Identify GHG Level for Well Repair to Identify Acceptable Leak Rate

20-WARI-06

Fred Wassmuth, PhD. – Manager In-Situ Recovery
Gerry Boyer, P. Eng. – Well Integrity Consultant

REPORT PREPARED FOR

PETROLEUM TECHNOLOGY ALLIANCE CANADA.

BY INNOTECH ALBERTA INC.

RESERVOIR & GEOSCIENCES
250 KARL CLARK ROAD
EDMONTON, ALBERTA T6N 1E4
CANADA

Contract No. 20200000504

Date Feb 20, 2021

NOTICES OF REPORTS

1. This Report & the Accompanying Spreadsheet was prepared as an account of work conducted at INNOTECH ALBERTA INC. ("INNOTECH") on behalf of PETROLEUM TECHNOLOGY ALLIANCE CANADA. All reasonable efforts were made to ensure that the work conforms to accepted scientific, engineering and environmental practices, but INNOTECH makes no other representation and gives no other warranty with respect to the reliability, accuracy, validity or fitness of the information, analysis and conclusions contained in this Report & the Accompanying Spreadsheet. Any and all implied or statutory warranties of merchantability or fitness for any purpose are expressly excluded. PETROLEUM TECHNOLOGY ALLIANCE CANADA acknowledges that any use or interpretation of the information, analysis or conclusions contained in this Report & the Accompanying Spreadsheet is at its own risk. Reference herein to any specified commercial product, process or service by trade-name, trademark, manufacturer or otherwise does not constitute or imply an endorsement or recommendation by INNOTECH.

2. The information contained in this Report & the Accompanying Spreadsheet includes information, which is confidential and proprietary to PETROLEUM TECHNOLOGY ALLIANCE CANADA and information, which is confidential and proprietary to InnoTech.

3. InnoTech confirms that PETROLEUM TECHNOLOGY ALLIANCE CANADA is entitled to make such additional copies of this Report & the Accompanying Spreadsheet as PETROLEUM TECHNOLOGY ALLIANCE CANADA may require, but all such copies shall be copies of the entire Report & the Accompanying Spreadsheet. PETROLEUM TECHNOLOGY ALLIANCE CANADA shall not make copies of any extracts of this Report & the Accompanying Spreadsheet without the prior written consent of InnoTech. InnoTech further confirms that PETROLEUM TECHNOLOGY ALLIANCE CANADA is entitled to distribute copies of this Report & the Accompanying Spreadsheet only to employees, agents and contractors of PETROLEUM TECHNOLOGY ALLIANCE CANADA under terms that prohibit any further copying or distribution of the Report & the Accompanying Spreadsheet.

4. Any authorized copy of this Report & the Accompanying Spreadsheet distributed to a third party shall include an acknowledgement that the Report & the Accompanying Spreadsheet was prepared by INNOTECH and shall give appropriate credit to INNOTECH and the authors of the Report & the Accompanying Spreadsheet.

5. Copyright INNOTECH 2020. All rights reserved.

EXECUTIVE SUMMARY

Petroleum Technology Alliance Canada (PTAC) has engaged InnoTech Alberta Inc. (InnoTech) to determine what an acceptable sweet gas leak rate may be on abandoned wells.

In 2008 the Alberta regulator stipulated that abandoned wells cannot have a welded sealed cap and the casing strings must be vented when the casing strings are cut and capped below ground level. The AER has observed that wells abandoned since 2008 have a much higher frequency of leaking to the surface than wells abandoned before 2008.

The primary question was to determine if more atmospheric greenhouse gases (GHGs in CO_2 equivalent) are generated in repairing a well with a very low rate methane leak than would have occurred from the actual leak. Since well remediation to repair a leak is complex and many different methods may be deployed, the objective was to provide a proof of concept (POC) Excel workbook, that can be utilized for a wide variety of field circumstances. This concept would only be applied to low rate sweet natural gas leaks without any liquids.

A POC workbook was designed with a user guide and the user may select the necessary equipment for well remediation, the length of time each piece of equipment is utilized and some field conditions. The fuel consumption for the field work is automatically calculated along with the associated GHGs that are generated. A methane leak from a well to atmosphere is entered and the resulting GHGs are calculated. The workbook also contains information on methane oxidation in soil and in the atmosphere. In the workbook, the sheets are linked with macros, formulas, and data tables.

The methane leak rate from the well is also entered into the POC workbook and the GHGs are calculated from the cumulative volume that would accumulate in the atmosphere. A comparison is then made for each source of GHG.

This project used existing research and studies to populate the subject workbook so that it can be used as a POC and as a working tool in industry. Gaps are identified where further research is recommended to address the majority of conditions in Alberta.

Since this project was structured as a proof of concept, the assessments were not down to every possible minutia of detail. For example, if trees or vegetation must be removed to gain access to a site in order to conduct the well remediation, the loss of CO_2 sequestration from the vegetation was not considered.

It is critical that any leak from an abandoned well does not adversely affect vegetation. Some guidelines are provided in the workbook and in this report to help minimize this risk. This issue has many variables and is a key area where more research is required. A proposed field practice in the POC workbook provides some information to help minimize the risk of an adverse effect on plant health resulting from a sweet gas leak from an abandoned well that is cut and capped below ground.

Methane is known to be oxidized in soil by methanotrophic bacteria, an aerobic bacterium. As part of the POC, this project examined criterion for determining how much methane from a leaking well with a vented subsurface cap, could be oxidized in soil under field conditions.

A study conducted at the University of Calgary (by V.B. Stien and J.P.A. Hettiaratchi[1]) provided enough details for InnoTech to develop a proposed field practice for the natural consumption of methane leaking from an abandoned well. The concept is to oxidize methane in soil in a cost-effective and environmentally acceptable manner.

The proposed field practice, utilizing loam containing methanotrophic bacteria, is expected to result in oxidation of about 40% of a methane leak rate from an abandoned well when under good climate and soil conditions. In the proposed field practice, the volume of methanotrophic loam that is required is proportional to the methane leak rate. The workbook is designed to allow user flexibility and has a provision to make an adjustment for Alberta climate conditions.

This report and the POC workbook demonstrate that there are conditions in which more GHGs are released to the atmosphere during remediationthan a leaking abandoned well would produce.

The primary technology gaps that are recommended for further research are:

1. Additional studies of vegetation tolerance to methane in soil for the most common Alberta soils and the most common types of vegetation cover in Alberta.
2. Construct a laboratory or field pilot to validate the results of the proposed field practice that was developed in this project.
3. Acquire additional data on fuel consumption of well remediation equipment and trucking equipment from private sources.
4. Additional studies of bacterial methane consumption, or oxidation, in the most common Alberta soils and under Alberta climate conditions from a source below the soils.

This study did not examine the cost benefit of allowing very low leak rate wells to be abandoned without remediation and then utilizing the unspent funds where a higher reduction of GHGs could be achieved. This is an important consideration for optimizing the use of limited funds especially considering that multiple attempts are usually required to remediate a low leak rate on a well. It is understood that the most effective strategy in mitigating GHGs is to deploy scarce funds to the most impactful methods of reducing GHGs.

All recommendations and proposals in this report are subject to local regulatory acceptance before any field trials are implemented.

A separate report on Cost Effective Wellsite Monitoring has also been provided for this project. This report covers various site monitoring and leak measurement technologies that are in use and some that are emerging. It also identifies some gaps where technology development is recommended.

TABLE OF CONTENTS

Identify GHG Level for Well Repair to Identify Acceptable Leak Rate

1.0 INTRODUCTION

Approximately 460,000 wells have been drilled in Alberta since the 1880s. Technology, best practices, and rules related to well integrity, well closure, the environment and emissions have changed immensely over the last 130 years. Alberta currently has roughly 40,000 existing wells that are leaking to surface. About seven percent of new wells that are drilled in Alberta leak from the time they are drilled.

Most wells in Alberta with surface casing vent flow (SCVF) or gas migration (GM) leak natural gas, mainly methane, at very low rates. Practical methods of prioritizing repair work on leaking wells are critical. Understanding the unintended consequences of conducting the remediation work is also very important.

There are various reasons why a significant number of leaking wells have accumulated in Alberta and Western Canada. Leaving leaky wells unrepaired has impeded the closure of many wells and the subsequent reclamation of the well sites. This has resulted in methane emissions that remain unresolved and with public concern over inactive well sites which have no deadline for reclamation.

Well remediation often requires the deployment of a significant number of specialized pieces of equipment, all of which generate GHGs during mobilization and when conducting the work. Repairing wells with very low leak rates is particularly challenging and multiple attempts are often required to achieve hydraulic isolation in the wellbore. Furthermore, the AER has information which indicates that historically about 17% of wells that are repaired before abandonment end up leaking again after the wells are abandoned.

Technical guidance, best practices and updated rules are all important elements to achieve reduced emissions and to accelerate well closure with enhanced outcomes. PTAC and InnoTech can play important roles in deploying science, technology development and industry knowledge to practical field applications for the benefit of all Albertans.

Additionally, well closure and emissions from leaking wells are world-wide problems. Solutions developed in Alberta can be exported to create employment and expanded business for Albertans and to help address climate issues and social concerns.

It is anticipated that this report may be used in conjunction with other studies which may drive improvements in industry best practices, government policy and regulations.

2.0 EXCEL PROOF OF CONCEPT TOOL

2.1 COMPONENTS OF THE POC WORKBOOK

To determine if more GHGs are generated in repairing a very low rate methane leak from a well than the GHGs that would occur from the actual leak, the details of remediation need to be quantified. Well remediation is complex and many different methods may be deployed.

The POC workbook accompanying this report can be utilized for a wide variety of well interventions. It is designed so that the user may select the necessary equipment, the length of time each piece of equipment is utilized, some field conditions and then the fuel consumption is automatically calculated along with the associated GHGs that are generated. The number of well intervention attempts that are expected to be required for a successful remediation can be also entered into the workbook.

A methane leak rate from a well can be entered into the workbook and the cumulative GHGs in equivalent tonnes of CO_2, are then calculated based on the time it takes for methane to oxidize in the atmosphere.

When using the POC workbook, the first observation is a simple comparison of the GHGs generated from well remediation to the GHGs that the leaking well would generate. As a proof of concept, this workbook provides other valuable information to users. Additional studies are proposed to continue with technology development to fill some gaps.

The workbook will also assess how much methane could be consumed in soil with a proposed field practice by oxidating methane using a layer of methanotrophic loam. A study by Stien and Hettiaratchi[1] is used to determine the required thickness of the loam and the radius of the loam based on the well leak rate. This proposed practice should be proven with more field studies.

Since plant root depth is believed to be a factor in the tolerance of vegetation to methane in soil, the workbook contains information on the rooting depths of common Alberta agricultural crops and on many native plant species.

The Excel workbook is designed to work in 2013 and newer versions of Excel. Tabs on the workbook sheets are color coded as follows:

- Sheets with yellow tabs are for general user information. An example is the *Instructions* sheet.
- Green tabs identify sheets where the user provides information and green cells are where the user enters data. On the *Fuel & GHG* sheets other cells are color coded where data is to be selected or entered into the cells.
- Sheets with tabs that are light purple color provide additional technical information for advanced users.
- Sheets with red tabs contain data tables and formulas for administrators use only in the workbook. The everyday user will not have access or be able to view these, other than the sheet called *Instructions in Excel*.

The sheets and components of this POC workbook are summarized as follows:

- *Instructions* – This sheet contains guidance on using the POC workbook.
- *Cover Page* - The user inputs the company name, the unique well identifier (UWI) and the type of well (inactive or previously abandoned). It also contains a button which takes the user to the next data entry sheet.
- *Site Conditions & Results* – The well leak rate and the average number of required well intervention attempts are entered on this sheet. There are also two selections related to the consumption of methane in soil. The final results from all workbook input and calculations are displayed on this sheet.
- *Fuel & GHG-Inactive Well* and *Fuel & GHG-Drilling Re-entry* – These sheets are where the user makes selections for the equipment and the time required to repair a leak on either an inactive well or a well that has been previously abandoned. An inactive well will typically have a well head and an abandoned well has previously been cut and capped below ground level.
- *Field Practice Drawings* – This sheet contains images that the user may follow to implement a method of oxidizing some of the methane from a leaking well in soil.
- *General Guide & ROT* – This sheet provides information to the user such as conversion factors used in the POC workbook and rules of thumb that the user may refer to.
- *Vegetation Roots* – This sheet contains the rooting depths of most agricultural plants in Alberta and some of the common native grass species for Alberta based on a Saskatchewan study. It may help the user in implementing the proposed field practice to reduce the risk of methane in soil adversely impacting plant health.
- *Well Leak GHGs* – On this sheet, the well leak rate, in m^3 /day of methane, is used to calculate the cumulative CO_2 equivalent in tonnes in the atmosphere.
- *Methane Consumption in Soil* – This sheet has data and results from the Stien and Hettiaratchi[1] study which is used along with information previously entered by the user to estimate the amount of methane that could be oxidized in soil. The results provide guidance for establishing a proposed field practice for this purpose.
- *Subsoil Methane Distribution* – This sheet was used by the POC author to generate drawings for a proposed field practice and these images are shown in *Field Practice Drawings*.
- *Natural Regions* – This sheet describes the terrain, soil and vegetation of the Natural Regions and Subregions in Southern and Central Alberta. It may help the user in implementing the proposed field practice to reduce the risk of methane in soil impacting plant health.
- *Drop Down Menus, Factors in Calcs, Diesel Consumption, Natural Gas Consumption & Instructions in Excel* - These sheets contain data tables, calculations or instructions which are password protected and are not accessible to the user.

The POC workbook is protected so that links between sheets, the formulas and the data tables cannot be changed without a password. It is designed so that a user can easily enter information to produce practical guidelines.

Appendix A *User Guide for POC Workbook* provides additional guidance on selecting equipment for conducting the well remediation work. This includes the equipment mobilization and deployment elements and the related fuel consumption for various conditions. A calculation of the GHG equivalent in tonnes of CO_2 is generated in the POC.

This Appendix also has information on how the proposed field practice in the POC workbook can facilitate some natural consumption of methane in soil.

It includes some information on how certain soil conditions and vegetation types are expected to better tolerate the permissible leak rates, per square meter of soil area, when following the proposed field practice.

Appendix B *Source of Workbook Contents* identifies the sources of information used to construct the POC workbook.

Appendix C *Vegetation Rooting Depths* has a table with information on the natural regions and subregions in southern and central Alberta. It is a summary of the terrain, soil types and vegetation for the following two regions:

- Grassland Natural Region - Dry Mixedgrass Natural Subregion, Mixedgrass Natural Subregion, Northern Fescue Natural Subregion, Foothills Fescue Natural Subregion
- Parkland Natural Region - Foothills Parkland Natural Subregion, Central Parkland Natural Subregion, Peace River Parkland

Appendix D *Natural Regions of Southern and Central Alberta* contains information on the rooting depths of the primary agricultural vegetation in Alberta. It also has information on the rooting depths of native vegetation species from a study conducted in Saskatchewan which could be considered as a proxy for eastern Alberta.

Appendix E *Global Methane Budget* provides information on the global sources of methane in the atmosphere.

Recommendations are made in this report to conduct studies that could further populate the data tables in the POC workbook for conditions in Alberta and other provinces. This could expand the POC workbook functionality to be a more complete user tool.

2.2 SELECTING EQUIPMENT AND DEPLOYMENT FOR THE REMEDIATION WORK

When an operation to conduct well remediation is being planned, personnel will typically raise an AFE (approval for expenditure) to acquire funds for the work. In this process, all of the required steps to engage and utilize equipment are identified and the time required to conduct the work is estimated to generate the AFE for the well repairs.

The POC workbook is structured so the same equipment and time of utilization are selected on either the sheet called *Fuel & GHG-Inactive well* for an inactive well or *Fuel & GHG-Drilling Re-entry* for a drilling re-entry operation to parallel the process required to generate the AFE for the required work. This includes mobilization, field work and operating conditions. When this data is entered into the workbook a calculation of the expected fuel consumption and the associated GHGs are generated for the entire remedial operation.

In most cases, the field remediation work will be on an inactive well with a wellhead that has not been cut and capped below ground level.

When a well has been abandoned, and cut and capped below ground level, a small drilling rig is sometimes used for the operation. Drilling operations require some specific support equipment which are listed in the *Fuel & GHG-Drilling Re-entry* sheet.

Further instructions on using the input sheets in the POC are outlined in Appendix A. After the required equipment has been identified, the user will make selections on each row for each piece of equipment. The selections are for mobilization and onsite working conditions. The fuel consumption and associated GHGs from CO_2 released are automatically estimated in the workbook.

2.3 WELL LEAK RATE AND FIELD CONDITIONS

The workbook sheet "*Site Conditions and Results*" is where the actual well methane leak rate is entered. It is important to have an accurate measurement of the leak rate. The GHG calculation from the leak occurs on the sheet called *Well Leak GHGs*. Since this concept is only for sweet gas wells, it is assumed that the leak is all methane. On the *Site Conditions and Results* sheet there are other user selections as follows:

- The average number of well intervention attempts that are expected to result in a successful remediation.
- The number of days where methanotrophic bacteria is estimated to be active in the soil for the region of interest in Alberta.
- A flow rate of methane through a layer of methanotrophic loam based on two selections from the Stien and Hettiaratchi[1] laboratory study. This option is for either a conservative or a moderate approach in units of methane flow through a cross sectional area of loam.

The two flow rate selections taken from the Stien and Hettiaratchi[1] laboratory study are converted from units used in the laboratory study to common field units so that the rates can then apply to a field site. More details are provided in Section 3 of this report. These two selections provide a range so that sensitivities may be examined for varying risk tolerance.

After all data is entered, and if the GHG generated by the well remediation exceeds the GHG from the well leak, before any oxidation of methane in soil, the difference is displayed. If the GHG from well remediation is less than the methane leak GHG, the answer is displayed as 'Not Applicable'. The same logic is applied to the case with partial oxidation of methane in soil.

If the user knows the type of vegetation that will cover the abandoned well, the rooting depths may be identified in the workbook. The specific plant rooting depth could be used as a guide to determine how much local topsoil is placed over the loam containing methanotrophic bacteria. This is expected to help reduce the risk of the vegetation being adversely affected by methane in the soil provided the guidelines in the POC are followed at the field location.

2.4 DATA SOURCES

A list of equipment and services commonly used for well remediation was structured in the workbook. An extensive search was conducted from public sources to collate relevant information on the following:

- Fuel consumption of the equipment.
- Methane oxidation in soil and in the atmosphere.

- Vegetation tolerance to methane in soil.

The public sources utilized to populate tables for the fuel consumption of equipment are listed in Appendix B. Wherever practical the calculated fuel consumption from these sources was cross checked with other information and guidelines as indicated in Appendix B.

As indicated, the POC user has the ability to make selections for factors affecting fuel consumption under field conditions. For the mobilization of some equipment, a fuel consumption was based on travel distance. Mobilization fuel consumption for other equipment was based on the truck capacity or engine size, the expected load factor and the time required for mobilizing/demobilizing.

Where the data did not cover exact power and load factors for the specified equipment, extrapolations were made to provide reasonable estimates of fuel consumption.

A 'reality check' table was constructed to compare the estimated fuel consumption of some pieces of equipment with a few commonly used 'rules of thumb' or ROTs.

A number of public studies were examined that determined the oxidation of methane in soil by methanotrophic bacteria under a variety of conditions. These studies were generally focused on methane that occurs naturally in soil or methane existing in the atmosphere rather than methane from a leak source below soil and were not used in this report. As discussed in Section 3 of this report, the Stien and Hettiaratchi[1] study was very well suited to this project.

Research projects assessing plant life tolerance to methane in soils were found, but the data was not well suited for Alberta conditions and any information that was used is referenced later in this report. Other key findings were related to the rooting depths of plants and the amount of oxygen in soil that plants require to remain healthy. Section 4 of this report provides more detail on these issues.

3.0 OXIDATION OF METHANE IN SOIL

3.1 ESTIMATING METHANE CONSUMPTION FROM A UNIVERSITY OF CALGARY STUDY

Publicly available sources were reviewed to find research that could be adapted to Alberta conditions and to help construct a proposed field practice for field applications. The criterion was examined to determine how much methane from a leaking well could be oxidized by bacteria in soil under field conditions.

The study conducted by Stien and Hettiaratchi[1] was an ideal source of information for assessing methane oxidation in soils. The study provided enough details for InnoTech to identify a proposed method of oxidizing methane in soil in a cost effective and environmentally acceptable manner.

The Stien and Hettiaratchi[1] study examined methane oxidation in three types of Alberta soils, sedge peat moss from Cochrane, landfill loam from Springbank and agricultural soil from Rockyview county.

In summary, the Stien and Hettiaratchi[1] used plexiglass cylinders containing soil with methane injected into the bottom of the cylinders and with air passed over the top of the cylinders. It was designed to simulate field conditions. A mass balance was conducted to determine how much methane was oxidized in each soil from the bacteria. The test results from Springbank landfill loam were key to developing a proposed field practice.

The steady-state oxidation rate of methane when passing through three different columns containing Springbank landfill (methanotrophic) loam was 39.9 %. During the testing, the methane flow rate through the soil samples varied and the study did not provide an average flow rate but did provide a minimum and a maximum limit for the methane flow. To propose a field practice, a midpoint flow rate was calculated and may be a proxy for achieving approximately 40% oxidation of methane in methanotrophic loam under ideal conditions.

The primary observations from the Stien and Hettiaratchi[1] study are summarized below:

- Methane injection ranged 2.5 to 5.2 ml/min in the study (midpoint 3.85, average unknown)
- In field units, and converted to square meters of soil surface area, the methane injection ranged from 0.0241 to 0.050 m^3 $m^{-2}d^{-1}$ (midpoint 0.0371)
- The ID of the test columns was 13.8 cm (area 149.6 cm^2), the soil height in the columns was 80 cm
- Landfill loam oxidized methane at a steady state average rate of 39.9% on three samples
- The average steady state CH_4 oxidation under different injection rates was 105 g $m^{-2}d^{-1}$ per day, based on the cross-section area of the test column
- The lowest methane flow rate through landfill loam had the highest steady state oxidation at 50%
- Moisture content is critical for optimal methane oxidation in soil ~16.5% may be optimal
- The optimal temperature for methane oxidation in soil is ~30 °C
- The optimal oxygen concentration in soil was ~ 0.75 to 1.3 % for methane oxidation

- It may be possible to achieve 100% oxidation at less than 83 g m^{-2} d^{-1} methane flux
- The ideal methane flux rate for oxidation is less than 83 g m^{-2} d^{-1} or 1.859 m^3 m^{-2} d^{-1}
- Methanotrophic bacteria must be present and may need to be seeded into soils if landfill loam is not available for a field practice
- Forest soils and soil from landfill cover sites will likely have methanotrophic bacteria
- Oxidation could occur as deep as 80 cm in soil
- The optimal soil type may vary depending on climate conditions and vegetation

Table 1 has a summary of the soil conditions for the Springbank landfill loam.

Table 1: Landfill Loam - Average Soil Conditions in Stien and Hettiaratchi[1] Study

Percent of CH_4 oxidized at steady state at different injection rates	39.9%
Density	1.159 g ml^{-1}
Moisture content	9.40% dry weight*
Water holding capacity	24.6% dry weight*
Organic matter	3.10% dry weight*
pH	8.45
Porosity (fraction)	0.61
Air filled porosity (fraction)	0.51

*Dry weight means dry soil weight

3.2 ADAPTING UNIVERSITY OF CALGARY STUDY TO FIELD CONDITIONS

When field conditions are structured to match the study conditions of the Stien and Hettiaratchi[1] test on landfill loam to the extent that is practical, an estimate can be made of methane oxidation in soil under defined conditions. For variables such as climate conditions, a generic adjustment could be formed such as the number of days per year that the bacteria are expected to be active in the soil.

Using landfill loam prepopulated with methanotrophic bacteria is key to developing a field practice. In the Stien and Hettiaratchi[1] study landfill loam contained methanotrophic bacteria which had developed due to a methane source under the soil at the landfill site.

Methane flow rates through the soil in the proposed field practice need to be the same per square meter as was used in the Stien and Hettiaratchi[1] study and with the same loam thickness of 0.8 m. The two flow rates derived from the study were 0.0241 m3 per day of methane per square meter of landfill loam (m3 m-2 d-1) at the low end and the midpoint value of 0.0371 m3 m-2 d-1.

Assessing both rates provides a sensitivity with different risk tolerances. The midpoint value is thought to be representative of approximately 40% methane oxidation under ideal conditions, a more conservative approach would be to use the flow rate at the low end of the range.

3.3 PROPOSED FIELD PRACTICE BASED ON METHANE OXIDATION

The proposed field practice to utilize landfill loam containing methanotrophic bacteria is structured to stay within the guidelines of the Stien and Hettiaratchi[1] study as much as possible but scale up to field applications.

A leak rate range from the study was converted to cubic meters per day of methane per square meter of surface area (m^3 m^{-2}). In the field, an equivalent amount of land fill loam can be placed over a cut and capped casing that is leaking to match the leak rate (m^3 m^{-2} d^{-1}) on a per unit basis. As in the laboratory study, the thickness of the loam cover to be deployed in the field is 0.8 m. A gas distribution system must be placed between the leak source and the loam to ensure that the methane is uniformly distributed underneath and through the loam soil surface area.

The POC workbook calculates the required radius of the loam cover in the form of a large cylinder like a hockey puck, determined by the specific well leak rate. Methane flow through the soil is in units of cubic meters of methane per square meter of soil per day (m^3 m^{-2} $d^{-1)}$.

Utilizing the proposed field practice when under good climate and soil conditions is expected to result in oxidation of about 40% of a methane leak rate from a cut and capped well that has been abandoned. No byproducts of methane oxidation were not considered in this study.

Ensuring optimal oxidation of methane in soil requires oxygen in the soil. In order to ensure that the soil has high permeability enabling the exchange of gasses in the soil, it may be beneficial to add sand or other materials which provide permanent permeability to the methanotrophic loam. Plant roots also require oxygen in the soil to ensure that plant health is not adversely impacted.

Studies regarding the optimal oxygen level in soil for plant health are referenced in section 4.1 of this report.

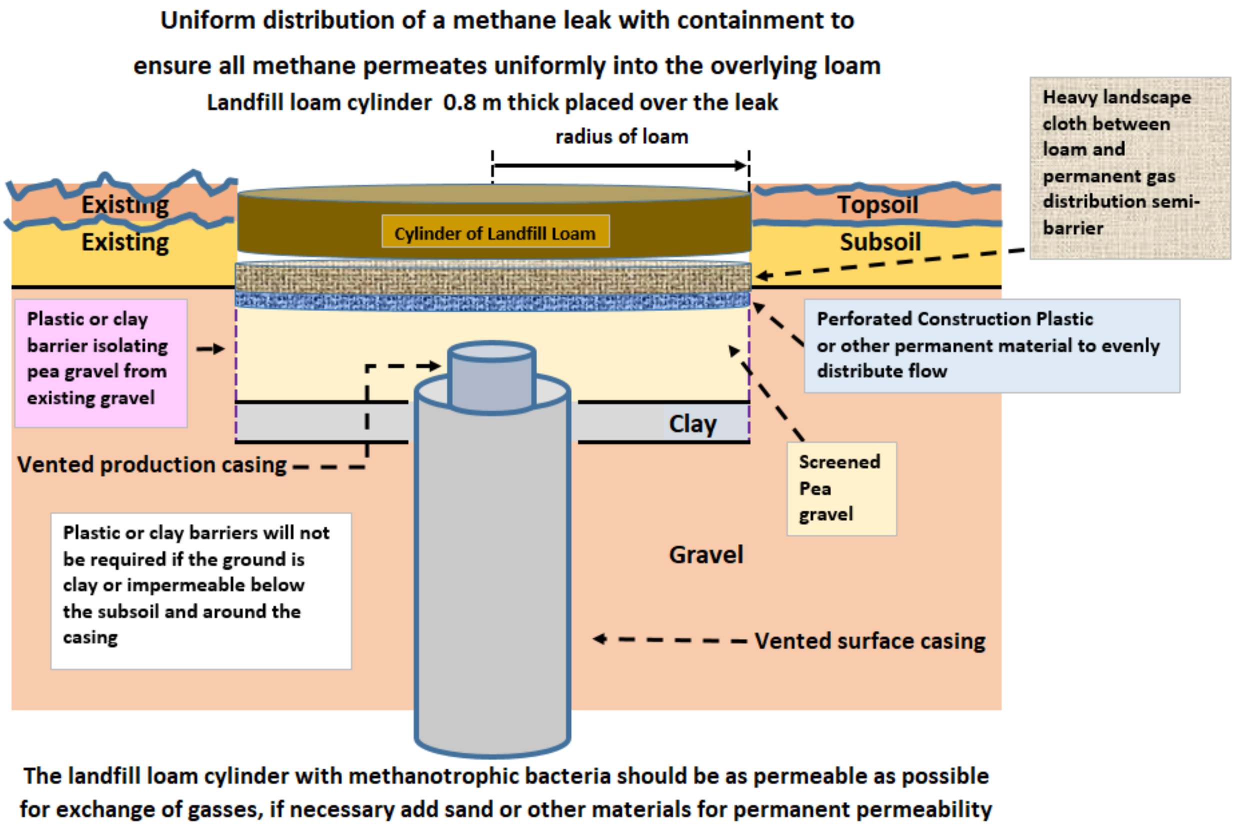
The proposed field practice in the POC has two options with the first being the method described above and shown in Figure 1. This could possibly be applied under conditions where using land fill loam as the surface soil is acceptable and where vegetation health is not adversely impacted. Figure 1 displays a procedure to ensure the uniform distribution of a methane leak through the methanotrophic loam.

Another option is to add an additional layer of local topsoil over the methanotrophic loam as shown in Figure 2. Option 2 may be required by local regulators. To ensure a high degree of permeability in the local topsoil it may be beneficial to add sand to it. As indicated in section 4 of this report, the local topsoil thickness and the rooting depths of the local vegetation should also be taken into consideration.

If the cut and capped casing string tops are in highly permeable earth such as sand or gravel, it is advisable to prevent migration of a methane leak away from the area where the landfill loam is placed. This may be achieved by placing a clay layer as a base below the level of the casing tops and by placing permanent and impermeable material as a barrier around the outside perimeter of the landfill loam.

Since climate conditions at Alberta field sites cannot be controlled to replicate laboratory conditions the number of days per year that bacteria are expected to be active in the soil, relative to laboratory conditions, can be entered into the POC workbook. This provides a method of adjusting the calculation to estimate annual consumption of methane in the soil. It also provides users with the ability to run sensitivities with different risk tolerances.

The POC user can select either 0.0241 $m^3\ m^{-2}\ d^{-1}$ at the low end or the midpoint value of 0.0371 $m^3\ m^{-2}\ d^{-1}$ of methane flow through soil. This provides a second method of conducting a sensitivity with different risk tolerances.



Uniform distribution of a methane leak with containment to ensure all methane permeates uniformly into the overlying loam

Landfill loam cylinder 0.8 m thick placed over the leak

Heavy landscape cloth between loam and permanent gas distribution semi-barrier

Perforated Construction Plastic or other permanent material to evenly distribute flow

Plastic or clay barrier isolating pea gravel from existing gravel

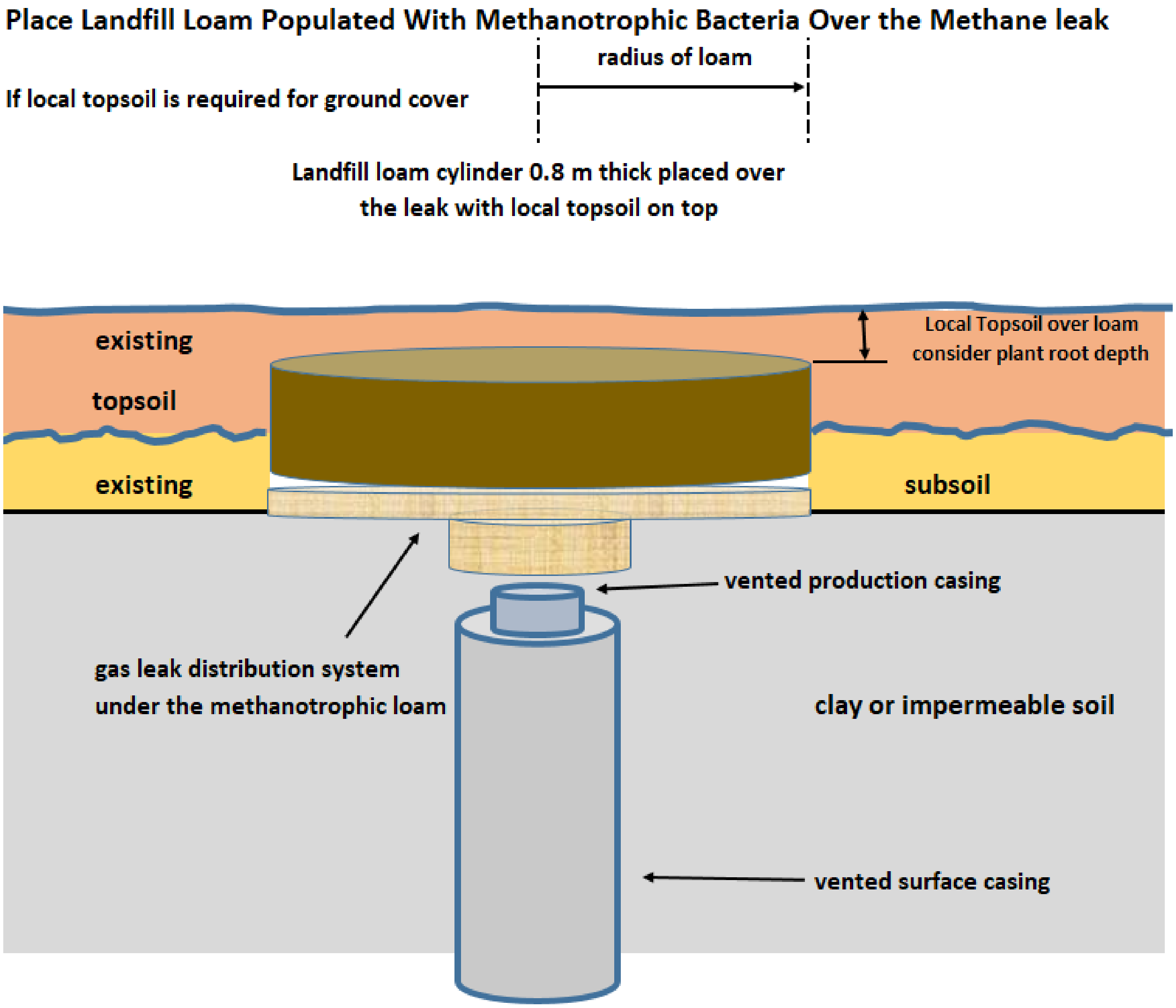
Plastic or clay barriers will not be required if the ground is clay or impermeable below the subsoil and around the casing

The landfill loam cylinder with methanotrophic bacteria should be as permeable as possible for exchange of gasses, if necessary add sand or other materials for permanent permeability

Figure 1: Image of Proposed Field Practice For Methane Consumption in Soil

Figure 1 is an image of how field reclamation work could be conducted when following the proposed field practice and calculations using landfill loam to consume some of the methane in soil with methanotrophic bacteria. Under good field conditions about 40% of the methane may be consumed and an annual estimate of methane oxidation is also estimated in the workbook.

Other methods may be utilized to ensure that methane leak from an abandoned well is contained and is uniformly distributed to pass through the methanotrophic loam.



Place Landfill Loam Populated With Methanotrophic Bacteria Over the Methane leak

The loam with methanotrophic bacteria and the topsoil over the loam should be permeable for exchange of gasses, consider adding sand or other permanently permeable material to the loam and topsoil

Figure 2: Image of Proposed Field Practice For Methane Consumption in Soil With Local Topsoil and With Impermeable Soil Around the Casing Strings

The image in Figure 2 illustrates how a cover of methanotrophic loam could be utilized when there is a requirement to have local topsoil covering the site. This example also illustrates a situation where impermeable soil prevents a methane leak from dispersing outside of a designed leak distribution cover over the casing which directs the methane uniformly into the methanotrophic loam. Details of how a leak distribution system could be structured are shown in Figure 1.

4.0 VEGETATION TOLERANCE TO METHANE IN SOIL

4.1 RESEARCH AND STUDIES

There is a paucity of research on vegetation tolerance to methane in soil from leaking abandoned wells for Alberta plant species. Studies have demonstrated a complex relationship between methane in soil, vegetation health, soil conditions and climate. However, some papers provide guidance on vegetation tolerance to methane in soil as it relates to plant rooting depth and the supply of oxygen in the soil.

Natural gas is composed primarily of methane and does not directly cause toxicity to plants. The presence of natural gas in the soil displaces oxygen in the soil pore spaces, which can result in anaerobic conditions (University of Maryland Extenstion, 2020). Anaerobic conditions may inhibit plant growth due to lack of oxygen, carbon dioxide toxicity, or by changing the availability of metals in soil such that they become available to plants at toxic concentrations (Flower, Gilman, & Leone, 1981).

In Pankhurst (1980), low oxygen concentration in soil was considered the most important cause of death when trees were exposed to natural gas. While anaerobic conditions may result from natural gas replacing oxygen in soil, methane oxidation resulting in methane consumption by bacteria is a key factor in the formation of anaerobic conditions. Flower et al. (1981), in reference to landfill gases containing methane, stated that “If [landfill gases] do not reach the root zone of vegetation, they will not cause injury”. In terms of plant tolerance to methane, it is important to consider rooting depth and factors that allow methane, carbon dioxide and oxygen to migrate through soil within the root zone.

While a standard minimum oxygen concentration for root growth does not exist due to the variability of environmental conditions and species-specific tolerance, “soil with less than 12% oxygen is likely to be detrimental to tree health… and soil with less than 6% certainly so” (Moffat & Houston, 1991).

When methanotrophic bacteria oxidizes methane in soil it consumes oxygen in the process. The resulting oxygen depletion in the soil can also contribute to the asphyxiation of vegetation.

When considering a leaking natural gas well that has been cut and capped, migration of gases depends on the depth and characteristics of the fill material placed over the well, the depth to the water table or to impermeable subsoil horizons, and the permeability of adjacent soil. A porous soil cover will contribute to more oxygen entering the soil and penetrating to deeper depths in the soil. Some researchers have speculated that plants with longer roots such as alfalfa may contribute to oxygen penetrating deeper in soils. The oxygen supply in soil contributes to plant health and to increase action of methanotrophic bacteria consuming methane in the soil.

If soil adjacent to the fill covering a leaking well is highly permeable, gases could migrate into this material and then vertically to the soil surface. Vegetation in the adjacent soil could experience adverse effects caused by methane in the soil. If the water table, or fine texture soils and clay soils saturated with water, are above the source of a leak, they could act as barriers preventing the movement of gases in the soil. The characteristics of both the fill material and adjacent soil should be considered, as lateral movement of gasses may occur.

Rooting depth is a key factor determining plant tolerance to methane. Trees are believed to be susceptible as they typically have deep root systems (Flower et al., 1981). Flower et al. (1981) observed that while trees died in certain areas due to landfill gases, the more shallow-rooted groundcover survived. When landfill gases are present in surface soil horizons, their concentration tends to increase with depth (Flower et al., 1981); the same phenomenon can likely be assumed for natural gas from leaking wells. The topsoil horizon can likely remain aerobic, as ambient air can diffuse into the soil and other gases can diffuse out. This provides an opportunity for shallow rooted species to grow in largely aerobic conditions. Chongyu & Minghung (1994) made a similar observation on a site that was highly impacted by landfill gas; grasses and herbs were found to tolerate high concentrations of methane and carbon dioxide in soil because of their shallow root systems.

Plant species vary in their tolerance to anaerobic conditions in the root zone. In a study by Flower et al. (1981) in New Jersey, nineteen species were evaluated for their tolerance to salinity based on above ground growth parameters; the authors ranked these species from most tolerant (black gum) to least tolerant (rhododendron). Interestingly, species with more shallow root systems were not necessarily the most tolerant (Flower et al., 1981) to soil salinity. However, there may not be a relationship between soil salinity and methane in soil with respect to plant health.

Chongyu & Minghung (1994) found that plants with more shallow root systems tended to tolerate elevated concentrations of methane and carbon dioxide in soil better. In a study by Trotter & Cooke (2005) in South Africa, grass species varied in their sensitivity to elevated soil CO_2 caused by landfill gases. This indicates that even within vegetation categories that would typically be considered shallow-rooted, there are species-specific effects.

Plant species that can tolerate anaerobic conditions tend to prefer moist environments and may not tolerate conditions if sufficient moisture is not available. For example, wetland vegetation which would typically have some tolerance to anaerobic conditions may not perform well in upland soils.

Impacts of natural gas on vegetation tend to be more readily identified in agricultural land, compared to northern forests and wetlands. For this project, the focus was on natural subregions in southern and central Alberta, including both native vegetation and agronomic species.

A report by Mitchel I., Christensen A., Smith B., and Drozdowski B.[2] was prepared for PTAC. This report reviewed important agronomic species in the province and their rooting characteristics. Nine species were found to account for 98% of land use for agriculture in Alberta, alfalfa, barley, canola, durum wheat, hay/fodder, mixed grain, oats, peas, and spring wheat.

Mitchel I., Christensen A., Smith B., and Drozdowski B.[2] also identified lentils as an important crop in 2016. While the proportion of each crop grown varies by region of the province, the same nine species tend to be dominant. Appendix C contains information on the rooting depths for these nine species.

A study conducted by Arif M. A. S. and Verstraete W.[3] examined the effects of methane in soil on maize, wheat, and spinach. In this research the dry shoot weight was used as the key metric for plant health with larger weights indicating enhanced plant health. The soil in this study was saturated with about 10% methane by volume but the methane concentration varied as methane was consumed and subsequently added to the soil.

Microbial biomass, or bacterial population, was assessed as methanotrophic bacteria consumed methane in the soil. The study also examined how plant life was affected when both methane and Long Ashton nutrient solution, an established blend of nutrients for plants, was added to the soil.

The following observations were derived from the Arif M. A. S. and Verstraete W.[3] paper:

- Methane oxidation occurred much faster in the soil with mineral nutrients.
- The nitrate (NO_3) content in the soil was significantly decreased in both the soil with methane added and the soils with methane and nutrients added due to biological activity.
- The loss of nitrate in the soil was not all accounted for with the increase in biomass and the amounts not accounted for was likely due to denitrification from other soil heterotrophs.
- The maize shoot weight decreased when the soil had only methane added to it. There was no report on wheat and spinach growth impacts when only methane was added.
- Maize shoot weight increased significantly when both methane and nutrients were added to the soil.
- Wheat and spinach shoot weight was adversely affected when methane and nutrients were added to the soil.
- Microbial biomass increased in the soil with only methane added and in the soil with methane and nutrients added but much more so in the latter.

4.2 PROPOSED FIELD PRACTICE FOR VEGATION GROWTH

The research papers referenced in Section 4.1 of this report indicate that plant life will not be adversely affected by methane in the soil provided there is enough oxygen, nutrients, and water in the soil. These conditions will vary for different plant species, soil and climate variables.

A proposed field practice, as described in Section 3.3 of this report to use methanotrophic loam over an abandoned well with a very low leak rate, requires field pilot testing to further assess the oxidization of methane in soil. The proposed field practice may be applicable to leaking wells, to landfill sites and other sources of underground methane. The field practice should also ensure that following conditions are met to the extent that is practical:

1. Ensure that the soils placed above a source of methane have as much porosity and permeability as possible to enable maximum oxygen penetration into the soil. Also, to allow methane that is not oxidized and carbon dioxide to escape from the soil.
2. Place enough soil containing methanotrophic bacteria over the leak to maximize the oxidation of methane and additional soil on top to provide soil depth for plant rooting.

Appendix C contains some information on rooting depths of vegetation and Appendix D has information on soil types in parts of Alberta.

3. Where possible select vegetation that is known to be tolerant to methane in soil for growth over a methane leak source.
4. To the extent possible compare vegetation growth with and without supplementary nutrients.

5.0 OXIDATION OF METHANE IN THE ATMOSPHERE

5.1 RESEARCH AND STUDIES

Methane oxidizes in the atmosphere and generates water vapor, ozone and other chemicals. This process occurs when methane reacts with the hydroxyl radical (·OH) in the troposphere or stratosphere to create the methyl $\cdot CH_3$ radical and water vapor.

$$CH4 + OH \rightarrow CH3 + H2O$$

Following the reaction of methane with the hydroxyl radical, two dominant pathways of methane oxidation exist. One leads to a net production of ozone, and the second causes no net ozone change. For methane oxidation to take the pathway that leads to net ozone production, nitric oxide (NO) must be available to react with $CH_3O_2\cdot$. Otherwise, $CH_3O_2\cdot$ reacts with the hydroperoxyl radical ($HO_2\cdot$), and the oxidation takes the pathway with no net ozone change. Both oxidation pathways lead to a net production of formaldehyde and water vapor.

Several research projects have been undertaken in recent years which assess the atmospheric lifetime of methane, or the time it takes for methane to oxidize, in the atmosphere. The most rigorous work in this regard seems to be from the IGPCC by Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K., Tignor M., and Miller H. L.[4]

The IGPCC has determined that methane remains in the atmosphere for an average of 12 years before it is oxidized. For the prupose of this study, the byproducts of methane oxidation in the atmosphere were not considered as GHG contributors.

5.2 APPLYING RESEARCH AND STUDIES

For the purpose of calculations in POC workbook, the life expectance of methane in the atmosphere was assumed to be 12 years. To calculate the GHG effect of methane in the atmosphere from a leaking well, the well leak rate per day was multiplied by 12 years to determine the total volume of methane that would accumulate in the atmosphere.

A factor of 25 by weight is a commonly accepted equivalency of methane (CH_4) for GHG climate effects, or global warming potential, to carbon dioxide (CO_2) in the atmosphere (Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K., Tignor M., and Miller H. L.[4]). Carbon dioxide has an 'index' value of 1 (i.e. 1 kg CH_4 is equivalent to 25 kg of CO_2 in the atmosphere).

In the workbook the cumulative twelve-year methane leak volume in the atmosphere was converted to a CO_2 equivalent volume of GHG by multiplying the methane volume by 25. The result was then multiplied by methane density (0.717 kg / m^3 at STP) to determine the number of kg and then divided by one thousand to determine the tonnes of CO_2 equivalent.

No assessment of the byproducts of methane oxidation in the atmosphere was taken into consideration in the GHG equivalency calculations in the POC workbook.

6.0 TECHNOLOGY AND DATA GAPS

6.1 FUEL CONSUMPTION OF REMEDIATION EQUIPMENT

For some field equipment there was no public data available on fuel consumption. In this case, the fuel consumption of similar stationary engines driving generators was utilized based on horsepower and load factors. This information was checked with several private sources and guidelines to ensure that the values were reasonable.

A study is recommended in which additional data is utilized from private sources to further refine the fuel consumption estimates for field equipment.

Potential sources of private data for fuel consumption may be; trucking companies, rig moving companies, well servicing and drilling companies and other industrial firms.

6.2 OXIDATION OF METHANE IN ALBERTA SOILS AND CLIMATE

Only one study related to the oxidation of methane in soil was used in this project. Additional studies similar to the Stien and Hettiaratchi[1] study are recommended to cover the majority of Alberta soils. In laboratory work of this nature, soils could be prepopulated with naturally occurring methanotrophic bacteria to accelerate the testing procedures if landfill loam is not available.

An examination of the many existing studies that were sourced for this project will provide guidance when planning new laboratory work or field pilots to achieve the best results with the least amount of time and cost. As much as possible the assessments of methane consumption in additional Alberta soils should be associated with the most common vegetation cover on these soils.

Further research is recommended on the biological and chemical changes that occur in soil when methane is oxidized in soil with the view of optimizing the natural oxidation of methane while minimizing any potential adverse impacts. This should be based on Alberta conditions.

6.3 VEGETATION TOLERANCE TO METHANE IN SOILS

The relationship between methane consumption in different types of soils and the vegetation tolerance to methane in these soils should be examined for the most common types of agricultural vegetation in these soils.

There is a lack of research on the tolerance of Alberta native plant species to methane originating below the soil. To accurately assess the impacts that a leaking natural gas well could have in Alberta, specific information regarding methane tolerance of native species in Alberta is required.

Greenhouse and/or field scale studies could be utilized to fill these knowledge gaps.

6.4 FIELD PILOTS

A field pilot is recommended to validate the calculations in the POC workbook based on using landfill loam and the proposed field practice. A pilot of this nature would help identify what factors for climate adjustments could be made to improve estimates of annual oxidation of methane in soil.

There are many variables that affect the tolerance of plant life to methane in soils. A longer term experimental field project is recommended in which the following items are evaluated with respect to methane having an adverse impact on plant life:

- Structure a facility where methane can be released under ground in a uniform and controlled manner while various types of plants are grown.
- The soil type could be common in various experiments and the climate would be common and the amount of soil moisture could be regulated.
- The three variables that could be assessed with respect to plant health under these conditions are; the type of vegetation, the amount of methane in the soil and the moisture content of the soil.

6.5 COMMERCIALIZATION

When enough data gaps are resolved, the POC workbook should be updated and converted into a robust and web-based tool with a fully populated database and with advanced features for users. A tool of this nature may need to be offered on a 'user pay' basis to generate revenue to maintain the web-based tool and to continue populating data into it.

An established commercial company with related software solutions would be a good home for this tool when fully developed.

Advancing pragmatic and science-based rules will benefit industry and will help address climate concerns. A fully developed tool of this nature, along with the supporting research, could impact government policy and regulations related to emissions management.

7.0 REFERENCE

1) V.B. Stien V. B and Hettiaratchi J.P.A. “Methane Oxidation on three Alberta Soils: Influence of Soil Parameters and Methane Flux Rates”, University of Calgary in the Department of Civil Engineering, Engineering for the Environment Program, 2000.

2) Mitchel I., Christensen A., Smith B., Drozdowski B., “Agronomic Receptor Evaluation for Direct Soil Contact Alberta (Report 18-00434)”, Millennium EMS Solutions Ltd. and InnoTech was prepared for PTAC, 2018.

3) Arif M.A. S. and Verstraete W. “Methane dosage to soil and its effect on plant growth” 1995.

4) Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K., Tignor M., and Miller H. L. “Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change” IGPCC.

8.0 ACKNOWLEDGEMENTS

Thanks to my career colleagues who have been part of my lifelong learning journey. In particular, I appreciate that you have shared your expertise in production operations, reservoir development, drilling, completions, well workover and closure and other operational areas that I have been honored to be employed in. Much of that expertise is included in this report in some way.

Several scientists at InnoTech contributed to this project. They are Sarah Thatcher, Simone Levy, Karen Budwill, Rares Bistran, Mohammad Chowdhuri and Jonathan Heseltine. Thank you all for your contributions big and small.

InnoTech is especially grateful for the financial support and oversite provided by PTAC to make this project possible.

9.0 APPENDIX A – USER GUIDE FOR POC WORKBOOK

9.1 INTRODUCTION & GENERAL GUIDANCE

The POC workbook is designed so that a user can estimate the fuel consumption and GHGs that would be generated from a field operation to remediate a SCVF or GM leak of sweet gas and compare that GHG estimate to the GHGs that would occur if the well continued to leak methane.

When a well is abandoned has a gas leak and is left with a vented cap below ground level, it is known that methanotrophic bacterial may consume some of the methane. If the leak rate exceeds a certain level, there is observable vegetation distress above the leak. The adverse effect on vegetation is due to a lack of oxygen in the soil as the bacteria requires oxygen while it consumes methane and also due to displacement of oxygen in the soil from methane and carbon dioxide.

A user can deploy the field practice outlined in the POC workbook to control some of the consumption of methane in the ground and to minimize the risk of vegetation distress resulting from a subsurface sweet gas leak.

When the workbook is opened, the macros must be activated. The sheets in the workbook in which a user may enter well and remediation specific data are as follows:

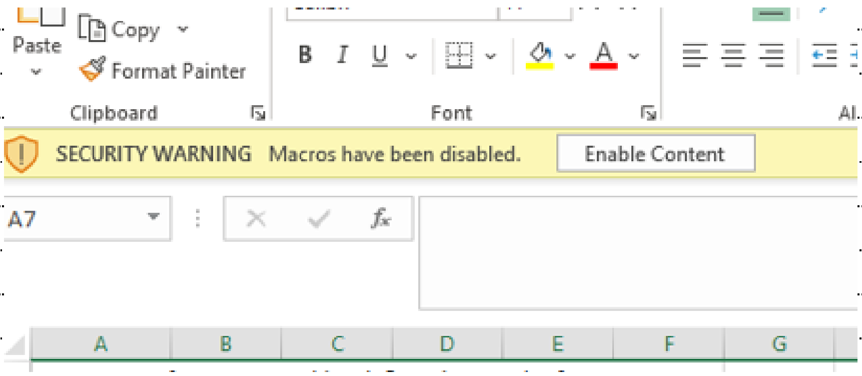
9.1.1 Instructions

This sheet in the POC workbook contains similar information as in this Appendix and this sheet is shown below.

Instructions for Using POC Workbook & Entering Data

Getting Started - Overview (ensure that you have Excel version 2013 or newer)

1 Enable macros in Excel - click the "Enable Content" button above the formula window:



SECURITY WARNING Macros have been disabled.

2 Cover Page

Step 1 - Fill in the company / licensee / permit holder name

Step 2 - Fill in well unique well identifer (UWI)

Step 3 - From the drop down menu, choose the type of well repair operation - inactive or abandoned well

Step 4 - Click the blue button to go to the appropriate "Fuel & GHG" data input sheet

3 Fuel & GHG Input Data Sheets

Depending upon the type of well operation chosen in step 3 , you will be taken to either the "Inactive Well" or "Drilling Re-entry" Fuel & GHG data input sheet

There is an option button at the top of each sheet to set the number of all units used to 0 (initialize)

Each input data sheet has instructions on how to fill in the various cells

There is an button at the bottom of the sheet to go to the "Site Conditions & Results" sheet

4 Site Conditions & Results Sheet

There are four values / selections to fill in on this page, starting with the actual well leak rate in m^3 / day

The second selection is the average number of intervention attempts reuired for a successful well repair.

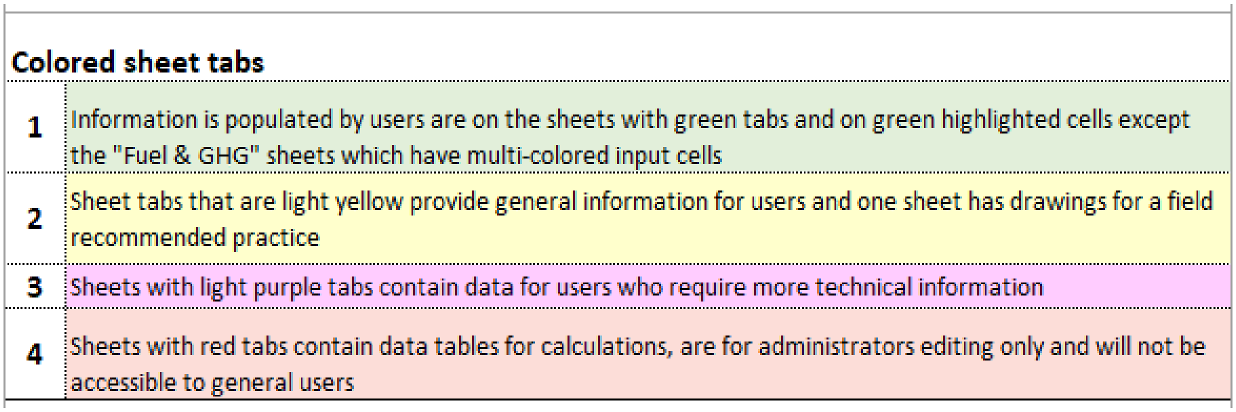
The third selection is for a conservative or moderate flow rate of methane through soil per m^2 area.

The fourth selection is the number of days per year that bacteria is expected to be active in the soil.

The results of the calulations are then shown on this sheet

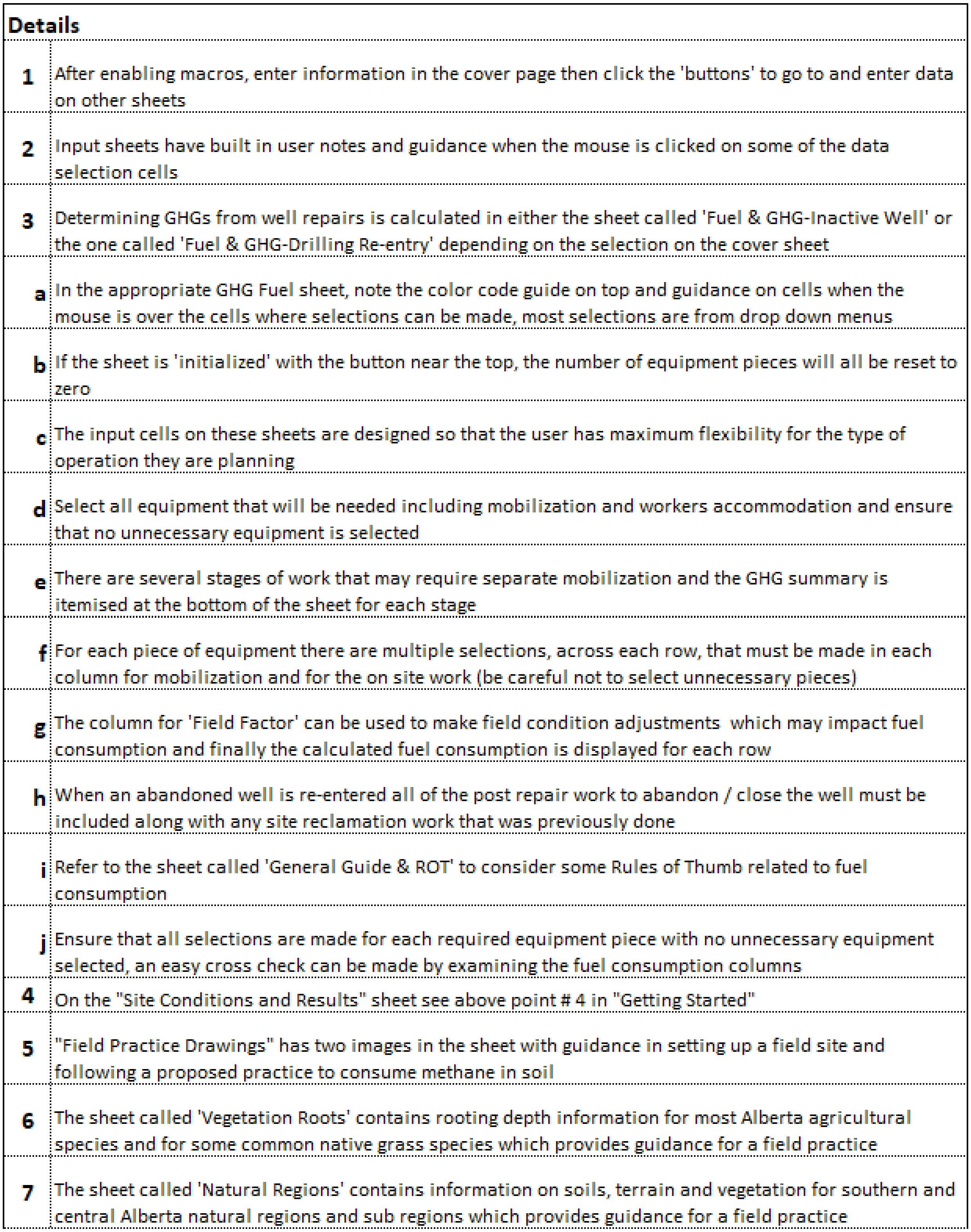
5 Field Practice Drawings

Images of a proposed field practice in which methane can be oxidized in soil are shown on this sheet



Colored sheet tabs

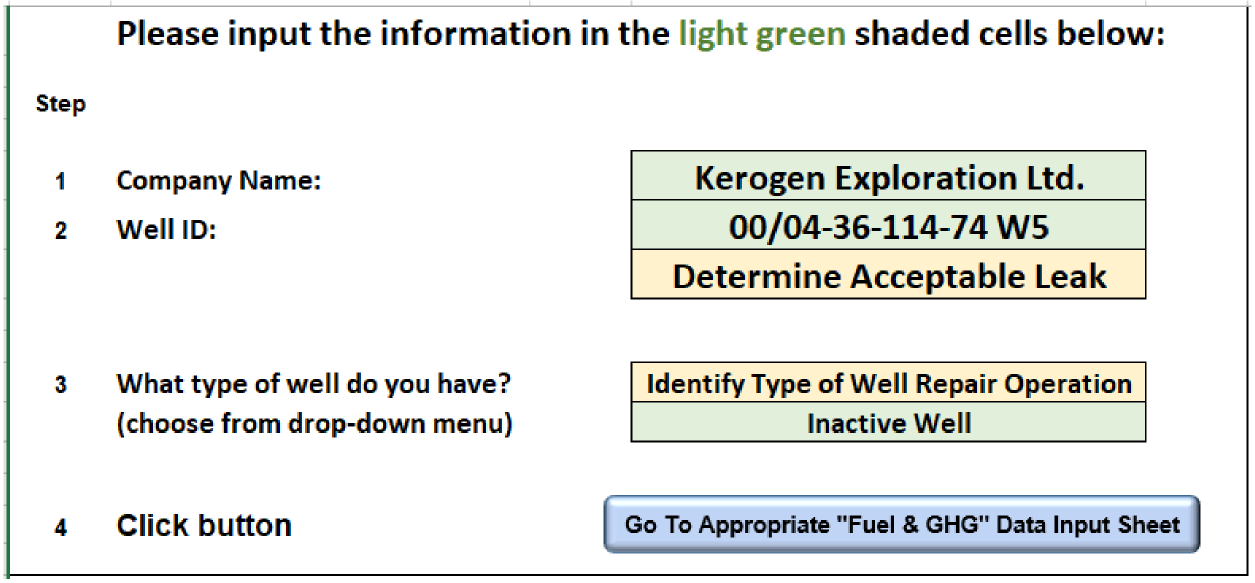
1	Information is populated by users are on the sheets with green tabs and on green highlighted cells except the "Fuel & GHG" sheets which have multi-colored input cells
2	Sheet tabs that are light yellow provide general information for users and one sheet has drawings for a field recommended practice
3	Sheets with light purple tabs contain data for users who require more technical information
4	Sheets with red tabs contain data tables for calculations, are for administrators editing only and will not be accessible to general users



Details	
1	After enabling macros, enter information in the cover page then click the 'buttons' to go to and enter data on other sheets
2	Input sheets have built in user notes and guidance when the mouse is clicked on some of the data selection cells
3	Determining GHGs from well repairs is calculated in either the sheet called 'Fuel & GHG-Inactive Well' or the one called 'Fuel & GHG-Drilling Re-entry' depending on the selection on the cover sheet
a	In the appropriate GHG Fuel sheet, note the color code guide on top and guidance on cells when the mouse is over the cells where selections can be made, most selections are from drop down menus
b	If the sheet is 'initialized' with the button near the top, the number of equipment pieces will all be reset to zero
c	The input cells on these sheets are designed so that the user has maximum flexibility for the type of operation they are planning
d	Select all equipment that will be needed including mobilization and workers accommodation and ensure that no unnecessary equipment is selected
e	There are several stages of work that may require separate mobilization and the GHG summary is itemised at the bottom of the sheet for each stage
f	For each piece of equipment there are multiple selections, across each row, that must be made in each column for mobilization and for the on site work (be careful not to select unnecessary pieces)
g	The column for 'Field Factor' can be used to make field condition adjustments which may impact fuel consumption and finally the calculated fuel consumption is displayed for each row
h	When an abandoned well is re-entered all of the post repair work to abandon / close the well must be included along with any site reclamation work that was previously done
i	Refer to the sheet called 'General Guide & ROT' to consider some Rules of Thumb related to fuel consumption
j	Ensure that all selections are made for each required equipment piece with no unnecessary equipment selected, an easy cross check can be made by examining the fuel consumption columns
4	On the "Site Conditions and Results" sheet see above point # 4 in "Getting Started"
5	"Field Practice Drawings" has two images in the sheet with guidance in setting up a field site and following a proposed practice to consume methane in soil
6	The sheet called 'Vegetation Roots' contains rooting depth information for most Alberta agricultural species and for some common native grass species which provides guidance for a field practice
7	The sheet called 'Natural Regions' contains information on soils, terrain and vegetation for southern and central Alberta natural regions and sub regions which provides guidance for a field practice

9.1.2 Cover page

The company name, well location (UWI) and type of well remediation are entered here and this information is linked to other sheets. The blue button can be clicked on to take the user to the next data input sheet.



Please input the information in the light green shaded cells below:

Step

1 Company Name: Kerogen Exploration Ltd.
2 Well ID: 00/04-36-114-74 W5
Determine Acceptable Leak

3 What type of well do you have? (choose from drop-down menu)
Identify Type of Well Repair Operation
Inactive Well

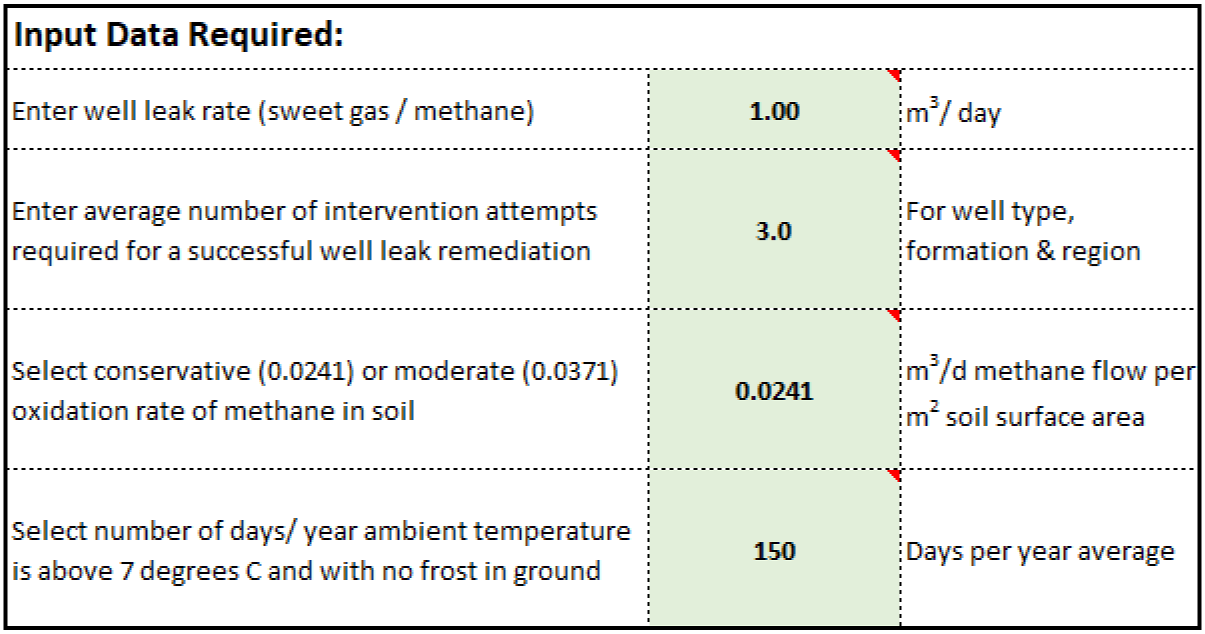
4 Click button

9.1.3 Site conditions and Results

Final results from all workbook input and calculations are displayed on this sheet. The well leak rate and the average number of well interventions that are required are entered on this sheet. There are also two selections related to consumption of methane in soil. The first option is for a conservative or moderate methane flow though soil. The second choice is the number of days bacteria is expected to be active in soil.

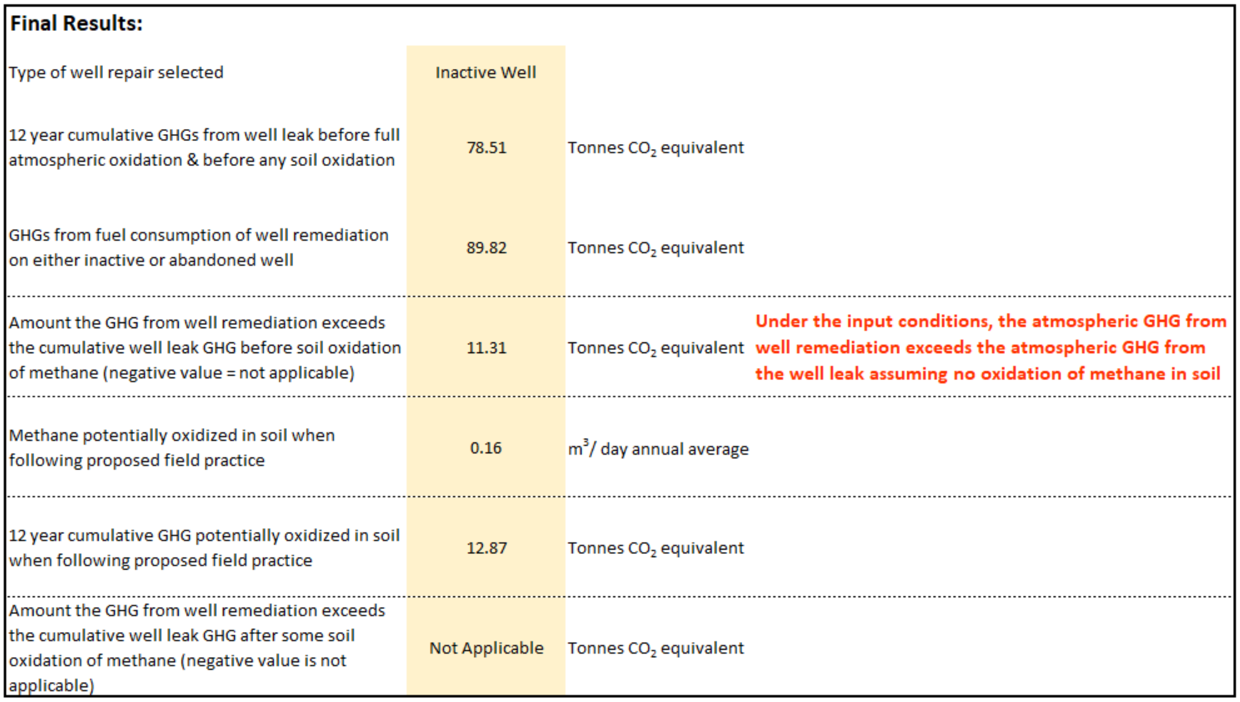
Kerogen Exploration 00/04-36-114-74/03 W5

Well Leak Rate, Field Conditions and Results



Input Data Required:		
Enter well leak rate (sweet gas / methane)	1.00	m^3/ day
Enter average number of intervention attempts required for a successful well leak remediation	3.0	For well type, formation & region
Select conservative (0.0241) or moderate (0.0371) oxidation rate of methane in soil	0.0241	m^3/d methane flow per m^2 soil surface area
Select number of days/ year ambient temperature is above 7 degrees C and with no frost in ground	150	Days per year average

After all data is entered, and if the GHG generated by the well remediation exceeds the GHG from the well leak, before any oxidation of methane in soil, the difference is displayed. If the GHG from well remediation is less than the methane leak GHG, the answer is displayed as 'Not Applicable'. The same logic is applied to the case with partial oxidation of methane in soil.



Final Results:			
Type of well repair selected	Inactive Well		
12 year cumulative GHGs from well leak before full atmospheric oxidation & before any soil oxidation	78.51	Tonnes CO_2 equivalent	
GHGs from fuel consumption of well remediation on either inactive or abandoned well	89.82	Tonnes CO_2 equivalent	
Amount the GHG from well remediation exceeds the cumulative well leak GHG before soil oxidation of methane (negative value = not applicable)	11.31	Tonnes CO_2 equivalent	**Under the input conditions, the atmospheric GHG from well remediation exceeds the atmospheric GHG from the well leak assuming no oxidation of methane in soil**
Methane potentially oxidized in soil when following proposed field practice	0.16	m^3/ day annual average	
12 year cumulative GHG potentially oxidized in soil when following proposed field practice	12.87	Tonnes CO_2 equivalent	
Amount the GHG from well remediation exceeds the cumulative well leak GHG after some soil oxidation of methane (negative value is not applicable)	Not Applicable	Tonnes CO_2 equivalent	

9.1.4 *Fuel & GHG-Inactive Well* and *Fuel & GHG-Drilling Re-entry*

An inactive well typically has a wellhead that is not cut and capped. An abandoned well is cut and capped below ground level. On the appropriate sheet, the user may select all of the relevant services and operating conditions that are required to remediate the SCVF or GM. Section 8.2 of this report provides more detail on making the appropriate selections.

9.1.5 *Field Practice Drawings*

This sheet contains images that the user may follow to implement a method of oxidizing some of the methane from a leaking well in soil.

9.1.6 *General Guide & ROT*

Additional guidance and Rules of Thumb (ROT) are included on this sheet for the user's reference. All the conversion factors used in the POC workbook are summarized in this sheet. The user can also compare the result of their selections regarding fuel consumption for specific pieces of equipment against common rules of thumb.

9.1.7 *Vegetation Roots*

The rooting depths of the most common Alberta agricultural products are tabulated in this sheet. Some native grass species are also listed with their rooting depths.

9.1.8 *Well Leak GHGs*

On this sheet the well leak rate, in m3 /day of methane, is used to calculate the cumulative CO2 equivalent in tonnes in the atmosphere.

9.1.9 *Methane Consumption in Soil*

The leak rate of the well and two other selections are populated into this sheet from the Site Conditions & Results sheet. This sheet also contains data from the Stien and Hettiaratchi[1] study and it will then determine the expected methane consumption by bacteria in the soil when following a recommended field practice. The required radius is calculated for the layer of methanotrophic loam covering the well leak in the proposed field practice.

9.1.10 *Subsoil Methane Distribution*

This sheet has original drawings of the proposed field practice.

9.1.11 *Natural Regions*

This sheet provides information on the terrain, soil and vegetation in the Natural Regions and Subregions in Southern and Central Alberta,

9.1.12 *Drop down Menus, Factors in Calcs, Diesel Consumption, Natural Gas Consumption & Instructions in Excel*

These are hidden and password protected sheets containing data tables with information from public sources. The data is used in various calculations for fuel consumption on different pieces of equipment and services required to conduct well remediation work. These sheets contain information for hidden formulas which cannot be edited without the password.

9.2 FUEL CONSUMPTION AND GHGS FROM WELL REMEDIATION

After someone has written a well remediation program and generated an AFE, they will have most of the basic information needed to use the proof of concept workbook. After entering the company information and the well location in the cover page of the POC workbook, the next step is to select the equipment necessary for conducting the field work.

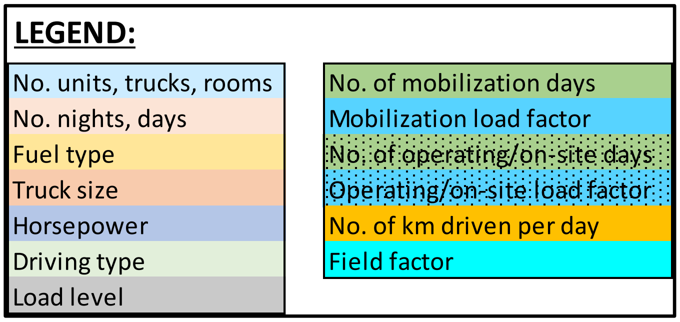
The input sheet for selecting the required equipment on an inactive well with a wellhead is *Fuel & GHG-Inactive Well*. When a well has been abandoned, cut and capped below ground level a small drilling rig is often used for the operation. Drilling operations require some specific support equipment which is listed in *Fuel & GHG-Drilling Re-entry* sheet.

After the required equipment has been identified, the user will make selections for the equipment. The selections either use drop down menus or will accept positive whole integers for input. In most cases there are selections for mobilizing the equipment to the field and for operating conditions while working on site. The POC workbook will then estimate fuel consumption for each piece of equipment during mobilization / demobilization and when the equipment is working onsite.

For each field operation some of the following criterion may be selected by the user but not all selections are required for all types of equipment:

- Man days in a hotel / motel / camp
- Number of units
- Type of fuel used
- Horsepower
- Driving type (city, combined, highway)
- Number of kilometers driven each day
- Field factor adjustment from ideal conditions
- Load level
- Number of mobilization days (days are 24 hours)
- Number of operating days (days are 24 hours)

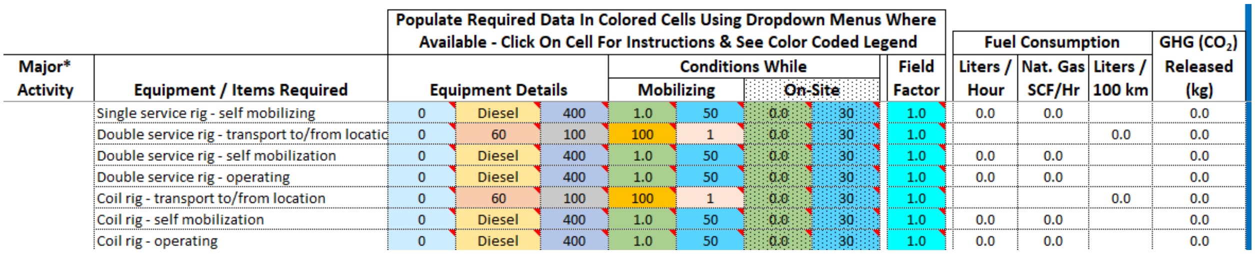
The selections listed above are color coded in the *Fuel & GHG* sheets according to the user requirements and adjustments to fuel consumption calculations.



LEGEND:

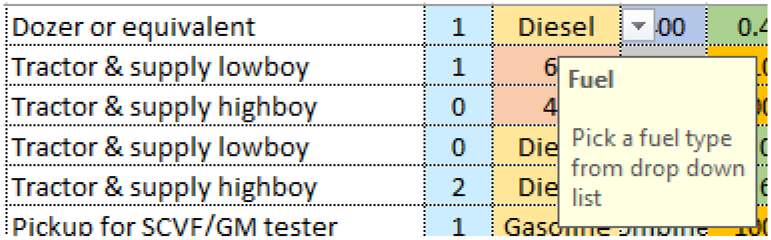
No. units, trucks, rooms	No. of mobilization days
No. nights, days	Mobilization load factor
Fuel type	No. of operating/on-site days
Truck size	Operating/on-site load factor
Horsepower	No. of km driven per day
Driving type	Field factor
Load level	

Below is an image with a sampling of equipment selections and other conditions that the user can chose for the wellsite work. As the selections are made along with the deployment time, the expected fuel consumption for each piece is displayed as reality check.



Major* Activity	Equipment / Items Required	Populate Required Data In Colored Cells Using Dropdown Menus Where Available - Click On Cell For Instructions & See Color Coded Legend								Fuel Consumption			GHG (CO_2)
		Equipment Details			Conditions While				Field				
					Mobilizing		On-Site		Factor	Liters / Hour	Nat. Gas SCF/Hr	Liters / 100 km	Released (kg)
	Single service rig - self mobilizing	0	Diesel	400	1.0	50	0.0	30	1.0	0.0	0.0		0.0
	Double service rig - transport to/from locatic	0	60	100	100	1	0.0	30	1.0			0.0	0.0
	Double service rig - self mobilization	0	Diesel	400	1.0	50	0.0	30	1.0	0.0	0.0		0.0
	Double service rig - operating	0	Diesel	400	1.0	50	0.0	30	1.0	0.0	0.0		0.0
	Coil rig - transport to/from location	0	60	100	100	1	0.0	30	1.0			0.0	0.0
	Coil rig - self mobilization	0	Diesel	400	1.0	50	0.0	30	1.0	0.0	0.0		0.0
	Coil rig - operating	0	Diesel	400	1.0	50	0.0	30	1.0	0.0	0.0		0.0

The required data selections and the field factor selections are made by utilizing drop down menus in each cell or by entering positive whole integers. The cells are protected so that an incorrect format cannot be entered, and each cell has a pop-up message to guide the user. In the example below the message is on the fuel selection cell for a Dozer indicating the user needs to click on the arrow symbol to select the correct fuel type (it is currently set to diesel).



Dozer or equivalent	1	Diesel	00	0.4
Tractor & supply lowboy	1	6		
Tractor & supply highboy	0	4		
Tractor & supply lowboy	0	Die		
Tractor & supply highboy	2	Die		
Pickup for SCVF/GM tester	1	Gaso		

Fuel

Pick a fuel type from drop down list

As the user makes selections in each row for each piece of equipment, similar guidance is provided. On some types of equipment, such as a tractor and lowboy, the user may have an option to select either a capacity size in tonnes or a horsepower rating for the unit.

For most pieces of equipment, the user can select the mobilization / demobilization time (in 24-hour days) and the expected load factor when mobilizing / demobilizing and the working time on site (in 24-hour days) and the expected load factor while working.

Because there are many variables that affect field operations in Alberta, especially during winter conditions, the user can also make a Field Factor adjustment for the expected fuel consumption. The fuel consumption columns help the user adjust the Field Factor to model actual field experience.

The fuel consumption columns can also be used as check to confirm that no unnecessary equipment weas selected to conduct the field work.

10.0 APPENDIX B – SOURCE OF POC WORKBOOK CONTENTS

The following sources of additional information were used in the POC workbook calculations and conversion factors:

Conversion Factors:
1 Horsepower (HP) = 0.7457 Kilowatts
1 US Gallon (gal) = 3.785412 Liters
1 Standard Cubic Foot (SCF) of Propane = 2,520 British Thermal Units (BTU)
1 SCF of Natural Gas = 1,000 BTU
BTU Ratio of Propane to Natural Gas = 2.52
1 US gal of Liquid Propane = 35.97 SCF of Gaseous Propane
1 Liter of Liquid Propane = 9.50 SCF of Gaseous Propane
1 gram (g) of methane = 22.4 liters (0.0224 m3) at 273 K (0 C) & 1 atm (1.013 bar) i.e. standard conditions (Air Liquide uses 68 kg/m3 at 1.013 bar and 15 C)

CO2 Emissions Data:
From US Environmental Protection Agency (EPA):
1 Liter of diesel burned produces 2.69 kilograms (kg) of Carbon Dioxide (CO2)
1 SCF of natural gas burned produces 0.0549 kg of CO2
1 Liter of propane burned produces 1.62 kg of CO2
1 Liter of gasoline burned produces 2.35 kg of CO2

From the Hotel Carbon Measurement Initiative (HCMI), the accepted standard for the hospitality industry is that 31.1 kg CO2 per room night is produced

Equipment Fuel Consumption Data:
Pickup Trucks (From Natural Resources Canada 2018 Fuel Consumption Guide)

		Liters/100 km			Miles/US Gal		
Fuel	Vehicle Type	City	Highway	Combined	City	Highway	Combined
Gasoline	Ford F-150 4X4 truck (5.0 Liter 8 cyl)	14.6	10.9	13.0	16.1	21.6	18.1
Diesel	Ford F-150 4X4 truck (3.0 Liter, 6 cyl)	11.8	9.3	10.7	19.9	25.3	22.0

A multiplying factor of 1.5 to reflect increased fuel consumption for larger/heavier pickup and crew trucks

Truck Tractor Rolling Stock Using Diesel Fuel:
Based on average values and highway driving from public data on heavy duty truck fuel consumption

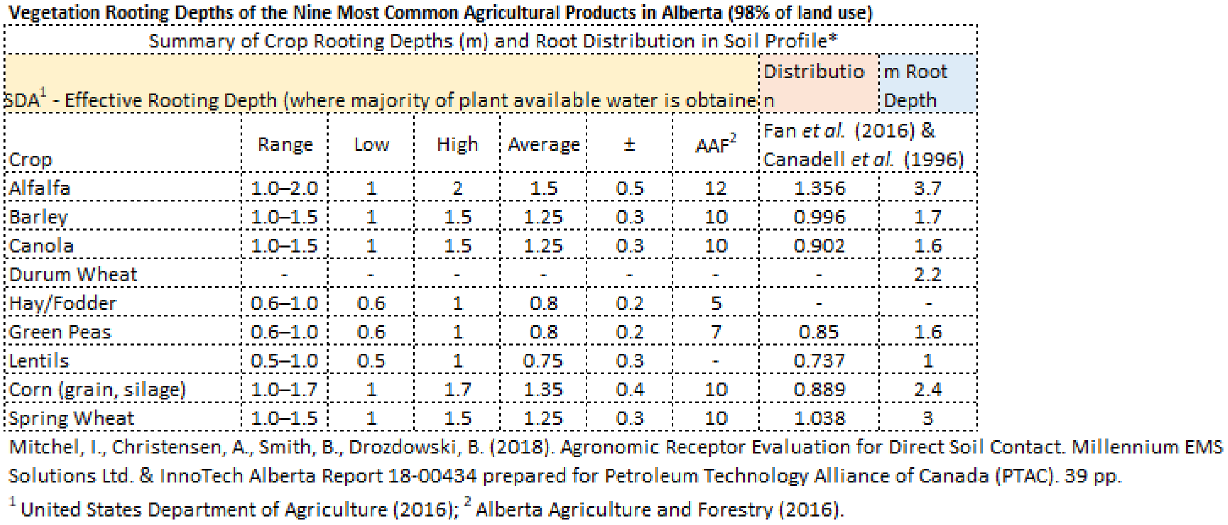
	Liters/100 km at Load %			Miles/US Gal at Load %		
Load Level %	*0%*	*50%*	*100%*	*0%*	*50%*	*100%*
42 tonne, 420 HP semi trailer	23.0	29.5	36.5	10.2	8.0	6.4
60 tonne, 420 HP full trailer	31.5	41.5	53.5	7.5	5.7	4.4

Generator Units:
Fuel consumption is based on fuel type (diesel, natural gas, propane), generator size (HP) and load factor (%). Fuel consumption tables were obtained from WorldWide Power Products, LLC and Bryan Power Generation both publicly available sources.

Rules of Thumb:
For Semi-trailer Truck & Trailer units (18 wheelers):
Diesel consumption = 29 - 59 liters of diesel per 100 km (based on 2016 fuel consumption values)
Highway consumption = 6 to 7 miles per US gal
Fast idle consumption is approximately 1 US gal per hour
Driving is approximately 11 US gal per hour

GHG equivalent of methane in the atmosphere to tonnes of CO_2 :
Volume of methane in m^3 x 25 x 0.717 (methane density) is equivalent to tonnes of CO_2

11.0 APPENDIX C – VEGETATION ROOTING DEPTHS



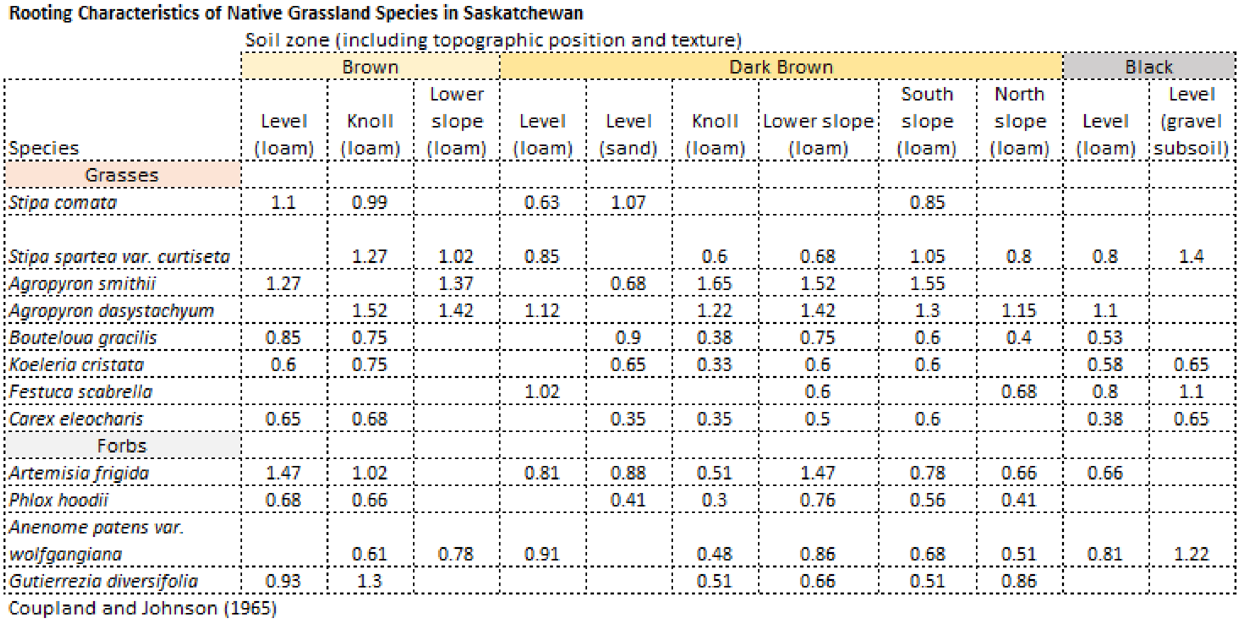
Vegetation Rooting Depths of the Nine Most Common Agricultural Products in Alberta (98% of land use)

Summary of Crop Rooting Depths (m) and Root Distribution in Soil Profile*

SDA[1] - Effective Rooting Depth (where majority of plant available water is obtaine							Distributio n	m Root Depth
Crop	Range	Low	High	Average	±	AAF[2]	Fan *et al.* (2016) & Canadell *et al.* (1996)	
Alfalfa	1.0–2.0	1	2	1.5	0.5	12	1.356	3.7
Barley	1.0–1.5	1	1.5	1.25	0.3	10	0.996	1.7
Canola	1.0–1.5	1	1.5	1.25	0.3	10	0.902	1.6
Durum Wheat	-	-	-	-	-	-	-	2.2
Hay/Fodder	0.6–1.0	0.6	1	0.8	0.2	5	-	-
Green Peas	0.6–1.0	0.6	1	0.8	0.2	7	0.85	1.6
Lentils	0.5–1.0	0.5	1	0.75	0.3	-	0.737	1
Corn (grain, silage)	1.0–1.7	1	1.7	1.35	0.4	10	0.889	2.4
Spring Wheat	1.0–1.5	1	1.5	1.25	0.3	10	1.038	3

Mitchel, I., Christensen, A., Smith, B., Drozdowski, B. (2018). Agronomic Receptor Evaluation for Direct Soil Contact. Millennium EMS Solutions Ltd. & InnoTech Alberta Report 18-00434 prepared for Petroleum Technology Alliance of Canada (PTAC). 39 pp.

[1] United States Department of Agriculture (2016); [2] Alberta Agriculture and Forestry (2016).



Rooting Characteristics of Native Grassland Species in Saskatchewan

Soil zone (including topographic position and texture)

	Brown			Dark Brown						Black	
Species	Level (loam)	Knoll (loam)	Lower slope (loam)	Level (loam)	Level (sand)	Knoll (loam)	Lower slope (loam)	South slope (loam)	North slope (loam)	Level (loam)	Level (gravel subsoil)
Grasses											
Stipa comata	1.1	0.99		0.63	1.07			0.85			
Stipa spartea var. curtiseta		1.27	1.02	0.85		0.6	0.68	1.05	0.8	0.8	1.4
Agropyron smithii	1.27		1.37		0.68	1.65	1.52	1.55			
Agropyron dasystachyum		1.52	1.42	1.12		1.22	1.42	1.3	1.15	1.1	
Bouteloua gracilis	0.85	0.75			0.9	0.38	0.75	0.6	0.4	0.53	
Koeleria cristata	0.6	0.75			0.65	0.33	0.6	0.6		0.58	0.65
Festuca scabrella				1.02			0.6		0.68	0.8	1.1
Carex eleocharis	0.65	0.68			0.35	0.35	0.5	0.6		0.38	0.65
Forbs											
Artemisia frigida	1.47	1.02		0.81	0.88	0.51	1.47	0.78	0.66	0.66	
Phlox hoodii	0.68	0.66			0.41	0.3	0.76	0.56	0.41		
Anenome patens var. wolfgangiana		0.61	0.78	0.91		0.48	0.86	0.68	0.51	0.81	1.22
Gutierrezia diversifolia	0.93	1.3				0.51	0.66	0.51	0.86		

Coupland and Johnson (1965)

12.0 APPENDIX D - NATURAL REGIONS OF SOUTHERN AND CENTRAL ALBERTA

Natural Regions and Subregions in Southern and Central Alberta (Downing and Pettapiece, 2006)

Natural Region	Natural Subregion	Percent of Province	Elevation (average asl)	Terrain	Soil	Vegetation
Grassland	Dry Mixed grass	7.1	800	Undulating plains; till with lacustrine, fluvial, eolian materials	Brown Chernozems; Brown Solonetz; wetlands are Gleysols	This sheet
	Mixed grass	3	975	Undulating plains with rolling to hummocky areas; till and lacustrine materials	Dark Brown Chernozems; wetlands are Gleysols	Mainly agricultural; native grasslands are needle and thread, porcupine grass, northern and western wheatgrass; buckbrush shrublands
	Northern Fescue	2.3	800	Undulating plains and hummocky uplands; till with lacustrine, fluvial, and eolian materials	Dark Brown Chernozems; Dark Brown Solonetz; wetlands are Gleysols	Plains rough fescue (moist), western porcupine grass (drier); buckbrush and rose shrublands; grass wetlands
	Foothills Fescue	2.1	1100	Hummocky and rolling to undulating; till, lacustrine deposits	Black Chernozems, wetlands are Gleysols	Mountain rough fescue on moister sites, western wheatgrass on drier sites; wet areas often shrubby
Parkland	Foothills Parkland	0.6	1250	Sloping lower foothills and hummocky uplands; till with lacustrine materials in valleys.	Black Chernozems, some Dark Grey Chernozems; wetlands mainly Gleysols	Aspen forests; areas of dense tall willow (north); grasslands (mountain rough fescue and Parry's oatgrass) more common on southerly slopes
	Central Parkland	8.1	750	Undulating plains, hummocky uplands; glacial till with lacustrine, fluvial, and eolian inclusions	Black Chernozems, some Dark Gray Chernozems; Solonetzic soils; wetlands are Gleysols	Extensively cultivated; aspen interspersed with grasslands dominated by plains rough fescue; tree cover increases with latitude; graminoid
	Pace River Parkland	0.5	625	Gently undulating plains, south-facing slopes of the Peace River; lacustrine deposits with colluvium on slopes	Dark Gray to Black Chernozems (often Solonetzic); Solonetzic and Luvisolic soils; slopes are Regosols and Dark Brown Chernozems; wetlands mainly Gleysols	Mostly cultivated; remnant aspen clones and continuous forest, interspersed with sedge–California oat grass–porcupine grass; Jack pine on sands; graminoid wetlands, often ringed by

Natural Region	Mean annual temperature (°C)	Mean temperature, warmest month (°C)	Mean temperature, coldest month (°C)	Growing degree days >5°C	Mean annual precipitation (mm)
Grassland	4	17.8	-11.7	1592	374
Parkland	2.3	16.4	-14.4	1391	447

Grassland Natural Region - Dry Mixed grass Natural Subregion, Mixed grass Natural Subregion, Northern Fescue Natural Subregion, Foothills Fescue
Parkland Natural Region - Foothills Parkland Natural Subregion, Central Parkland Natural Subregion, Peace River Parkland

13.0 APPENDIX E - GLOBAL METHANE BUDGET

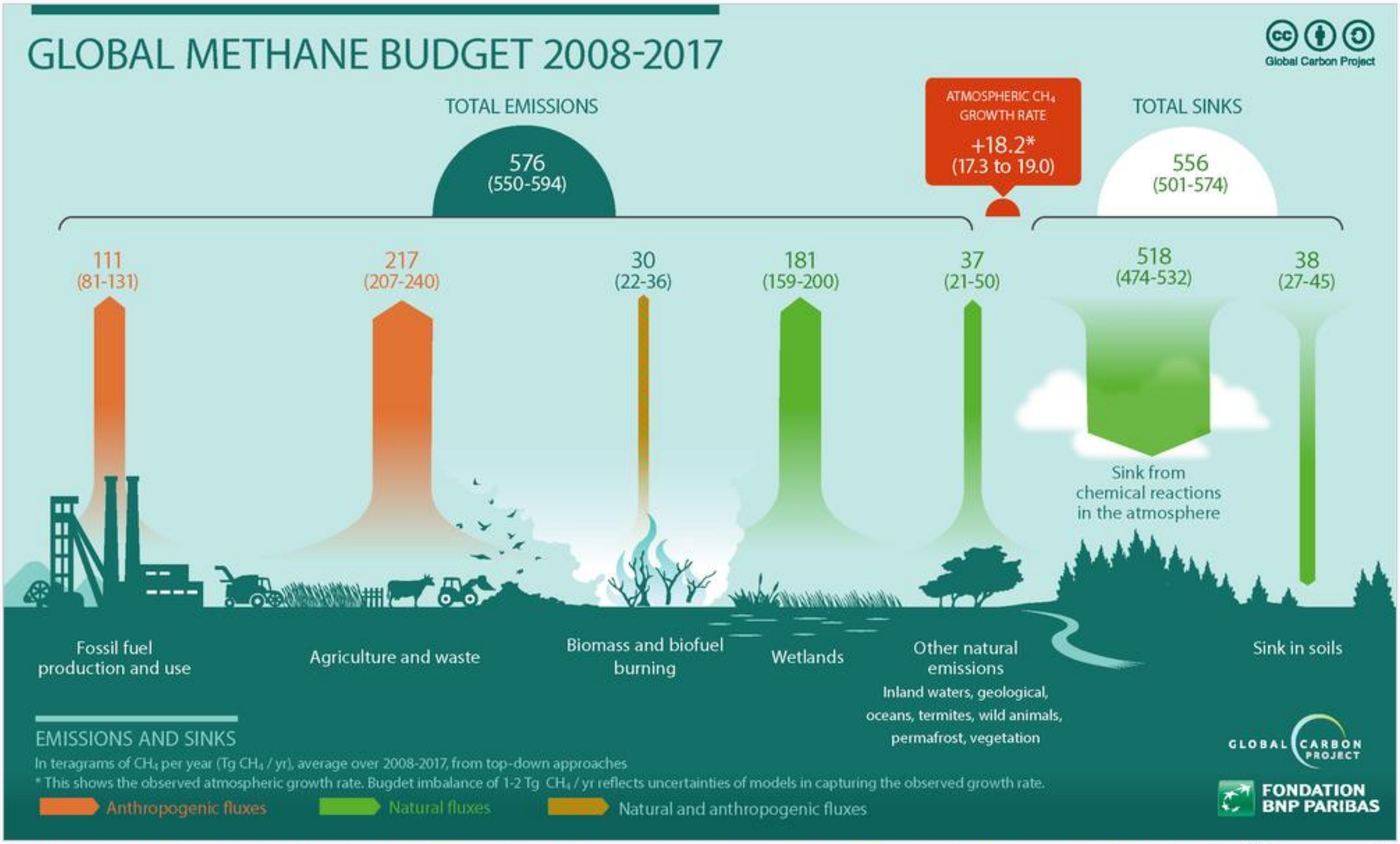


Diagram showing the main sources of methane for the decade 2008-2017, produced by a global report on global methane emissions by the Global Carbon Project[31]