH4/yr ($\pm$ 70%), respectively, for a combined annual emission of about .95 Tg/yr ($\pm$ 50%), which is equivalent to 3.83×10^6 m^3/day CH_4 at normal conditions (1.013 bar and 15°C), as compared to the inferred total and total non-serious (<300 m^3/day) SCVF releases from Alberta and British Columbia wells that are estimated at 1.67×10^5 m^3/day and 8.14×10^4 m^3/day respectively. Others have attempted to understand the impact of unmanaged agricultural wastes on soils and pastures.

AGRICULTURAL METHANE EMISSIONS FROM ENTERIC FERMENTATION

Estimates of agricultural greenhouse gas emissions are based upon two main categories, those that are livestock related and those that are soil and cropping related. Soil and cropping related emission are not considered here, except for the impact of soil compaction on microbial methanotrophy, as described above and below. Enteric fermentation represents about 28% of the global anthropogenic methane emissions inventory and it is commonly listed as the single largest anthropogenic methane emissions sources (IPCC, 2013). Enteric fermentation has been carefully studied for several domestic species both in enclosed chambers and in free ranging experiment, but it would be mistaken to conclude that there is either a consensus or single best practice for estimating this source of emissions. Storm et al. (2012, Table 9) reviewed the measurement of methane emissions from ruminants (Table 9). They summarized animal methane models, concluding that there were significant differences in the models and that these would result in uncertainties in the calculation of emissions based on the size animal populations, as shown below:

Table 9: Animal methane models as reviewed and summarized by Storm et al., (2012).

Reference	Equation	R^2	N
IPCC [98] [a]	Methane (kg/dag) = GE (MJ/d) × Y_m/55.65		
Yan *et al.* [103] [b]	Methane (L/d) = 47.8 × DMI − 0.76 × DMI^2 − 41 (kg/d)	0.75	315
Yan *et al.* [103] [bc]	Methane (L/d) = 0.34 × BW (kg) + 19.7 × DMI (kg/d) + 12	0.77	315
Kirchgessner *et al.* [104] [d]	Methane (g/d) = 63 + 79 × CF + 10 × NFE + 26 × CP − 212 × Cfat (kg/d)	0.69	24
Jentsch *et al.* [101] [de]	Methane (kJ/d) = 1.62 × d_CP − 0.38 × d_Cfat + 3.78 × d_CF + 1.49 × d_NFE +1142 (g/d)	0.90	337
Ellis *et al.* [21]	Methane (MJ/d) = 0.14 × forage (%) + 8.6	0.56	89
Mills *et al.* [105] [f]	Methane (MJ/d) = 0.07 × ME (MJ/d) + 8.25	0.55	159
Mills *et al.* [105] [b]	Methane (MJ/d) = 0.92 × DMI (kg/d) + 5.93	0.60	159
Mills *et al.* [105] [b]	Methane (MJ/d) = 10.3 × forage (%) + 0.87 × DMI (kg/d) + 1.1	0.61	159
Grainger *et al.* [26] [b]	Methane (g/d) = 18.5 × DMI (kg/d) − 9.5	0.56	16

[a] GE = gross energy intake; Y_m = emission factor; [b] DMI = dry matter intake; [c] BW = body weight; [d] CF = crude fibre; NFE = N-free extract; CP = crude protein; Cfat = crude fat; [e] The equation is based on digested amounts which is designated with "d"; [f] ME = metabolizable energy intake.

In Canada ruminants and manure management contribute the single largest source of agricultural GHG's, comprising 42.9% of the agricultural emissions, which are themselves 8% of the national emissions total on a CO2equivalent basis, whereas animal manure contributes 22.8% of Canadian agricultural emissions (Janzen et al., 2008). Livestock-related emissions, primarily from enteric fermentation are estimated at 17,696 kt CO_2 equivalents annually as CH_4 while total manure management is estimated to contribute 9,400 kt CO_2 equivalents as both CH_4 and N_2O. Between 1990 - 2000 there was an inferred increase of 11.6 % in total livestock emissions while emissions from soils decreased by 3.5 %. Most of the increase in livestock-related emissions was attributed to increased cattle production.

NATURAL MIGRATION PATHWAYS, SEEPAGES AND EMISSIONS TO THE SURFACE

Leakage to the surface and atmosphere is the eventual fate of all petroleum (Figure 12) although it may be oxidized microbially prior to being emitted to the atmosphere.

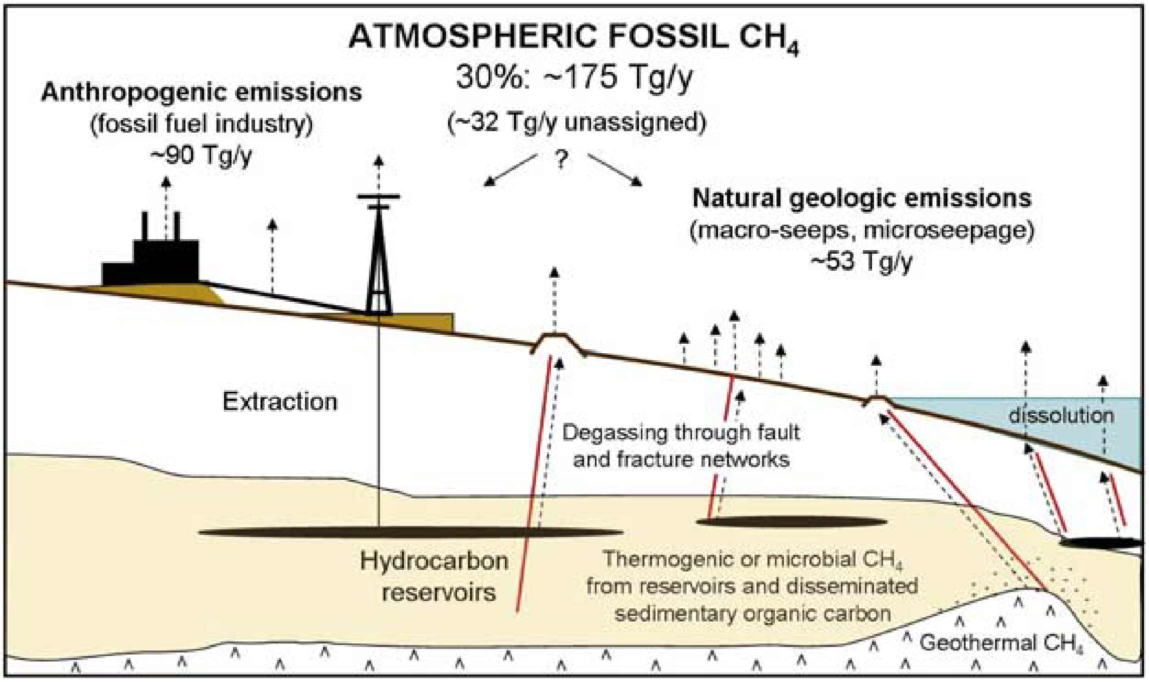

Figure 12: The importance, key pathways and role of natural petroleum (methane and other gases and liquids (in the environment (Etiope et al., 2008). The figure provides a schematic representation of natural and anthropogenic emissions of fossil methane. Rocks and tectonic discontinuities such as faults or fracture networks are envisaged to provide natural, but not necessarily the only pathways of natural methane and other hydrocarbon degassing. Estimates of uncertainties were omitted for clarity. At the time of their publication the un-allotted methane budget was ~32(±42) Tg y-1 of fossil CH4 that were of uncertain, either anthropogenically or naturally emitted to the atmosphere.

Wellbore leakage is simply a facilitation and mass and rate change of the natural seepage process that augments the natural flux of petroleum into the near surface and atmosphere. There are a few rare cases where thermally stimulated bitumen recovery wells have manufactured gases that leak into the near surface and atmosphere, but these are rare and not discussed further. Many of the earliest identifications of natural gas in Alberta occurred at surface seepages (e.g. Osadetz, 1986; Osadetz et al., 2008; Allen and Osadetz 2013). As a result, the natural and anthropogenically facilitated migration of petroleum remains an important contributor to natural seepages and anthropogenic leakages into the near surface environment and the atmosphere.

Figure 13: The Trail River, natural "sour" thermogenic gas seepage, Yukon Territory near the Trevor Fault, a thrust fault that involves the Paleozoic succession (Allen and Osadetz, 2013). These photos illustrate the naturally occurring discoloured water on Trail River (above). At the seepage stones are coated with grayish-white slime (?chemosynthetic bacteria) and there is a strong sulfurous odour is evident. The location was visited both in summer (above), with hammer for scale, and winter (below), with a person for scale. The seepage might not be identified if not for the anomalous freezing behaviour associated with the site. Natural seepages are the least well constrained pathways, as they are commonly sourced from very deep in the subsurface and follow an essentially uncertain and unknowable pathway through lithic rock succession.

Natural seepages are typically poorly characterized, intermittent, difficult to identify in the absence of a significant environmental impact, such as anomalous freezing behavior in water bodies (Figure 13), bubble trains in calm water, or significant vegetation impacts in soils. Where macroseepages are more easily identified the smaller the rate of migration and less persistent the surface environmental impact, the more difficult it is to quantify the spectrum of natural seepages. Natural seepages clearly contribute to identifying petroleum potential in the subsurface, but to what degree the natural flux is identifiable and verifiable is uncertain. Schumacher and Abrams (2000) compiled many case and methodological studies of natural petroleum seeps, and the constituent papers discuss the impacts of natural seepages at the surface, some of which are described below (e.g. Noonan et al., 2012), and on which Etiope and his colleagues based their estimates of natural or "geosourced" methane fluxes to the atmosphere. Where some of the contributions are clearly indicative of seepages or their suppression by hydrogeological and lithological features, few consider explicitly the effect of soil microbial communities on any natural seepage signal, except where it results in the biodegradation of liquid petroleum or where it produces a noticeable impact on the flora.

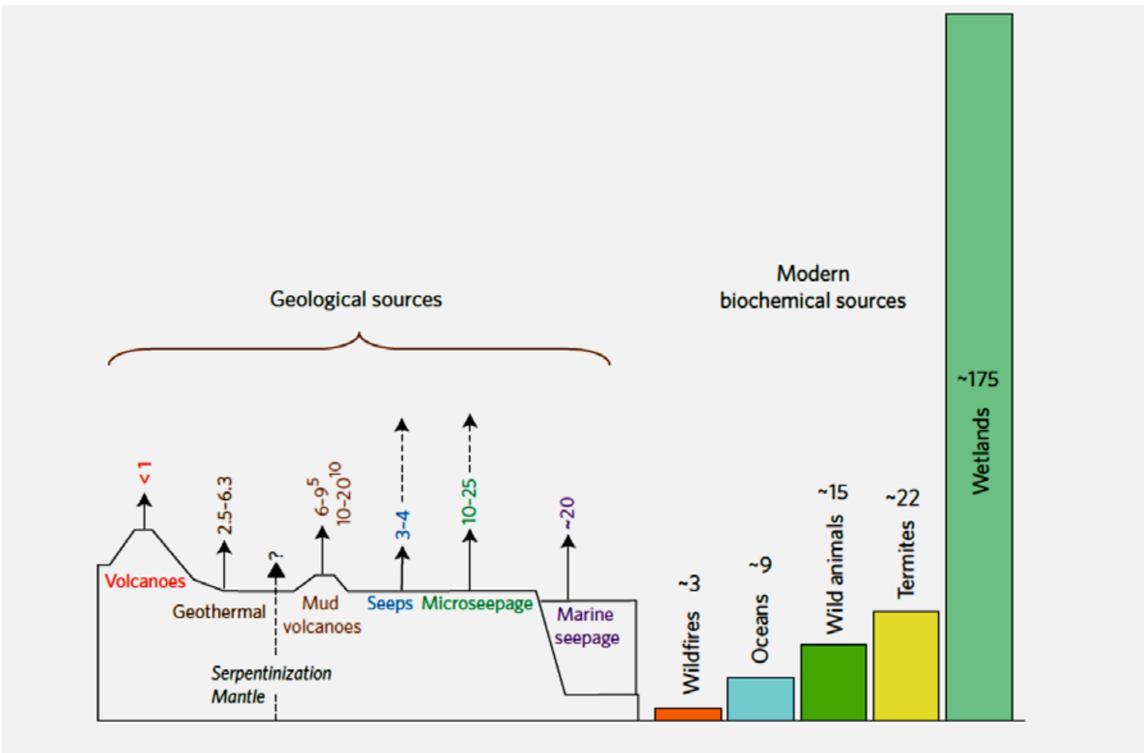

Figure 14: Etiope's (2012) comparison of "earth degassing versus modern natural methane sources. Methane and other hydrocarbon gases generated in the subsurface can escape to the atmosphere through terrestrial and marine seepage in sedimentary basins and, subordinately, by geothermal vents and volcanoes (italics denote uncertain methane sources). Methane emissions from these geological sources amount to around 60 Tg per year according to bottom–up estimates and up to 80 Tg per year according to top–down estimates, while additional observational data from the pan-Arctic to suggest that emissions from terrestrial seepage may significantly increase due to cryosphere degradation (dashed arrows from seeps and microseepage). All fluxes are provided in units of Tg per year."

Etiope (2012, Figure 14) indicates that the natural petroleum seepages of methane are poorly quantified, but potentially very significant contributors of atmospheric methane, perhaps being second only to wetlands as a natural source. The background seepage from sedimentary basins containing petroleum, kerogen and coals may be among the largest natural fluxes. Brandt et al. (2014, their figure 2, discussion in supplemental data) estimated US natural seepage rates considering both EPA (2010) and Etiope et al. (2008) tables, scaled proportionally to the land area of the United States.

	Global CH_4 emission	Median C_2/C_1	Ethane emission	Median C_3/C_1	Propane emission
Mud volcanoes	6-9	0.0007	0.008-0.012	0.00008	0.001-0.002
Onshore seeps	3-4	0.018	0.10-0.14	0.009	0.074-0.1
Microseepage	10-25	0.068	1.28-3.21	0.031	0.85-2.13
Marine seeps	20	0.012	0.45	0.0017	0.09
Geothermal	2.5-6.3	0.013	0.06-0.15	0.0013	0.009-0.022
Volcanic	<1	0.022	<0.041	0.010	<0.027
Total geologic	**42 – 64**		**~ 2 – 4**		**1 - 2.4**
Biogenic			0.80		1.63
Oceans			0.78		1.06
Anthropogenic			5.70		6.51
Forest-savanna burning			2.29		0.41
Total POET			**9.57**		**9.61**

Figure 15: Etiope and Ciccioli's (2009) global distribution of geologic sources of gaseous hydrocarbons (black dots), which they implied indicative of the main petroleum seepage areas globally. They also indicated in red, the main geothermal and volcanic areas; and in blue the primary submarine seepage sites on continental shelves from which they provided estimates of ethane and propane emissions (Table below, in Tg year−1) which they also used to compare geosourced sources with other natural and manmade sources.

Etiope is also strongly critical of the IPCC method of accounting for the size and impact of geosourced methane, ethane and propane fluxes (Figure 15) (Etiope, 2015; Etiope and Ciccioli, 2009). They employed a small number of geosources on which they based their estimates Etiope (2015) for example cites only 26 studies of four types of natural seepage from only 12 countries with no data from Canada. Indications for seepage data for six types of natural seepage shown in Figure 3 are provided in supplemental material to Etiope and Ciccioli (2009; http://science.sciencemag.org/content/sci/suppl/2009/01/22/323.5913.478.DC1/Etiope.SOM.pdf and references therein, Table 10).

Table 10: Number and references of geosourced ethane/methane and propane/methane data (from: Etiope and Ciccioli 2009, supplemental materials retrieved as described by the URL in the text and references)

Table S1. Number and references of ethane/methane and propane/methane data

Source category	N. of data		References
	C_2/C_1	C_3/C_1	
Mud volcanoes	139	39	S5
Onshore seeps	56	49	S5, S6, S9, S10, S11
Microseepage	9 mean values (9 areas) from >4000 samples	9 mean values (9 areas) from >4000 samples	S12, S13, S14, S15
Marine seepage	10	6	S16, S17, S18, S19
Geothermal	13	9	S20, S21
Volcanoes	11	8	S21, S22, S23
TOTAL	238	120	

The quantity and quality of data Etiope and Piccioli (2009) provide is both small and in some cases questionably obtained – especially for microseepage sites. Those sources include both published maps and literature, but they did not include dispersed, diffuse gas micro-seepage from soils that occur potentially in all sedimentary basins with petroleum production. The global CH_4 emissions associated with the study of natural ethane and propane seepages are similarly sparse and wanting (Etiope et al., 2008), and were somewhat improved by the estimates provided by Etiope (2015). Etiope and Ciccioli (2009) employed median ethane/methane (C2/C1) and propane/methane(C3/C1) ratios from data from >230 gas manifestations and > 4000 soil-gas samples published in the references that they cite in their supplemental materials. However, it is the available data set and it illustrates the current poor understanding of soil-methane flux, especially using "bottom-up", or discrete subsurface and near surface sampling. Still, their work represents the initial comprehensive and still best global compilation of natural seepages that indicate the great uncertainties in the estimation of the natural atmospheric flux from surface and near surface sources.

Brandt et al. (2014 and supplemental data) provided an excellent compilation of both bottom-up and top-down seepage (atmospherically-based monitoring) of methane and other petroleum gas sources in the United States, as discussed below. Their work represents the most comprehensive and well documented study of regional/continental methane emissions available. In the scope of this study, not all of the references, methods and estimates could be appraised in detail, but we do note that the key well-based studies (Alvarez et al., 2012; Harrison et al., 2011 and Clearstone et al., 2002) focus on upstream petroleum facilities and not wellbore leakages. Their study was strongly dependent on the remotely sensed estimates from airborne methods (Karion et al., 2013; Petron et al., 2012). Like studies of landfills, discussed below, they found major differences between bottom-up and top-down monitoring survey results.

There is a clear and important indication of the importance of the geosourced natural seepage to the surface and near surface, especially in western Canada. This includes the strong indication that the biogenic alteration of petroleum that produced the bituminous sands in the Athabasca and other regions of the Western Canada Sedimentary Basin produced, also produced, as a metabolic bio-product, immense volumes of "secondary" biogenic methane, most of which we can confidently infer to have been lost into the atmosphere. From mass balance analysis of petroleum systems, their history and the alteration of resulting oils we know that the natural flux of methane through Alberta aquifers and soils is huge, although the specific rates are not well constrained. For example, in the oil sands region >4991 trillion cubic feet (Table 11, 141.3 X 10^{14} m^3) of secondary biogenic methane was generated accompanying the biodegradation of the oil sands, practically all of which has been lost to the atmosphere, probably since mid-Eocene time (Huang, 2015). Aravena et al. (2003) concluded that methane in Elk Valley coalbeds was of biogenic origin, which leads one ponder the fate and history of the methane and carbon dioxide evolved during the coalification process, in much the same way that the secondary biogenic methane from petroleum alteration is not well accounted for by the assertion of Rowe and Muehlenbachs (1999a, 1999b) who interpret Colorado Group "low maturity thermogenic gases" as indigenous and non-migrated. Similarly, Tilley and Muehlenbachs (2006) concluded that WCSB gas maturity was generally consistent with the maturity of the host sediments such that they concluded that migration and mixing of gases was not pervasive on a broad regional and stratigraphic scale, except in the "deep basin". Yet, there is significant indication for potential gas migration through the Upper Cretaceous succession since other observe that secondary biogenic methane and primary coalification gases are typically not preserved.

Table 11: Estimates of the enormous volume of secondary biogenic methane that was generated during the formation of the bitumen and heavy oils in Lower Cretaceous Manville Group strata (Huang, 2015). These estimates ignore the secondary biogenic methane that would have accompanied the biodegradation of other crude oils in the WCSB (e.g. Osadetz et al., 1994), and as such should be treated as a minimum estimate of secondary biogenic methane volumes, essentially all of which has been emitted into the atmosphere.

Oil sands area	Oil sands deposit	Initial volume in place		Biodegradation PM level	Degradable material removed	Oil degraded	Generated secondary biogenic methane	
		10^6 m^3	billon bbl		fraction	billon bbl	Tcf	trillion m^3
Athabasca	Upper Grand Rapids	5817	37	7	0.55	45	86	2.4
	Middle Grand Rapids	2171	14	7	0.55	17	32	0.9
	Lower Grand Rapids	1286	8	7	0.55	10	19	0.5
	Wabiskaw-McMurray (mineable)	20823	131	8	0.6	197	377	10.7
	Wabiskaw-McMurray (in situ)	131609	828	8	0.6	1242	2385	67.5
	Nisku	16232	102	8	0.6	153	294	8.3
	Grosmont	64537	406	8	0.6	609	1170	33
Cold Lake	Upper Grand Rapids	5377	34	6	0.52	37	70	2
	Lower Grand Rapids	10004	63	6	0.52	68	131	4
	Clearwater	9422	59	6	0.52	64	123	3
	Wabiskaw-McMurray	4287	27	7	0.55	33	63	2
Peace River	Bluesky-Gething	10968	69	5	0.48	64	122	3
	Belloy	282	2	5	0.48	2	3	0
	Debolt	7800	49	5	0.48	45	87	2
	Shunda	2510	16	5	0.48	15	28	1
	Total	293125	1844			2600	**4991**	**141.3**
Heavy oil		2354	15	4	0.42	11	**21**	**0.6**

Therefore, it is reasonable to assume that natural gas seeps and their fluxes are an important part of the Alberta landscape in general. To what degree this has and is occurring currently relative to anthropogenic wellbore leakage and gas migration due to well integrity issues should also be a subject for consideration and analysis, as the natural fluxes in both the near surface succession into the atmosphere could be the significant source methane emissions.

8 IMPACTS OF METHANE EMISSIONS AND LEAKAGE

IMPACTS OF WELLBORE AND OTHER LEAKAGES TO THE SURFACE:

The impacts of Wellbore and other Leakages to the surface and into the atmosphere are known both directly from studies of wellbore leakages (, but it is also informed importantly by other sources of leakages, some of which have been studied both in greater detail and for a longer time. The key additional leakage sources that inform the impact of petroleum, particularly methane, leakages include:

- Leakages from gas distribution systems.
- Leakages from mines, especially coal mines.
- Leakages from waste management sites, particularly landfills.
- Agricultural practices, particularly the management of animal manure which is deposited on soils.
- The geological and geochemical prospection for petroleum using surface seepage identification and characterization.

The impacts of petroleum, particularly natural gas leakage in the subsurface and into the near surface and atmosphere has the following potential impacts:

- Human and animal health and safety,
- Plant health and crops yields,
- Risks to infrastructure,
- Soil and lithic mineral composition that might impact agricultural soil value,
- Microbial community ecology, which can in turn effect both leakage flux and human and animal health,
- Groundwater quality, and
- Greenhouse gas emissions to the atmosphere.

NON-SAFETY IMPACTS ON PETROLEUM TRANSFERS BETWEEN STRATAL UNITS AND SUBSURFACE AQUIFERS:

Transfers of petroleum assets between, whether intended or unintentional, and the contamination of subsurface aquifers with petroleum is not permitted by regulation, particularly where acid gases might be involved.

SAFETY IMPACTS ON HUMAN, ANIMAL AND PLANT HEALTH AND RISKS TO INFRASTRUCTURE:

The key impacts to health, safety and infrastructure of all types are toxicity (chemical poisoning), suffocation and combustion/explosion. These two impacts are not much dealt with herein, as they present imminent dangers that must be dealt with directly, and which in the case of well and transportation leakages are already mitigated by combinations of safety procedures that involve set-backs from facilities, conduit and container material specifications, detection/alarm procedures and required interventions to stop and repair leakages. Still these risks are worth considering in brief.

Toxic gases, particularly H2S can be produced both inorganically, most notably by the thermochemical sulphate reduction, which is the primary mechanism the results in the "souring" of Alberta gases and biogenically by sulphate reducing bacteria, often in association with fecal or other surface introduced contamination of water wells, although concentrations are commonly low in the second case. Although H_2S is beneficial to human health in extremely low concentrations it quickly becomes toxic at, 3×10^{-3}%(C%v.v), causing irreversible tissue damage. The strong "rotten-egg" odor of H_2S is identifiable at trace (parts per million, ppm) concentrations although human sensing of the gas rapidly decreases after exposure. Infrastructure damage (e.g. pipeline corrosion) is not a concern if H_2S concentrations remain below 200 ppm.

Suffocation by natural seepages are also a source of mortality. Methane suffocation is rare, but mortality due to carbon dioxide has resulted in both individual and mass mortalities. CO_2 is a colorless and odorless gas, commonly associated with some natural petroleum and injected processes gases from gas plants that remove Sulphur from sour gases. At surface CO_2 is chemically unreactive and hence undetectable by the human senses. Elevated CO_2 concentrations (1–3% air by volume, C%v.v) cause no physical damage but lead to rapid breathing, headaches, and tiredness. Above 3%(C%v.v) incomplete gas exchange in the lungs causes CO_2 concentration in the blood to increase hence altering the pH. This condition is called hypercapnia and leads to brain malfunction, loss of consciousness, and death at concentrations above 5–10%C%v.v. Cases of, as in the case of natural releases from African lakes, the worst of which, Lake Nyos killed 1,700 people and 3,500 livestock on August 21, 1986. In Italy, where there are at least 286 natural CO_2 gas seeps there have been 19 human and hundreds of animal lives during the past fifty years, primarily attributed to hypercapnia. There is no record of such mortalities in Canada.

Cases of nonfatal poisonings are, with a few exceptions, not well documented and could not be considered. Such cases are atypical for Canadian settings with the greatest risk being associated with H_2S toxicity. Hessel et al. (1997) surveyed the H_2S health effects of 175 petroleum workers in Alberta, one third reported having been exposed to H_2S, and 14 workers (8%) experienced knockdown, a term for the loss of consciousness due to inhaling high concentrations of hydrogen sulphide. The workers who had experienced knockdown exhibited the respiratory symptoms of shortness of breath, wheezing while hurrying or walking up hill, and random wheezing attacks. They found no "measurable pulmonary health effects as a result of exposure to H2S that were intense enough to cause symptoms but not intense enough to cause unconsciousness”. From 2000-2009 there were 117 environmental H_2S releases in Canada from petroleum or gas, waste water treatment plants and pulp and paper factories. Gas well blowouts were the most common cause, in the petroleum sector. The 1982 Lodgepole blowout is perhaps the most significant and well documented incident. The death of two Portage La Prairie municipal workers in 1969 at a sewage lagoon shows that the risks are not only related to petroleum sector settings.

Distribution system leakages of manufactured gas from coal contained compounds including ethylene and other toxic components some of which reacted with groundwater and carbon monoxide to form hydrocyanic acid, which produced toxic compounds, especially affecting plants in the vicinity of leaking pipelines. The general replacement of manufactured gas by natural gas during the interval 1950-1970 provides some of the most important information regarding the impacts natural gas leakage on the near surface. In part this is because domestic gas distribution systems are located in the soil near the surface, but also because the switch from manufactured gas to natural gas resulted in a large number of leaks, explosions and other impacts. This occurred because the old cast iron pipes used to convey manufactured gas, particularly in the Netherland, United Kingdom and eastern parts of the United States (Figure 9 were joined by soldered oakum filled joints. As generally non-toxic natural gas is drier than manufactured gas. This humidity change desiccated the oakum packing leading to large numbers of leaks, accidents and impacts and more detailed study of the impacts of pipeline leaks for leakage detection and impact avoidance.

Appropriate safety procedures can avoid both combustion and explosions, which are both a safety and infrastructure threat. Methane concentrations become a safety issue at >1 mg CH_4/L– the lower explosion limit of (Harder, 1995, Louisiana Water Resources Pamphlet #14) and can be distinguished from non-safety (< 1 mg CH_4/L) impacts. Adoption of suitable set-backs from wells and facilities, is generally the Canadian requirement provides for the quick dissipation of the combustion and explosion hazard, although there have been notable and spectacular exceptions (e.g. TCPL Winnipeg event).

NON-SAFETY IMPACTS ON HUMAN, ANIMAL AND PLANT HEALTH AND PRODUCTIVITY:

There is no link to human or animal health for non-safety exposures to methane, itself, despite the great concern and uncertainty suggested by the Canadian Council of Academies report. This is clearly demonstrated by several facts including that Neither the Canadian (http://www.hc-sc.gc.ca/ewh-semt/alt_formats/pdf/pubs/water-eau/sum_guide-res_recom/sum_guide-res_recom_2014-10_eng.pdf) nor World Health Organization drinking water (http://www.who.int/water_sanitation_health/publications/2011/who_gdwq_japanese_4thed.pdf?ua=1) guidelines proscribe or even mention methane. There is also common practice in many areas, particularly in the petroleum producing regions of southwestern Ontario, where farm wells have separated methane gas from water and used both. Methane should not be confused with disinfection by-products that result in chlorinated hydrocarbons which are health hazards (Gopal et al., 2007). Both a significant proportion of humans and all ruminants produce methane in their digestive tract (Sahakian et al., 2010). Methane has anti-inflammatory properties and it is proposed as a therapeutic substance from some human gastro-intestinal conditions (Liu et al., 2012).

However, West et al. (2006) indicated that the reaction of methane with NOx's, primarily in urban settings contributes to a growing global background concentration of tropospheric ozone (O3). Using epidemiological ozone-mortality linkages They inferred that a 20% global anthropogenic methane reduction, begun in 2010, would decrease the average daily maximum 8-h surface ozone by 1 ppbv globally, which they inferred might prevent ~370,000 between 2010 and 2030.

Below, we cite indirect impacts on plants attributed to methane contamination of soils (Godwin et al., 1990) where a chain of events:

- Methane contamination of soil, promotes
- Microbial CO2 production, that induces
- Groundwater acidification, which results in
- Mineral dissolution that additionally contaminates groundwater.

While the resulting associated impacts were inferred to be toxic for plants, perhaps surprisingly, there is no indication of similar mechanisms affecting human health. The environmental protection (https://www.epa.gov/privatewells/how-contaminated-water-can-affect-human-health) and epidemiology of groundwater toxicity do not mention methane contamination, either directly or indirectly, and methane contamination of groundwater is not a priority topic for the International Association of Medical Geologists (Bunnell et al., 2007; Centeno et al., 2016). Jackson et al (2011) concluded, "Nonetheless, we found essentially no peer-reviewed research on its [methane's] health effects at lower concentrations in water or air".

The direct effects of atmospheric methane exposure on plant species are variable and depend on a number of factors both physical and biological, which includes the activity of microbial communities in soils (Steven et al., 2006). Whereas, leaks of manufactured gas included toxicity especially for plants (the common test was to plant a tomato plant above a suspected leak because ethylene from manufactured gas resulted in severe epinasty of tomato leaves within 24 hours (Davis, 1977). Because of the interaction methane with soil microbes and plants the impact of soil methane contamination on plants is discussed in the following section.

SOIL MICROBES, METHANE FLUX AND ITS IMPACT ON PLANTS:

It was initially believed that commercial natural gas was, in the absence of H_2S, non-toxic and claims of plant damage or mortality were generally denied until Hoeks (1972) demonstrated the mechanism that was dominated by a reduction in soil oxygen to nearly zero and an increase in soil carbon dioxide, related to both methane displacement of soil oxygen and the production of carbon dioxide by methanotrophic microbes which consumed the methane. Hanson and Hanson (1996) reviewed methanotrophic bacteria, including their diversity, ecology and their environmental role, particular as related to the beneficial impacts of "their capacity to degrade environmental pollutants that are considered hazardous to human or ecosystem health". Methanotrophs are particularly important for the bioremediation of trichloroethylene by plants (Brigmon et al., 1999).

Nooman et al. (2012) provided an excellent illustration of the impact of a protracted petroleum seep on plants in conjunction with their development of remote sensing technologies for the identification of such sites using image analysis (Figure 16).

Figure 16: *Typical pattern of plant impacts at the site of natural petroleum seepage from Nooman et al. (2012, their Figure 4). In the centre of the seep vegetation is either absent or attenuated. This is surrounded by a halo of "green vegetation that gives way to "background" vegetation. The affected area has a radius of about 30 m, a person is shown scale on the left.*

Le Mer and Roger (2001) reviewed soil processes and microbial ecology in soils subjected to methane fluxes. Methane gas can migrate in the through the geosphere into the biosphere and atmosphere. Under saturated conditions, CH_4 remains a dissolved phase, but, gas ebullition in groundwater results in small bubbles that can migrate upwards (Hoch et al., 2003). Eventually, CH_4 migrates into the free gas phase in the partially saturated at which point physico-chemical conditions change significantly as the system changes from anaerobic to aerobic. As oxidation-potential rises under partially saturated and unsaturated conditions, so the activity of methanogenic bacteria is reduced and the influence of methanotrophic bacteria increases. Thus, methane transported into a becomes subject to 'consumption' (i.e. oxidation to CO_2) by methanotrophs. This is well documented in landfill caps through which considerable quantities of CH_4 can migrate (Crossman et al., 2004). Methanotrophs adapt their oxidative activity to the availability of CH_4 (Steven et al., 2006) and CH_4 oxidation rates in municipal landfill caps in can be as high as 4500 mol m^2/yr (Brown et al., 1999).

They and others have found that key factors effecting microbial methanogensis and methanotropy in soils depends on a number of factors, including:

1. Oxygen content and Eh,
2. Water content and hydrogeological conditions,
3. Organic Matter content, including plant litter and animal waste,

4. Climate,
5. Soil compaction/porosity,
6. Cultural and agricultural practices which themselves include, natural versus chemical fertilizers, the use of pesticides and insecticides, submersion of the crop.

These, in turn, are effected by factors that control gas migration within the soil including water table fluctuations, gas flux and soil stratification and permeability. The range of effects and impacts on plants associated with pipeline leaks are identical to those associated with identified wellbore leakage and natural seepages.

European studies related to pipeline leaks predominated, in part because of the wider use of cast iron pipes in European gas systems, especially where drier natural gas supplies replaced manufactured gas and there were many safety and non-safety related issues related to the dehydration of oakum joints in short cast iron distribution systems. Among the European studies there was the construction of a major test facility at the University of Nottingham (Smith et al., 2004) which studied the effects of soil methane impacts on the bacterial depletion of both oxygen and methane in the presence of pasture grasses and other crops between 2002 and 2005 (Steven et al., 2006). Small amounts of methane were found to have beneficial effects, but larger methane fluxes were found to have variable detrimental effects (Steven et al., 2006). The studies were carefully conducted and the impacts on crops monitored such that changes in plants detectable from remote sensing methods could be used to search for pipeline leaks in soils (ibid.). After 2005 the Nottingham test site (ASGARD) was used to evaluate the effects of CO2 leakage (Patil, 2012).

Another group at the University of Nottingham (Shaw et al., 2014) studied labelled methane migration through a soil in a study related to radioactive waste disposal. They performed laboratory and field experiments to obtain information on the probable rates of a) diffusive transport and b) oxidation of 12/13CH4 in a typical British agricultural soil. They observed low rates of CH4 oxidation the field where soil columns were undisturbed. In contrast they found that a re-packed soil homogenized topsoil column oxidized ambient atmospheric CH4 20% faster than that of the undisturbed soil column. In contrast to low observed CH4 oxidation rates in the undisturbed soil column the effective CH4 diffusion through the soil was rapid. Isotopically labelled methane injected 45 cm below the surface diffused to the surface and entered the atmosphere between 8 to 24 hours following its introduction. They also found that CH4 diffusion rate was where ryegrass roots, which increase soil porosity and decreased water content, were present. In the laboratory they also observed a fractionation effect that led them to conclude that the majority of 14CH4 that entered a low methanotrophic activity soil would be emitted to the atmosphere after diffusing rapidly through the soil column.

In general petroleum gases, specifically their hydrocarbon gas components, induce soil environmental changes that are dependent on:

- plant species,
- soil type and
- gas seep characteristics.

Soil oxygen is displaced by both hydrocarbon gases (Schumacher, 1996) and metabolic CO2 produced by aerobic methanotrophic bacteria (Steven et al., 2006). Bacterial oxygen depletion is accompanied by an increase in carbon dioxide (CO2) which can reach concentrations of 5%–15% (Hoeks, 1972). Godwin et al. (1990) showed that up to a distance of 9 m from a leaking gas well, manganese increased 5 to 10-fold, approaching toxic levels and that wheat growth was impacted within about 3 m of a leaking gas well, but that canola seed exhibited reduced growth up to 7 m away. The decreased oxygen and increased CO2 concentrations adversely effects plant growth, decreasing root and shoot growth (Drew, 1991). Trees and other plants may die as a result of both impaired root respiration and ground water acidification, while an anaerobic soil that increases trace elements contents including manganese and ferric iron, potentially to toxic levels for plants. Beaubien et al. (2008) identified a transition zone populated by tolerant species between the centre of a CO2 gas seep and the unaffected vegetation beyond the release. Pysek and Pysek (1989, in German as described in Noonan et al., 2012) used an artificial soil gas leak to induce change in vegetation diversity because of the species dependent response to soil gas.

In summary the results of a hydrocarbon gas leakage in soil can produce similar effects, regardless of source. These effects include potential plant mortality that can result in a barren soil zone at the centre of the seep that is surrounded by a change in both species diversity and individual plant characteristics, either beneficial or detrimental in the surrounding transition to the background. Noonan et al (2012) recognized that these changes, generally attributable to a change in chlorophyll content were not necessarily diagnostic of a gas leak and Van der Werff et al. (2006) found that pixel based image analysis resulted in the identification of natural hydrocarbon seeps <50% of the time. Noonan et al. (2012) attributed this poor result to the non-unique physical characteristics of the vegetation impacts that produced many false anomalies, but which they inferred could be reduced by the incorporation of additional information, like spatial patterns or alignments of potential seep anomalies, which Noonan et al (2012) attempted at natural seepages in California.

Other instances of methane leakage impacts include mass mortalities of trees in Boston and Washington (Figure 9), among numerous cases as discussed above, where they were used as indicators of natural gas distribution pipeline leaks (Phillips et al., 2013).

IMPACTS ON CLIMATE:

Impacts on climate are easily attributed because the global warming potential of methane is about 25 times that of carbon dioxide. In the absence of monitoring of other methane emitters, it is only possible to compare the measured and monitored well SCVF/GM data against the inventory estimates of other sources of methane. This needs to be re-evaluated in light of the apparent overestimation of SCVF/GM contributions in the 2010 national inventory for Alberta (Environment Canada, 2014). In contrast to the United States, Canadian atmospheric methane values do not exhibit concentration anomalies and there is neither an observed correlation with regional methane anomalies and sedimentary basins, nor among compounds that would suggest that fugitive emissions from petroleum activity contributes significantly to atmospheric methane. In particular, while the magnitude of wellbore SCVF and GM leakage can be estimated it is not possible to estimate the atmospheric flux from some of the other potential major emitters, in part because the role of microbial soil communities that might oxidize methane is not well understood relative to the emissions from natural backgrounds, landfills and coal mines. This is due to the fact that there are very few actual measurements of these emissions and there are apparent and significant differences between the top-down and bottom-up approaches at monitoring the various contributions, based on studies elsewhere. In short, we are uncertain as to the relative net contributions and rank of the various sources of emissions to the atmosphere, which makes the most efficient strategy for identifying the best targets for emissions reductions poorly known. Neither do we know how such reductions of any kind would compare to the background methane flux and if the effort would produce any tangible impact on the overall flux to the atmosphere. It would be a mistake to interpret Canadian needs from the perspective of American data, experience and practice.

9 DISCUSSION

SCVF/GM is measured annually and centrally compiled by some Provincial regulatory agencies such as the AER and BCOGC. Many leaking wells have been remediated, especially well leaking wells >300 m^3/day. Currently, (2016/06/02) the Alberta annual SCVF/GM emission rate is inferred to be about 84.4×10^6 m^3, (~56.5 kt methane). The 2010 Alberta SCVF/GM methane emissions data was 63.5 kt methane or about 42% of the National Inventory value. Monitored SCVF/GM emissions have decreased since 2008 and they are 11% less than 2010, but 62% lower than the 2010 Alberta National Inventory estimates, an unexplained difference. Existing literature and reports do not portray wellbore SCVF/GM leakage accurately, primarily due to the reduction of these emissions with time, but also because they contain errors in fact. The situation in Canada is inferred different from that in the United States, where atmospheric methane emission increases are due to increased upstream petroleum activities. Canadian air quality studies find methane concentrations like the global atmospheric average and anomalies in heavier volatile organic carbon compounds were attributed to transportation emissions primarily.

Other major sources and sinks of methane emissions for soils and the atmosphere include:

- Coal mines, primarily surface mines in Western Canada.
- Landfills receiving municipal solid wastes;
- Agricultural practices, including soil impacts, manure management, and enteric fermentation;
- Natural gas transportation infrastructures, particularly pipelines;
- Natural background emissions from the landscape resulting from the buoyant migration of petroleum.

In general, the emission from these sources are inferred using more easily measured data, such as the mass of municipal solid waste input to landfills and the emissions estimates are provided as cumulative mass estimates of CO_2 equivalent emissions, rather than requiring actual measured methane emissions. While such inferences may be appropriate for the estimation of national and global budgets they are inappropriate for detailed knowledge and management of both specific gas emissions and individual sectoral and specific sources of emissions.

The estimates of emissions from Canadian coal mines are the most credible. The national inventory GHG estimates can be confirmed by comparison of the Canadian annual produced coal volume against average values of American estimates for Coal Mine Methane emissions per tonne of coal produced at surface mines. The resulting daily annual Canadian Coal Mine Methane emission estimates of between around $1.70 \times 10^5\ m^3$ to $2.18 \times 10^5\ m^3$, can be compared to daily non-serious Alberta and British Columbia SCVF methane emissions.

We prefer not to attempt any quantitative comparison to landfill gas methane emissions. Rather we recommend that landfills should become the focus of more intensive monitoring efforts to understand their actual role as anthropogenic sources. Generally, the amount of landfill methane generated is inferred from the mass of solid waste input. The resulting methane production estimates are often poorly reconciled to bioreactor models of landfill gas production and not well correlated against monitoring studies of landfill methane emissions. Monitored landfill methane estimates vary by up to six orders of magnitude and rather than improving with time the monitoring discrepancies have remained, especially when bottom-up soil based emission studies are compared against top-down atmospheric emissions monitoring methods. The source of these discrepancies appear partly attributable to combinations of:

- The temporally and spatially variability of landfill and soil cap emissions.
- Variable effectiveness of soil cap physical and microbial processes that mitigate atmospheric emissions.
- Variability in the landfill gas production, and
- Differences in the monitoring techniques.

Where landfill gas is recovered or monitored there are either good data or the potential to capture good data regarding volumes and compositions of recovered gas. However, unresolved large discrepancies between estimates of landfill gas recovery efficiencies and differences in the treatment of soil cap impacts on methane flux indicate that the landfill system and its atmospheric emissions are not as well understood or reliable as either SCVF or surface coal mine emissions.

Agricultural systems appear to be better understood. While there remain uncertainties regarding the best estimation methods for enteric methane emissions from domestic animals the methods are generally comparable and both the emissions per animal, specifically in high intensity settings, and the numbers in herds inform national inventories in detail. Likewise, direct emissions attributable to manure management and crop production are well studied and these descriptions inform national inventories. More uncertain is the impact of agriculture on soils as the most significant global sink for atmospheric methane. Some studies have shown either that agricultural field practices reduce methanotrophic bacteria in the unsaturated soil by as much as 70%, while other studies suggest that actively cultivated soils may have less than one-third of the capacity to degrade atmospheric methane that is observed in the best natural soils. Whether the degradation of microbial soil methanotrophy should be considered an industrial anthropogenic impact comparable to coal mining and leaking petroleum wells should be discussed. No specific estimates or comparisons are made, although we note that the cumulative CO_2 equivalent emissions from Canadian agriculture ~68 Mt CO_2e, dwarf the methane emissions impact from both surface coal mines, ~4 Mt CO_2e, and the even smaller emissions from leaking non-serious petroleum wells, prior to considering the impact of soil sink methanotrophy reduction attributable to agricultural practices.

An average natural Alberta leakage flux would permit comparison of wellbore leakage from SCVF/GM to the natural seepage, but since the natural seepage rate is effectively undetermined such a comparison cannot be made. There are some global estimates of natural seepage rates (e.g. Etiope, 2016), but their applicability to Alberta is uncertain. Similar uncertainties attend estimates and relative the relative importance and impact of other emitter, most notably landfills and coal mines, although it is clear that even collectively the most conservative estimates of total Alberta wellbore leakage are comparable to some American landfill sites were methane recovery is proceeding.

There are clear potential safety and non-safety impacts on human and animal health, infrastructure and plants. Non-safety impacts affect plants primarily and these impacts range from mildly beneficial to mortal threats depending on both the flux rate and the response of the microbial community in soils. Although not studied in detailed in a Canadian context, or for Canadian soils and climate, both the approaches and the general nature of such studies can be informed by studies that are related to studies initially motivated by gas pipeline leaks. The European studies of impacts on vegetation and crops illustrate how complicated the gas migration pathway and its microbial soil interactions can complicate such studies, such that specific dosages are not even available for European crops.

The impacts on climate are calculable but uncertain since the Alberta ambient atmospheric methane values are close to global averages. The situation in Canada appears much different from that inferred for the United States where recent, mainly top-down studies of atmospheric methane emission anomalies inferred related to upstream petroleum activities are significantly higher than those estimated previously using bottom-up techniques.

Greater emphasis should be placed on measured methane fluxes, as is the case at wells, as opposed to using the IPCC worksheets that depend on much inference and may not appropriately reflect actual methane emissions. The reconciliation of top-down and bottom-up monitoring discrepancies should be resolved, as it has implications for the mechanism of emissions and the role of soil cover.

While there is much excellent isotopic data about methane and other hydrocarbon gas composition throughout Western Canada, which critically informs aspects of both emissions and contamination studies none of these studies appear to be consistent with the inferred massive flux of secondary biogenic methane that represents one of the largest quantified fluxes into the atmosphere. Neither is the isotopic fingerprinting commonly associated with material migration studies, which should also be a part of most migration studies, particularly where contamination of other resources is alleged.

It is appropriate to distinguish migration and leakage from contamination in the Canadian situation. Contamination implies not just a compositional similarity, but also demonstration/proof of a source, a migration pathway and a mechanism for the migration. This can be performed in the field using tracer compounds, but such studies are costly, time-consuming and very rare. Suffice it to say that most Canadian contamination complaints and studies rely on compositional similarity, often with a strong emphasis on isotopic compositional traits, without any study or modelling that would demonstrate that a physical migration has taken place or is even likely or more likely than local contamination from landowner practices. Since the potentially contaminated sites, commonly water wells and surface waters/soils, and the alleged contaminating sources, usually petroleum wells, are both communicating with the same petroleum system it is surprising that authorities consider compositional data as the definitive data (sufficient condition) in alleged cases of contamination, where it is more probably a necessary condition for contamination. This situation would suggest that much more emphasis should be placed on the physical migration aspects of alleged contamination than is currently the case, especially; since methods are available (Praagman and Rambags, 2008). From the current interpretation of gas isotopic compositions and the complete lack of their accommodation of secondary biogenic methane production or migration we should consider serious the re-examination and re-evaluation of all migration and contamination arguments that are based on isotopic characteristics solely.

10 CONCLUSIONS & BEST PRACTISES RECOMMENDATIONS

CONCLUSIONS:

Conclusions are provided as answers to the questions identified above:

- *What is the magnitude of methane emissions from leaky wells to the atmosphere and to the subsurface, and how does it compare to other sources?*
    - Currently, (2016/06/02) the Alberta annual SCVF/GM emission rate is inferred to be about 84.4×10^6 m^3, (~56.5 kt methane).
    - The 2010 Alberta SCVF/GM methane emissions data was 63.5 kt methane or about 42% of the 2010 National Inventory value.
    - Monitored SCVF/GM emissions have decreased since 2008 and they are 11% less than 2010, but 62% lower than the 2010 Alberta National Inventory estimates, an unexplained difference.

  - Existing literature and reports do not portray wellbore SCVF/GM leakage accurately, primarily due to the reduction of these emissions with time, but also because they contain errors in fact.
  - SCVF/GM are lesser sources of atmospheric methane emissions, even within the Upstream Petroleum Industry, probably <7%, rather than the about 15% that was attributed to them in the 2010 national Inventory. As such SCVF/GM is much smaller than most agricultural sources but somewhat comparable to surface coal mines.
- What is the impact of methane leakage on the environment: impact on groundwater quality and soil, and attendant impacts to biota?
  - The key potential impacts of such leakages are on:
  - Safety, where explosive limits are reached or poisoning or asphyxia occurs.
  - Impacts on vegetation and crops, which are well studied, easily identified, but for which specific exposure limits are not understood, in part because of the multiple factors, including microbial activity, which affects soil methane, and potential emission to the atmosphere.
  - On the atmosphere where, the effects of either methane or, should the leakage be microbially oxidized, the additional carbon dioxide have known potential climate impacts.
  - However, there is no indication for an impact on human health for non-safety impacts and methane is not included in potable water guidelines. This distinguishes gas migration and leakage issues from issues related to induced hydraulic fractures, where there is uncertainty about the impacts of chemical additives to the fluids employed.
- What, if any, is an acceptable leakage rate?
  - We don't know, but many of the wells leak at very low rates and the determination of appropriate rates that would show both responsible climate stewardship and harmonization with permitted rates from other sources should be sought. In the meantime, it might be suitable to provide some relaxation of currently stringent remediation requirements until an answer is known.

RECOMMENDATIONS

As we clearly don't have answers to the above questions, then:

- What currently existing or ongoing studies, knowledge, technology, or regulatory changes could be applied to help answer the questions?
  - Safety issues are currently addressed adequately by provincial regulations and they are actively enforced. Non-safety issues are being and should be addressed in a number of ways including:
    - A more detailed, well specific study of wells that have SCVF and gas migration issues, similar to the recent Pennsylvania study, but looking for risk-based indicators that would inform future

regulation, i.e. is surface casing deep enough for the area in which the well is drilled and other simply actions that would improve well construction practises and reduce wellbore leakage? This may have been done recently by the AER, but it not apparent from their latest publication on the subject (AER, 2016a).

        - Development of best practises for monitoring technologies that resolve or at least reconcile the differences between top-down and bottom-up based monitoring estimates.
        - The application, as appropriate to create an improved monitoring-based estimate of Canadian methane sources, both natural and anthropogenic, that use similar techniques and produce comparable results stated in similar ways.
        - Specific studies of crops and vegetation sensitivity to methane exposure as a function of an independent of microbial activity in soils. Theresa Watson has presented such a proposal, which essential would replicate the ASGARD study in England.
        - Specific studies of microbial methanotophism and methanogenesis in soils that examine the best anthropogenic actions, such as reduced soil compaction and type of fertilizers that would enhance methanotrophy in Canadian soils, as a function of their use, composition and climate.
        - Direct support for Canadian innovation and technology development, to improve Canada's already substantial monitoring instrument industry to provide a made in Canada first to market solution for global methane monitoring and remediation technologies for all anthropogenic sources.

- What knowledge and technology gaps remain?
    - Wellbore SCVF/GM leakages are clearly the most comprehensively monitored, reported and the most aggressively remediated sources of Canadian methane emissions.
    - Other sources should emulate the monitoring and remediation example provided by SCVF/GM actions. Other methane emitters should move from IPCC worksheet calculations of inferred methane sources to real, monitoring based studies that consider the role of all natural and anthropogenic sources and sinks, especially those that consider the local role of specific soils and their microbial communities.
    - Top-down and bottom up technologies for methane flux characterization need to reconciled, which is both a knowledge and technology gap.
    - Development of uniformly described databases of Canadian methane leakage sources from both natural and anthropogenic sources into the atmosphere and into the shallow subsurface, using appropriate

combinations of top-down and bottom-up approaches that specifically cross-validate survey results.

  - Improved, less costly wellbore leakage remediation technologies should be supported and developed since Dusseault et al. (2014) indicated that leakage issues are higher for horizontal wells than conventional wells (Their Figure 3.8).
  - Knowledge of climate and other resource responsible stewardship of wellbore leakage that permits emissions and leakage at appropriate rates without negatively impacting either groundwater or soil resources and their uses.
- What R&D will help address these gaps?
  - Co-ordinated calls and funding to address all the above ongoing studies and

11 EXTENSION PLAN

- SCVF/GM result in both atmospheric and soil/groundwater emissions, but their significance appears to be small and their impacts on soil, groundwater and human health are, uncommon, not significant generally, and only locally impactful.
- Therefore, we do not recommend an extension of this particular study. This work identifies that the AER and BCOGC are reliable sources of SCVF/GM data. The associated SCVF and GM data are dynamic and they should be treated as such. This study identified that there were issues with previous reporting and even some peer-reviewed contributions related to the characterization of SCVF/GM numbers of wells, rates and volumes emitted.
- There may be some value in encouraging the authors of this report to discuss the historical discrepancies in the peer-reviewed literature to more widely communicate that particular finding of this study for the purpose of correcting some widely-held but erroneous impressions about the magnitude and impact of SCVF/GM methane migration and emissions.
- This study found that the most carefully measured and monitored source of anthropogenic methane emissions were SCVF and GM. Even in the Upstream petroleum sector the, but especially outside of the upstream petroleum industry, the inventory and worksheet based estimates of inferred emissions are essentially irreconcilable to the SCVF/GM dataset and the effort to reconcile other emitters to SCVF/GM sources would be very expensive and out of scope.
- As discussed immediately above, this work did identify a significant number of research gaps, that might be addressed, but that many of these problems have been considered previously and that previous study has not been particularly successful, sometimes do to the geographic size of the problem, but also due to the complexity of some of the interactions. Key opportunities identified include:

- Development of specific soil gas migration limits that would reduce damage to plants and crops, difficult though this might be;
- Development of a reconciliation between top-down and bottom-up methane monitoring methods and technologies to resolve the common discrepancies between these two approaches.
- Better characterization natural or geosourced, background methane flux and its impacts, as well as the development of methods to distinguish natural gas migration from anthropogenic gas migration/contamination.
- Better understanding of gas migration and contamination issues and process associated with water wells, their recognition and their attribution, as this would both help to clearly recognize contamination from petroleum sources as opposed to and in contrast to contamination from domestic and agricultural sources.

- <u>This study could not find any indications that the AUPRF should make significant effort or expenditure to study the impacts of these migrations and emissions on human health.</u>

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