Implementation and Operation of a Multidisciplinary Field Investigation Involving a Subsurface Controlled Natural Gas Release, Northeastern British Columbia

A.G. Cahill, The University of British Columbia, Vancouver, BC, acahill@eoas.ubc.ca

B. Ladd, The University of British Columbia, Vancouver, BC

J. Chao, The University of British Columbia, Vancouver, BC

J. Soares, The University of British Columbia, Vancouver, BC

T. Cary, University of Calgary, Calgary, AB

N. Finke, The University of British Columbia, Vancouver, BC

C. Manning, The University of British Columbia, Vancouver, BC

C. Chopra, The University of British Columbia, Vancouver, BC

I. Hawthorne, The University of British Columbia, Vancouver, BC

O.N. Forde, The University of British Columbia, Vancouver, BC

K.U. Mayer, The University of British Columbia, Vancouver, BC

A. Black, The University of British Columbia, Vancouver, BC

S. Crowe, The University of British Columbia, Vancouver, BC

B. Mayer, University of Calgary, Calgary, AB

R. Lauer, University of Calgary, Calgary, AB

C. van Geloven, British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Prince George, BC

L. Welch, British Columbia Oil and Gas Commission, Kelowna, BC

R.D. Beckie, The University of British Columbia, Vancouver, BC

Cahill, A.G., Ladd, B., Chao, J., Soares, J., Cary, T., Finke, N., Manning, C., Chopra, C., Hawthorne, I., Forde, O.N., Mayer, K.U., Black, A., Crowe, S., Mayer, B., Lauer, R., van Geloven, C., Welch, L. and Beckie, R.D. (2019): Implementation and operation of a multidisciplinary field investigation involving a subsurface controlled natural gas release, northeastern British Columbia; *in* Geoscience BC Summary of Activities 2018: Energy and Water, Geoscience BC, Report 2019-2, p. 95–104.

Introduction

Fugitive gas, comprising primarily methane, can be unintentionally released from upstream oil and gas development either at surface from leaky infrastructure or in the subsurface through wellbore integrity failure. For the latter, compromised cement seals around well casings can permit flow of natural gas into the subsurface, tending toward ground surface and potentially into the atmosphere. Concerns associated with fugitive gas release at surface and in the subsurface include contributions to greenhouse gas emissions, subsurface migration leading to accumulation in nearby infrastructure and explosive risk, and impacts to groundwater quality. Current knowledge of fugitive gas is incomplete, including how to best detect and monitor it over time, particularly its migration and fate in the subsurface at the individual event scale. Consequently, an experimental field observatory has been established to evaluate surface and subsurface fugitive gas leakage in an area hosting historic and ongoing hydrocarbon resource development within the Montney resource play of the Western Canada Sedimentary Basin, northeastern British Columbia (BC). At the field laboratory, natural gas was intentionally released at various low rates (<10 m^3 per day), durations and configurations. Resulting migration patterns and impacts are being evaluated through examination of the geology, hydrogeology, hydrogeochemistry, isotope geochemistry, hydrogeophysics, vadose zone and soil gas processes, microbiology and atmospheric conditions.

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/s/SummaryofActivities.asp.

The ongoing progress through 2018 is outlined here, including a summary of the unsaturated zone experiment, final preparation and enabling works for the saturated zone injection experiment, completion and installation of the saturated zone injection system, execution of the saturated zone injection experiment, multidisciplinary monitoring activities and some initial example results.

Background

Fugitive methane (CH_4) from energy wells causes concern as it poses three potential risks to human health and/or the environment. Firstly, fugitive CH_4 poses an explosion hazard if released into a confined space (lower explosive limit 5% in air [LeBreton, 2009]). Secondly, CH_4 is a potent greenhouse gas (a factor of 25 times greater in a 100-year period than carbon dioxide [CO_2]; Intergovernmental Panel on Climate Change, 2014). Considering emissions of CH_4 from energy-resource development (particularly shale gas operations) have been identified as potentially significant (Caulton et al., 2014), fugitive CH_4 therefore has potential to contribute significantly to climate change (Shindell et al., 2009). Thirdly, fugitive CH_4 can impact groundwater resources by migrating in the aqueous phase and forming an explosion risk following extraction, and also following microbial attenuation (based on availability of electron acceptors, according to the redox sequence; Christensen et al., 2000; Le Mer and Roger, 2001) where it may generate undesirable byproducts (e.g., H_2S, Fe^{2+}, Mn^{2+}) or potentially induce the release of trace metals (Bennett and Dudas, 2003; Van Stempvoort et al., 2005, 2007; Amos et al., 2012; Ng et al., 2015). Although much research has recently been undertaken with respect to fugitive CH_4, it has for the most part taken the form of retrospective environmental forensic studies to assess if detectable impacts to groundwater have occurred. Unfortunately, little research has comprehensively assessed migration, impacts and fate of fugitive CH_4 in a holistic manner or at the single event scale. Exceptionally, a recent multidisciplinary study (Cahill et al., 2017), upon which the current study builds, monitored groundwater, soil gas and surface efflux at high spatiotemporal resolution during release of a small volume of natural gas into a shallow (i.e., ~9 m depth) unconfined aquifer system. Results from this study showed that although a significant proportion of injected gas reached the surface and emitted to atmosphere (with some oxidation observed in the unsaturated zone), a large portion remained in the saturated zone where it created a dispersed and laterally extensive volume of impacted groundwater (Cahill et al., 2017). Although this study provided important and detailed insights regarding fugitive CH_4, it forms only a single site specific study and its overall applicability and relevance to regions of resource development (e.g., Western Canada Sedimentary Basin) is limited. Consequently, many knowledge gaps remain and more studies such as this are needed in a range of geological settings where petroleum resource development takes place in order to improve an understanding of fugitive CH_4.

In March 2017, Geoscience BC entered into a contribution agreement with The University of British Columbia's Energy and Environment Research Initiative (UBC EERI; co-directed by R. Beckie and A. Cahill), located at the Department of Earth, Ocean and Atmospheric Sciences, in order to better understand fugitive gas impacts, particularly in a BC context. Cahill et al. (2018) described the initiation of this project including the significant leveraging of base funding provided by Geoscience BC to bring more disciplines into the research program. Subsequently, it described activities undertaken in order to select and attain two separate field locations near Hudson's Hope in northeastern BC: 1) a saturated (i.e., a confined aquifer) zone site and 2) an unsaturated zone (vadose zone) site (Figure 1). This paper includes a description of the follow-on work

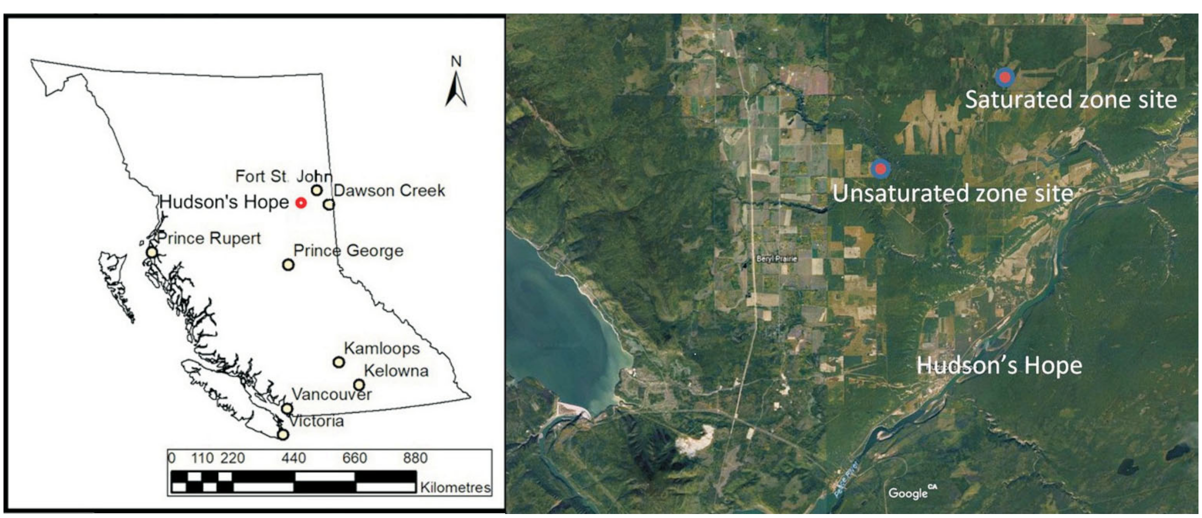

Figure 1. Location of unsaturated and saturated zone sites, Hudson's Hope area, northeastern British Columbia.

from this successful first year. Activities at both sites are described but there is a focus on the saturated zone site, including final set-up for the injection experiment, execution of the injection and ongoing monitoring activities with some examples of experimental results.

Summary of Activities and Progress

Unsaturated Zone Injection Experiment

Following attainment and set-up at the unsaturated zone site (as described in Cahill et al., 2018), 29 m^3 of compressed natural gas were injected at 12 m depth over five days with monitoring of gas migration and fate conducted for a further 28 days at the end of 2017. After 28 days (i.e., as of early November 2017), monitoring was unexpectedly ceased prematurely by a severe snowstorm and damage to equipment by cattle following an escape. No further sampling was undertaken during the winter and spring period (2018) and one final round of soil gas samples were collected at the site in August 2018.

The unsaturated zone injection experiment has proved highly successful and generated data of great significance in the context of gas migration and fugitive gas. Currently EERI is in the process of publishing several peer-reviewed journal articles related to this experiment:

1) barometric-pumping controls fugitive gas emissions from a vadose zone natural gas release by O.N. Forde, A.G. Cahill, R.D. Beckie and K.U. Mayer (submitted to Nature Geoscience), and
2) quantification of attenuation capacity and fate of fugitive gas leakage into unsaturated soils by O.N. Forde, A.G. Cahill, I. Hawthorne, A. Black, R.D. Beckie and K.U. Mayer (to be submitted to Science of the Total Environment or a similar journal).

Figure 2 shows methane and ethane percent composition for the final soil gas samples taken in August 2018, nearly one year after the injection of gas. Results show gas still present where elevated ethane is correlated to elevated methane. The presence of ethane above detection is conclusive evidence for persistence of the injected gas (as ethane is not naturally present in this shallow soil system). All other results are being reviewed and assessed with full conclusions on the migration, impacts and fate of injected gas to follow in short order.

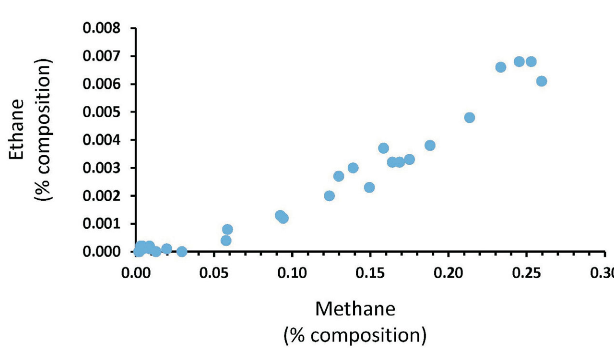

Figure 2. Methane versus ethane percent composition in soil gas samples taken in August 2018, showing persistence of low levels of natural gas one year following injection of compressed natural gas at the unsaturated zone site, northeastern British Columbia.

In order to insure integrity of overall findings from this study and to avoid compromising publication of results in top journals (which stipulate results must not have been previously published elsewhere) no further results from this experiment will be presented in this Summary of Activities paper. However, published journal articles will be provided to Geoscience BC and intermediate results will be made available via the Geoscience BC website in due course.

Saturated Zone Injection Experiment

Preparation and Execution

In 2017, significant effort was made to characterize the geology, hydrogeology and groundwater quality of the saturated zone site (as described in Cahill et al., 2018). Following on from this, in 2018, the site was further characterized, various multidisciplinary monitoring networks were established/installed, injection infrastructure constructed (including a synthetic Montney gas designed by the experiment team) and the injection experiment was conducted. In summary, 100 m^3 of a synthetic Montney gas (Table 1) was injected at 26 m vertical depth into the aquifer at a rate of 1.5 m^3/day, commencing on June 12, 2018, and continuing for 72 days. Figures 3 and 4 show the injection system and an aerial image of the experimental site with all infrastructure in place. The following sections describe the activities of each discipline-specific team. It should be noted that this experiment is still ongoing and results are still being collected and interpreted. Consequently, only example results are shown and no full results, conclusions or key findings are presented here.

Discipline-Specific Activities

Hydrogeology

In the first half of 2018, additional hydrogeological-focused intrusive investigations were performed to prepare for the injection experiment. In January 2018, nine cone penetration test (CPT) holes were pushed to depths ranging from 12.2 to 23 m below ground level (bgl) directly around the injection zone. These tests allowed greater character-

Table 1. Proportional composition of a typical Montney gas and The University of British Columbia's Energy and Environment Research Initiative (EERI) synthetic Montney gas formulated for the saturated zone injection experiment. Abbreviations: C1, methane; C2, ethane; C3, propane; C4, butane; >C4, all hydrocarbons with a chain length greater than 4.

Gas	C1	C2	C3	>C4	CO_2	N_2	He
Typical Montney gas	0.85	0.08	0.03	0.02	0.001	0.002	0.0001
EERI synthetic Montney gas	0.85	0.08	0.05	0	0.01	0.005	0.005

Figure 3. Completed injection system at the saturated zone site, northeastern British Columbia.

Figure 4. Aerial drone image of saturated zone experimental site with solar array, injection control laboratory and various multidisciplinary monitoring systems around the injection point, northeastern British Columbia.

ization of stratigraphy and heterogeneity and showed the confined upper diamict layer to be relatively continuous (i.e., 12 m thick) with the underlying confined aquifer (composed of interbedded sand, silt, gravel) being highly heterogeneous with limited lateral continuity of permeable zones. The detailed stratigraphy provided by CPT results allowed identification of horizons of potentially higher permeability in which to install sampling screens. Consequently, 13 multilevel monitoring wells (MW), with monitoring ports at various depths (e.g., 12, 16, 18, 20 m bgl), and six single-screened larger diameter (12.5 cm) monitoring wells were drilled and installed around the injection zone in March and April 2018. In summary, prior to injection a total of six single-screened (PW) and 13 multilevel MW with 35 water-flowing monitoring ports were installed (Figure 5). Subsequently, background groundwater samples were collected prior to the injection through various sample points and several sampling campaigns showed a weakly basic (pH ranging from 7.1 to ~7.48) Ca-Mg-HCO_3 water type with relatively moderate total dissolved solids (620–735 mg/L) and very low dissolved natural CH_4 (~0.01–0.1 mg/L) of biogenic origin.

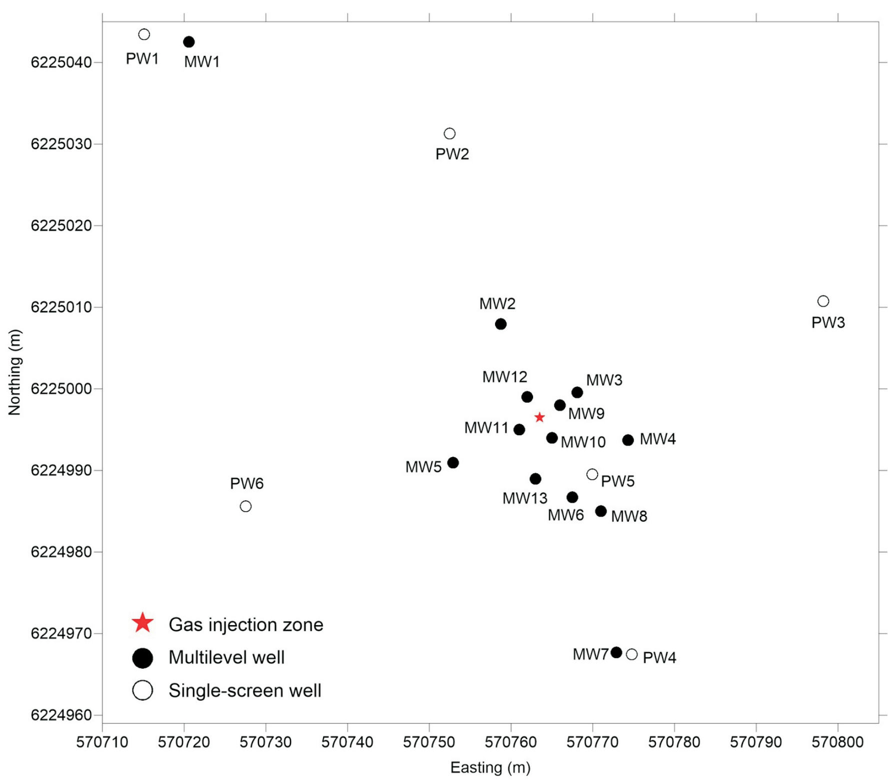

Figure 5. The layout of the 13 multilevel monitoring wells (filled-in circles), six single-screened monitoring wells (open circles) and gas injection zone (red star), northeastern British Columbia.

Physical (i.e., temperature, specific conductance, pH, oxidation-reduction potential) and aqueous chemistry (cation, anion, dissolved gas composition) were subsequently monitored through all groundwater sampling infrastructure every one to two weeks before, during and after injection. Monitoring will be ongoing through 2019.

Geophysics

The geophysics team visited the site approximately every two weeks from the time of injection until the end of September. During these visits, refraction seismic surveys and electrical resistivity tomography (ERT) surveys were carried out. These surveys were designed for time-lapse analysis. Hence, the location of each survey

Figure 6. Vertical seismic profile set-up, saturated zone site, northeastern British Columbia.

Table 2. Samples taken for microbial community analyses and process rate measurements at the saturated zone site, northeastern British Columbia. Abbreviations: 10X, first borehole drilled; CC, cell counts; MD, microbial diversity; MG, methanogenesis; MOX, aerobic methane oxidation; MW, multilevel monitoring well; PW, single-screened monitoring well; SAG, single cell amplified genomes; SRR, sulphate reduction rates.

Date	Wells	Samples
Oct. 19, 2017	PW1–6, 10X	H_2S, CC, SAG, MD
May 1–5, 2018	MW1, 3, 6	Soil
Jun. 6–13, 2018	PW1–6, MW1–13	H_2S, CC, SAG, MD, MOX, MG, SRR
Jun. 27–29, 2018	MW1, 9, 11	CC, SAG, MD
Jul. 12–13, 2018	MW1, 9–12	CC, SAG, MD
Jul. 27–30, 2018	MW1–3, 9–12	CC, SAG, MD
~Aug. 5, 2018	MW2, 7,10	MOX, MG, SRR
Aug. 15, 2018	MW1–3, 9–12	CC, SAG, MD
Aug. 27, 2018	MW1–3, 9–12	CC, SAG, MD
Sep. 18, 2018	MW1–3, 9–12	CC, SAG, MD

was the same for each visit. To accomplish this, permanent electrodes were installed in the ground in early June. During the May drilling campaign, fibre optic cables were installed in four wells. These cables were used to measure temperature variations in the subsurface during injection, known as distributed temperature sensing (DTS). Vertical seismic profile (VSP) data were collected pre-injection (June 5) and post-injection (September 25) to create a time-lapse dataset (Figure 6). In total there are seven ERT and refraction seismic datasets. Analysis of the data is ongoing.

Microbiology

Background sampling for microbiological analyses commenced in October 2017 (Table 2). At that time only the six PW wells had been installed. Those wells were sampled to recover microbial biomass through chemical flocculation. Samples were also collected for cell counting and single cell genomic analyses, as well as for ΣH_2S determination. The samples collected for ΣH_2S will also be used for determining the S-isotopic composition of relevant S-pools. During well installation consolidated materials were recovered for microbial community analyses.

Further sampling was conducted June 6–13, 2018, immediately prior to gas injection. All wells were sampled at this time for ΣH_2S, microbial community analyses, cell counting and single cell genomics. Process rate measurements (methane oxidation, methanogenesis, sulphate reduction) were conducted on wells MW2, MW7 and MW10 in early August. This subset was justified given that MW2 was upstream of the injection well, serving as a pseudocontrol, MW7 and MW10 were downstream at varying distances and thus likely to capture a time-resolved response to injection. Following injection, the majority of the sampling was focused on MW wells in the immediate vicinity of the injection well. Samples were collected roughly every two weeks, however, low temperatures precluded sampling in late September. Going forward, the sampling strategy will capture wells where CH_4 is detected in addition to the two innermost rings of wells around the injection well, so as not to miss wells receiving migrating gas. Microbial sample analyses and interpretation is ongoing.

Soil Gas and Surface Efflux

To monitor soil gas concentrations and surface effluxes, 12 dynamic long-term chambers (8100-104, LI-COR, Inc.) were deployed and 21 soil gas sampling ports were installed around the field site, primarily along two transects radiating from the injection zone. The 12 long-term dynamic chambers each periodically measure CO_2 and CH_4 effluxes at the designated locations, providing high-resolution time series data. The 21 soil gas sampling locations were manually augured with sampling ports at 0.45 and 1.15 m below ground surface, allowing for the collection of soil gas samples for compositional and isotope analyses. Additionally, 103 survey collars were placed in the ground and an additional set of analyzers allowed for survey flux measurements of CH_4 and CO_2 to be obtained across the site, providing detailed spatially distributed data at selected times. Figure 7 shows installed infrastructure at the site. Survey flux measurements and soil gas samples for isotopic and compositional analysis were collected every 2–4 weeks starting on May 28, 2018, and ending on October 1, 2018, due to weather restrictions. An example of CO_2 efflux from the site as measured from long-term chambers is shown in Figure 8.

Eddy Covariance and Micrometeorology

The eddy-covariance (EC) system was installed at the saturated zone site on May 14, 2018, and was powered up on June 1 (Figure 9). It was located at 56.1649°N, 121.860°W. Various climate sensors were added in the following few weeks, and the entire system, with all the necessary components has been fully operational since June 28, 2018. The

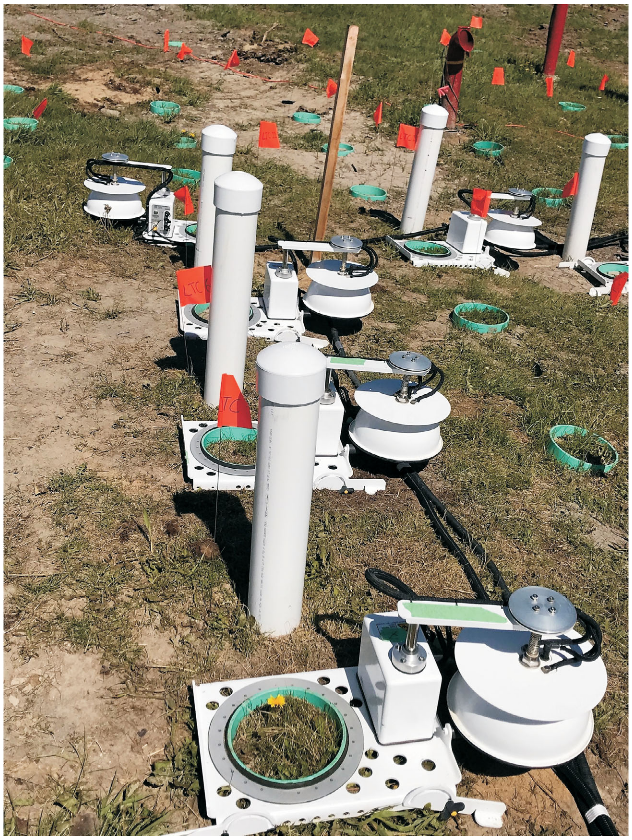

Figure 7. Long-term chambers (rectangular-based instruments), survey collars (green circles) and soil gas sampling wells (white standpipes) at saturated zone site, northeastern British Columbia.

EC system comprises a 3-D sonic anemometer (CSAT3B, Campbell Scientific, Inc. [CSI]), which measures wind direction and speed in three dimensions and also provides the sonic air temperature (Figures 10, 11). The gas analyzers being used are the LI-COR, Inc. LI-7700 for CH_4, which is an open-path system, and a LI-COR, Inc. LI-7200 for CO_2 and water vapour, which is an enclosed infrared gas analyzer. There is also a flow module (7200-101) with the LI-7200, which is responsible for maintaining a precise and controllable flow of air. An LI-7550 analyzer interface unit (AIU) was also set-up, which integrates data from the sonic anemometer, and LI-7200 and LI-7700 analyzers. A self-contained climate system was also set-up and has been fully operational since June 28, 2018. This consists of a net radiometer (CNR4, Kipp & Zonen B.V.), a 2-D anemometer (WindSonic, Gill Instruments Limited), and CSI sensors (manufactured by Vaisala Corporation) for barometric pressure (CS106), temperature and relative humidity (HMP155A). Three sensors (GS3, Decagon Devices, Inc.) were also installed to measure soil moisture content, soil electrical conductivity and soil temperature over the 0 to 5 cm depth. Two soil heat flux plates (HFP01-L, HFP01SC-L, Hukseflux Thermal Sensors B.V.) were installed at a depth of 5 cm, the latter being self-calibrating. There is also a tipping bucket rain gauge (TE525WS, Texas Electronics, Inc.), which is designed to be used with a precipitation adapter in case of snow.

A datalogger (CR1000, Campbell Scientific, Inc.) at the site collects all the climate data from the various components, and compiles it giving the averages, maximum and minimum values of these traces for each half hour. These data together with the computed EC fluxes (by a SmartFlux 2 System, LI-COR, Inc.) are transmitted to the UBC Biometeorology Soil and Physics Group lab daily at 6 a.m. via a modem (RV50, Sierra Wireless S.A.). The high-frequency data are collected onto a USB data stick present at the site, which is sent back and forth between the site and UBC on a biweekly basis. This arrangement allows for the continual reprocessing of the high-frequency data, the use

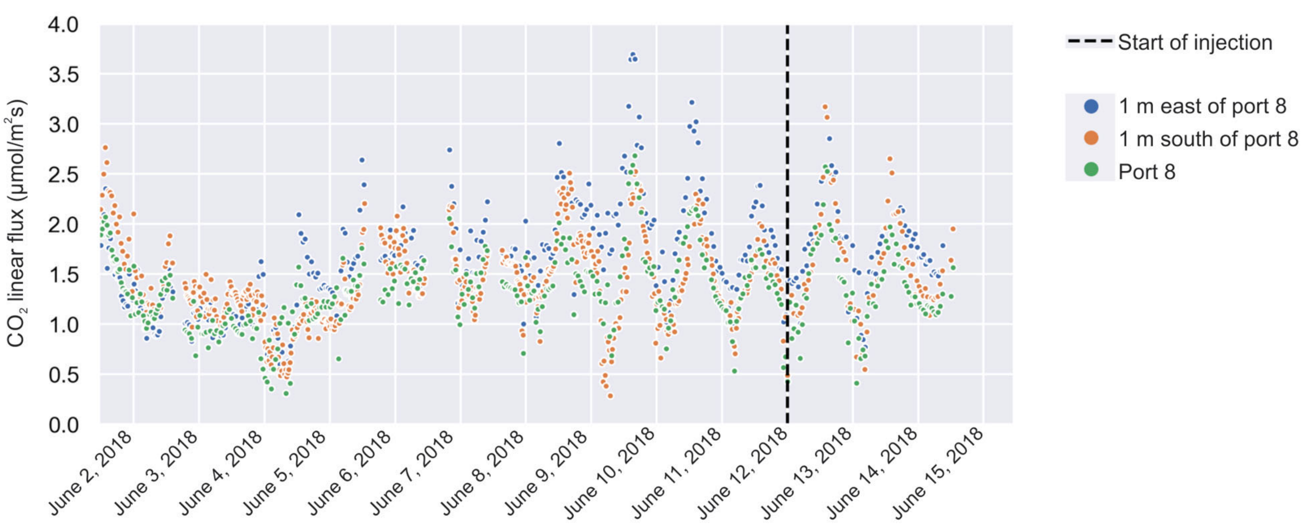

Figure 8. Example of carbon dioxide fluxes as measured from the long-term dynamic chambers, saturated zone site, northeastern British Columbia. It shows natural fluctuation before and shortly after injection (June 12) commenced.

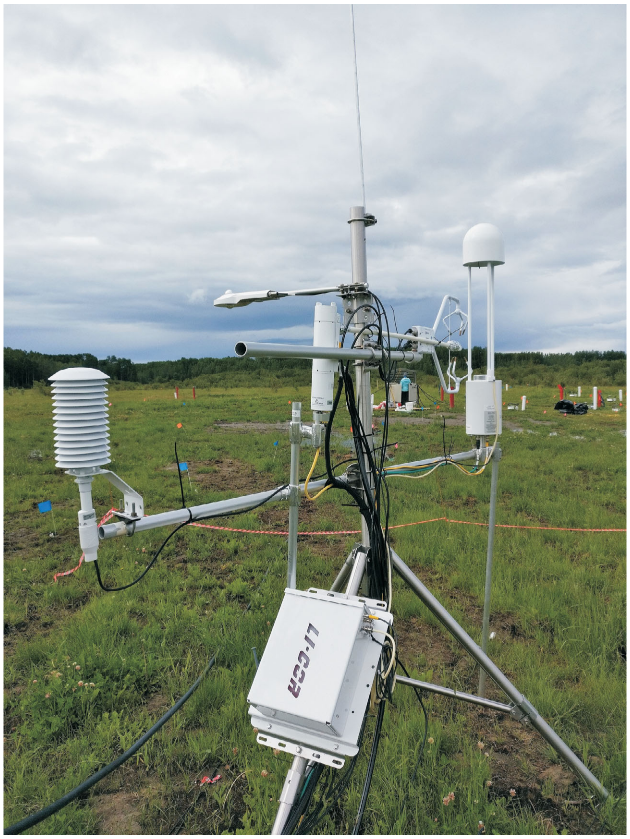

Figure 9. Eddy-covariance flux tower at the saturated zone site, northeastern British Columbia.

Figure 10. The instruments shown are the 1) sonic anemometer (CSAT3B, Campbell Scientific, Inc.), 2) open-path methane analyzer (LI-7700, LI-COR, Inc.), and 3) air sampling tube connected to the enclosed infrared gas analyzer for carbon dioxide and water vapour (LI-7200, LI-COR, Inc.).

of different computational methods and the application of corrections to flux calculations.

Routine tests were carried out to ensure accurate functioning of the components. Regular filtering of the data is done to account for the effects of wind direction and turbulence.

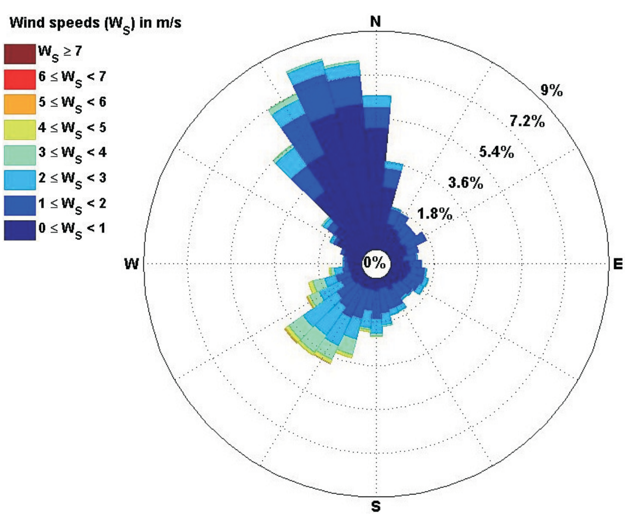

Figure 11. Windrose generated from eddy-covariance system measurements recorded at the saturated zone site, northeastern British Columbia. The majority of the winds are from the northwest, along with a portion of the high-speed winds from the southwest. Wind speeds at the site were usually between 1.5 and 3 m/s.

For the LI-7700 gas analyzer to adjust to the onset of winter, its temperature settings were changed, as recommended by LI-COR staff, from warm to cool mode on September 20. This was done because the sensor would not be able to perform a line-lock as lasers drift during cool temperatures. Following this, analyses to assess energy balance closure were carried out, because good closure indicates correct functioning of the EC system, and hence reliable flux measurements.

The complete EC system has collected continuous high-resolution data (including concentrations of CH_4 and CO_2 as well as complementary detailed micrometeorology measurements), which will allow the detection, quantification and assessment of any experimental injected gas that reaches the atmosphere. Measurements are ongoing and planned to continue until summer 2019. Processing of results is also ongoing.

Public and First Nations Engagement

The UBC EERI team has taken care to create opportunities for engagement by First Nation communities and other interested stakeholders. In late 2017, two information letters were sent to neighbouring First Nations communities to in-

Figure 12. The University of British Columbia's Energy and Environment Research Initiative's Field Demonstration Day, July 25, 2018.

form them of the upcoming controlled natural gas release experiment to be performed in the summer of 2018, as well as to ask for input and provide details on a line of communication for questions, concerns or comments. These were sent in October and December of 2017. On March 13, 2018, the UBC EERI team attended the Northeast Water Strategy meeting in Fort St. John. They described their projects, including the controlled natural gas release experiment, to various stakeholders. Once the experiment was underway, a Field Demonstration Day was held on July 25 for funders, government officials, industry and community leaders. Unfortunately, no First Nations members attended. Starting with a tour of the resource development in the Montney region, proximal to the sites, and a quick geology and hydrogeology lesson, the 32 attendees ended the day with a tour and 'show-and-tell' of the saturated zone site and the various monitoring methodologies in use. The day was a great success and generated discussion and insights, formed new relationships and increased buy-in from the various stakeholders (Figure 12).

Ongoing Work

Research is ongoing at two separate but closely located sites at which controlled gas release experiments have been performed. Data from the unsaturated zone gas injection experiment is being processed and publications are being formulated to report key findings and conclusions to the wider scientific community. This experiment has generated an extensive and important dataset from which many insights with respect to fugitive gas leakage into unsaturated soils is set to be gained. The saturated zone experiment is ongoing. Monitoring to track and assess migration, impacts and fate of injected gas will continue in a multidisciplinary manner into 2019. Reporting of results in peer-reviewed publications will begin in due course.

Summary of Progress

The following forms a summary of the progress made to date with respect to The University of British Columbia's Energy and Environment Research Initiative's controlled natural gas release experiment:

- the unsaturated zone experiment was completed and manuscripts are being formulated for submissions to top-tier journals (one article in submission with Nature Geoscience);
- preparations for injection and set-up of the extensive multidisciplinary monitoring networks to track migration, impacts and fate of fugitive gas at the saturated zone site were successfully performed;
- 100 m^3 of a synthetic Montney gas analogue was successfully injected at 26 m vertical depth into the saturated zone site aquifer at a rate of 1.5 m^3/day, commencing on June 12, 2018, and continuing for 72 days;
- large multidisciplinary datasets are being developed to show in high spatiotemporal resolution the impacts of the injected gas migration and its fate in the environment following its release into the saturated zone; and
- reporting of main findings and conclusions from the saturated zone experiment in peer-reviewed literature will follow in short order.

Acknowledgments

Peer reviewed by L. Smith. This work was funded by Geoscience BC and the Natural Resources Canada's Energy Innovation Program.

References

Amos, R.T., Bekins, B.A., Cozzarelli, I.M., Voytek, M.A., Kirshstein, J.D., Jones, E.J. and Blowes, D.W. (2012): Evidence for iron-mediated anaerobic methane oxidation in a crude oil-contaminated aquifer; Geobiology, v. 10, issue 6, p. 506–517, URL <https://doi.org/10.1111/j.1472-4669.2012.00341.x> [November 2018].

Bennett, B. and Dudas, M.J. (2003): Release of arsenic and molybdenum by reductive dissolution of iron oxides in a soil with enriched levels of native arsenic; Journal of Environmental Engineering and Science, v. 2, issue 4, p. 265–272, URL <https://doi.org/10.1139/s03-028> [November 2018].

Cahill, A.G., Chao, J., Ford, O., Ladd, B., Prystupa, E., Mayer, K.U., Tannant, D., Black, A., Crowe, S., Hallam, S., Mayer, B., van Geloven, C., Welch, L., Levson, V. and Beckie, R.D. (2018): Establishment of field stations for the multidisciplinary study of controlled natural gas releases, northeastern British Columbia; *in* Geoscience BC Summary of Activities 2017: Energy, Geoscience BC, Report 2018-4, p. 65–76.

Cahill, A.G., Steelman, C.M., Forde, O., Kuloyo, O., Ruff, S.E., Mayer, B., Mayer, K.U., Strous, M., Ryan, M.C., Cherry, J.A. and Parker, B.L. (2017): Mobility and persistence of methane in groundwater in a controlled-release field experiment; Nature Geoscience, v. 10, issue 4, p. 289–294, URL <https://doi.org/10.1038/ngeo2919> [November 2018].

Caulton, D.R., Shepson, P.B., Santoro, R.L., Sparks, J.P., Howarth, R.W., Ingraffea, A.R., Cambaliza, Sweeney, C., Karion, A., Davis, K.J., Stirm, B.H., Montzka, S.A. and Miller, B.R. (2014): Toward a better understanding and quantification of methane emissions from shale gas development; Proceedings of the National Academy of Sciences of the United States of America, v. 111, no. 17, p. 6237–6242, URL <https://doi.org/10.1073/pnas.1316546111> [November 2018].

Christensen, T.H., Bjerg, P.L., Banwart, S.A., Jakobsen, R., Heron, G. and Albrechtsen, H. (2000): Characterization of redox conditions in groundwater contaminant plumes; Journal of Contaminant Hydrology, v. 45, issue 3–4, p. 165–241, URL <https://doi.org/10.1016/S0169-7722(00)00109-1> [November 2018].

Intergovernmental Panel on Climate Change (2014): Climate change 2013: the physical science basis – contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change; T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed.), Cambridge University Press, Cambridge, United Kingdom and New York, New York, 1535 p., URL <https://doi.org/10.1017/CBO9781107415324> [November 2018].

LeBreton, E. (2009): Confined space; Transport Canada, URL <https://www.tc.gc.ca/eng/canutec/articles-confined-456.htm> [December 2017].

Le Mer, J. and Roger, P. (2001): Production, oxidation, emission and consumption of methane by soils: a review; European Journal of Soil Biology, v. 37, issue 1, p. 25–50.

Ng, G.H.C., Bekins, B.A., Cozzarelli, I.M., Baedecker, M.J., Bennett, P.C., Amos, R.T. and Herkelrath, W.N. (2015): Reactive transport modeling of geochemical controls on secondary water quality impacts at a crude oil spill site near Bemidji, MN; Water Resources Research, v. 51, issue 6, p. 4156–4183, URL <https://doi.org/10.1002/2015WR016964> [November 2018].

Shindell, D.T., Faluvegi, G., Koch, D.M., Schmidt, G.A., Unger, N. and Bauer, S.E. (2009): Improved attribution of climate forcing to emissions; Science, v. 326, issue 5953, p. 716–718, URL <https://doi.org/10.1126/science.1174760> [November 2018].

Van Stempvoort, D., Maathuis, H., Jaworski, E., Mayer, B. and Rich, K. (2005): Oxidation of fugitive methane in groundwater linked to bacterial sulfate reduction; Groundwater, v. 43, issue 2, p. 187–199.

Van Stempvoort, D.R., Armstrong, J. and Mayer, B. (2007): Microbial reduction of sulfate injected to gas condensate plumes in cold groundwater; Journal of Contaminant Hydrology, v. 92, issue 3–4, p. 184–207, URL <https://doi.org/10.1016/j.jconhyd.2007.01.006> [November 2018].