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Canadian Natural Resources Limited

Area Fugitive Emission Measurements of Methane & Carbon Dioxide

Synthesis and Assessment Report

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AECOM: 2015-04-13

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1. Introduction

Canadian Natural Resources Limited (Canadian Natural) was the lead applicant in a proposal to Emissions Reduction Alberta (ERA) to field validate and commercialize solutions surrounding the quantification of fugitive methane (CH_4) and carbon dioxide (CO_2) emissions, both greenhouse gases (GHGs) from large industrial area sources which are characterized by complex terrain and heterogeneous air emissions zones. The impetus for the work was that the techniques currently used to measure and model air emissions from these sites as required by Alberta Environment and Parks (AEP) are limited in their ability to provide spatial and temporal coverage.

1.1 Project Summary

The project was conducted at the Horizon oil sands facility, particularly mine pits and tailings ponds. The aim of the project, as proposed to ERA, was to demonstrate, validate, and compare various technologies including inverse dispersion modelling, fixed sensors including smart poles, open path systems, drones, and satellites.

More explicitly, the goals of the project were to:

- Develop a robust, accurate reliable sensor with low background interference and power requirements capable of the continuous measurement of CO_2 and CH_4 for an extended period of time in all four seasons.
- Develop/ improve existing air models to more accurately represent conditions in the field under various meteorological conditions.
- Conduct measurements during the colder months, October to April, to determine if there are any changes in fugitive Greenhouse Gas Emissions.
- Develop a guidance document for government and industry to conduct area fugitive emissions measurements, listing the equipment specifications and placement of sensors to conduct Inverse Dispersion Modelling (IDM) of area fugitive emissions.

The project team included Alberta Environment and Parks (AEP), the University of Alberta (UofA), the University of Guelph (UofG), Southern Alberta Institute of Technology (SAIT), RWDI, Boreal Laser, Luxmux and Spectral Sensor Solutions (S3).

Measurement approaches by RWDI, UofA and S3 were implemented at the Canadian Natural Horizon oil sands facility (the Facility) and were used to estimate annual greenhouse gas (GHG) emissions from the Canadian Natural Horizon External Tailings Facility Pond (the pond) and Open pit surface mine areas. The UofG participated in measurement campaigns largely providing auxiliary meteorological measurements and modelling support. SAIT participated in the measurement campaigns performing drone-based concentration measurements and trailer-based concentration and meteorological measurements. Luxmux worked to develop their SmartPole system but were ultimately unable to fully deploy a working field version of the SmartPole system during the scheduled monitoring period.

1.2 Role of the Synthesis

This synthesis report aims to examine all measurement approaches in relation to the four goals of the project. The synthesis report will focus on evaluating the efficacy of alternative emission estimation methodology to the currently

AEP-approved Flux Chamber (FC) measurement approach. Finally, the synthesis report aims to provide recommendations based on the evaluations and to identify gaps that require filling.

1.3 Information Sources

The main source of information for the synthesis report were project partner final reports and references therein. Final reports were submitted by RWDI, UofA, UofG, Luxmux and S3. Project partner progress reports and updates were also reviewed. Key reports reviewed were summarized in literature review tables and have been appended to this report (Appendix 1). Figures from the reports were used in the synthesis report to aid in understanding the alternative flux measurement methods and to present key findings.

2. Measurement Project Structure and Participant Roles

The ERA-funded project was a collaborative undertaking with Canadian Natural co-ordinating efforts of the various project partners. Project proponents RWDI, UofA and UofG implemented their emission estimation methodologies at the Horizon Pond and Mines to estimate emission fluxes. RWDI measured emission fluxes using FCs as well as their AEP-approved alternative CALPUFF Inverse Dispersion Modelling (IDM) based approach. The UofA employed Eddy Covariance (EC) and a WindTrax backward Lagrangian Stochastic (bLS) model to estimate emissions. S3 implemented their GreenLITE IDM approach along with their advanced REVEAL 2-D wind vector mapping instrumentation. The three IDM approaches differ in their choice of model as well as their measurement approach. Detailed descriptions of the different emission estimation methodologies employed are provided in Section 3.2 below.

The UofG provided meteorological measurement support and worked to improve meteorological model inputs that were adopted by the RWDI CALPUFF IDM approach. Boreal Laser provided CH_4 and CO_2 measurements in spring 2018. Finally, Luxmux also attempted to deploy their Smart Pole Alpha Prototype, whose development was initially a major focus of the ERA project, however successful implementation of the prototype was never fully realized. Satellite observations were also posited as a potential measurement approach. GHG satellite data was reviewed but satellite observations available during the study period were found to be too coarse to be usable.

Ultimately several emission estimation campaigns were carried out by project partners between 2017 and 2020 that measured Pond and Mine fugitive emissions in all seasons.

3. Assessment

3.1 Flux Chamber Measurement – The Current AEP Standard

Oil sands mining facilities are regulated in Alberta under the Specified Gas Reporting Regulation (SGRR) (Government of Alberta, 2020a) and are additionally subject to the newly implemented Technology Innovation and Emissions Reduction Regulation (TIER). The SGRR requires facilities that emit 10,000 tonnes or more of specified gases to submit annual reports on their emissions. These emissions must be quantified in accordance with the guidance outlined in the Specified Gas Reporting Standard (Government of Alberta, 2020b). Under this regulation fugitive emission estimation from the large industrial area sources such as the Horizon Pond and Mine surfaces are addressed by the AEP Quantification of Area Fugitive Emissions at Oil Sands Mines documentation (Government of Alberta, 2019). Currently, AEP only approves of the use of Flux Chambers (FC) for emission estimation at oil sands facilities (Government of Alberta, 2019). Alternative methodology may be implemented by seeking approval on a case-by-case basis. In light of the regulation, it is therefore paramount that any assessment of emission estimation methodology to be made relative to the FC technique.

The FC method works by applying mass balance to a control volume of air over the emission source. This can be done using a static chamber where the volume of air is sealed, and the emission rate is determined by the time rate-of-change of concentration inside the chamber. Alternatively, a dynamic chamber where "clean" air is used to continually flush the chamber. In the case of the dynamic chamber method the emission rate is given by the gas concentration in the exhaust multiplied by the exhaust rate. The EPA approved approach is to use the dynamic FC method.

FC is relatively simple to implement, repeatable, inexpensive, and accessible by non-experts. However, the method provides an emission measurement over a small footprint (US EPA FC chambers cover 0.13 m^2) requiring many measurements to fully characterize a large source, particularly when this source may not have spatially uniform emissions. To address this issue AEP outlines specific guidance on the number of sampling locations and emissions zones that are required for ponds and mine surfaces. The FC method as implemented according to AEP guidance is deployed to these zones to obtain 30 to 90-minute samples from the emitting surface. Collected data are then extrapolated, both spatially and temporally, to obtain annual area source emission rates.

Furthermore, the FC chamber sits on the measurement surface and in turn has the potential to modify the surface emission profile.

3.2 Key Assessment Attributes

Flux measurements were evaluated based on several key criteria:

Sensitivity, stability and temporal resolution to meet data quality objectives. For an alternative emission estimation method to be implemented it needs to be comparable to the FC method in terms of sensitivity. Alternative real-time methods also need the added sensitivity required to distinguish between the ambient background and the enhancement due to the surface (or ΔC) being monitored. RWDI reported that for the Horizon Facility the CH_4 background was found to be ~2 ppm with ΔC up to 0.2 ppm. In the case of CO_2, the background ranged from 400-500 ppm, with a diurnal variation as large as 140 ppm, and a ΔC up to 30 ppm. Instrumentation employed also needs reasonable stability to handle variation in temperature, pressure, precipitation and other influencing factors. Finally, the flux measurement should be able to estimate both CH_4 and CO_2 emissions.

Spatial coverage. The sheer scale of large industrial sources such as the Horizon Pond and Open Pit Mines offers a challenge to the FC measurement technique. As described in Section 3.1 above the challenges related to spatial coverage are driven by the small footprint measured by FC (typically on the order of ~0.13 m^2) and the need to representatively sample the much larger non-uniform area sources. Alternative methods will need to address this issue in some manner, be it in providing a direct measure of the average surface emission rate or by multiple measurements as is the case with the FC method. An additional feature to consider with the Pond is the beach area on the east side of the Pond that is, due to safety concerns, not accessible for FC sampling. The ability to identify and estimate emissions from emission hot spots adds value to a measurement technique. Of note, the AEP recommends that 80% of the emitting surface be sampled by alternative techniques.

Ability to monitor temporal and seasonal trends. Emission estimates need to be reported annually and are typically extrapolated/scaled up from shorter term averaging period. This extrapolation adds inherent uncertainty to the emission estimate as a result of the inability to monitor potential emission changes during diurnal or seasonal emission trends. Measurement techniques that offer a snapshot or are unable to be effectively deployed for longer periods and/or under certain typically encountered seasonal or diurnal conditions are as such inherently more uncertain.

Relevance to implementation in varying terrain and in complex topography. The Horizon Pond and the Horizon Mines offer very distinct measurement surfaces each with its unique challenges. The complex terrain of open pit mines and the constantly shifting surface environments are less easily addressed by flux measurements approaches. Conversely, the open water emitting surface of the pond along shifting pond shorelines provide non-trivial safety and logistical sampling challenges.

Other issues or gaps in the flux measurement. Alternative flux measurement approaches and methodology may suffer from issues or gaps not addressed by the categories above. These gaps may be inherent to the flux measurement approach itself, a result of current sensor implementation, or simply a result of the novel nature of the employed emission estimation approach.

Value of Measurement. A final metric that is being addressed is whether or not the measurement approach is deemed to be of high value or not. In order to be objective, this attribute will be assessed as a combination of the rough cost of flux measurement implementation, ease of field measurement implementation, and the quality of the data collected.

3.3 Flux Measurements Assessed

3.3.1 Flux Chamber – RWDI

3.3.1.1 Sampling Program Design

RWDI indicated that FCs were sampled during Spring 2018 and during Summer and Fall 2019. During these sampling periods 9 flux chamber measurements were taken in each of the Mines (i.e., 9 in the East Pit and 9 in the West Pit). Each set of 9 samples were taken in clusters of 3: 3 FC samples measuring Mine areas with less than 1 week of exposure (freshly mined), 3 FC samples measuring mine areas with >1 week and <6 months exposure, and 3 FC samples in mine areas with >6 months exposure.

3.3.2 CALPUFF Inverse Dispersion Modelling – RWDI

This approach relies upon combining concentration measurements with a CALPUFF-based IDM approach. IDM is characterized by the ability to use non-disturbance measurements and micrometeorological-based modelling methods to calculate emissions. IDM is considered a “top-down” approach, in that it captures emissions information from the site and apportions emission rates based on site knowledge. The IDM process typically requires answering the question “what would the emission rates have to be to cause the observed increase in downwind concentrations?”

IDM relies on ambient concentration measurements taken downwind of an emission source (C) and dispersion modelling to estimate source emission rates based on the prevailing winds and the turbulence regime at the time of the measurement. An upwind measurement (C_b) is also required to account for non-zero background concentrations upwind of a source. As such IDM is concerned with the increase in concentration downwind of an emissions source, ΔC ($\Delta C = C - C_b$).

To implement IDM, concentration measurements may be conducted with any valid ambient measurement technique. Measurements may be conducted using either point sampling or open-path systems, although measurement systems are ideally identical during a single deployment for optimal performance.

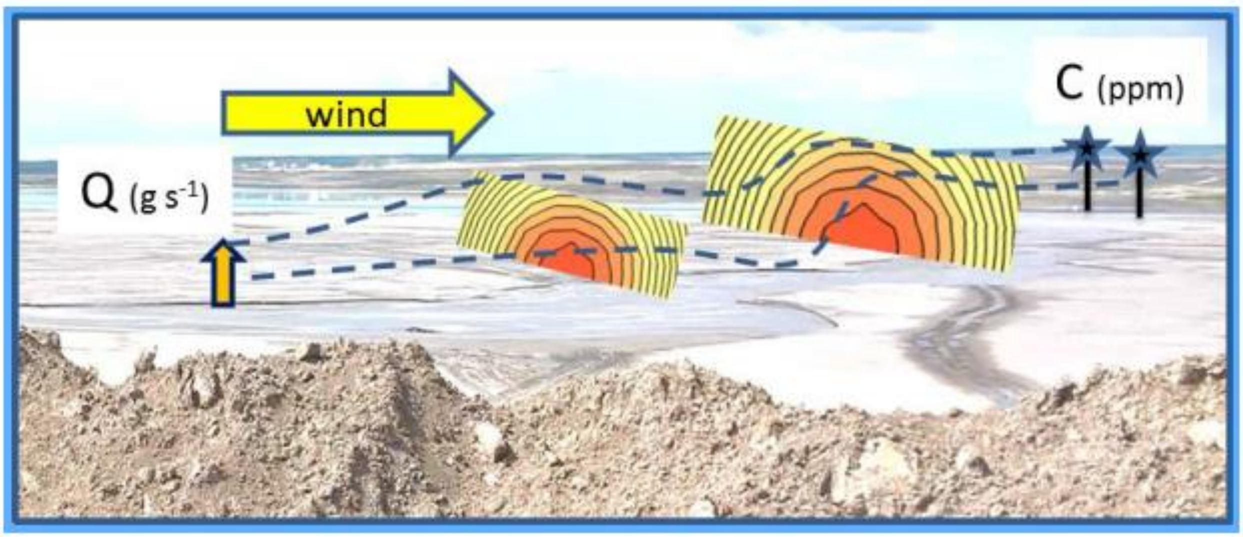

Figure 1: IDM Conceptual Picture. Q is the source emission rate and C the ambient concentration measured downwind of the source (Figure 2 in RWDI 2020).

CALPUFF was the IDM model implemented by RWDI. CALPUFF simulates the movement and dispersion of individual puffs emitted in each time step and overlays the puffs for each pre-selected receptor location. Movement and dispersion of the puffs requires that grid spacing in the horizontal and vertical direction is fine enough to reflect terrain effects in the flow. When the CALMET/CALPUFF modelling system is sufficiently accurate, the prediction should agree with synchronous observation at the same location modelled within a range of uncertainties in time without substantial bias. The IDM component works by taking observed data and finding an emission rate that best explains the observation. Typically, this involves an iterative process.

The RWDI CALPUFF IDM approach has been employed at the Canadian Natural site since 2015. The method has been approved on an annual basis by the regulator as an alternative method to flux chamber measurements.

3.3.2.1 Sampling Program Design

Up to six meteorological stations were positioned around the site during each campaign with each station measuring wind speed and wind direction, and in some cases temperature. Pressure and relative humidity, which are also required as inputs into CALMET were obtained from a single station. Two-dimensional (2D) (WINDSONIC1, Campbell Sci.) and 3D (CSAT-3, Campbell Sci.) sonic anemometers were used at the monitoring stations deployed. These stations were setup at a height of 10 m (per the Air Monitoring Directive (AMD) guideline) and measured at 10 Hz. Air data was also used from the nearby local Wood Buffalo Environmental Association (WBEA) airshed which operated a three-cup anemometer (Met One 010C/020C). 2D wind measurements are adequate as CALMET does not require the 3D component of wind direction as an input. Data from the WBEA stations and meteorological data from the eddy covariance system were used as inputs the CALMET meteorological mode.

Typically, four cavity ring-down spectrometers (CRDS) (LGR-UGGA, Los Gatos Research Inc., Mountain View, CA) were position around the area source of interest. Instrument repeatability and precision were <0.6 ppb for CH_4 and <100 ppb for CO_2 (10 second averaging time). Instrumentation were field calibrated during the field campaign and cross calibration of instrumentation was performed before and after the field campaign.

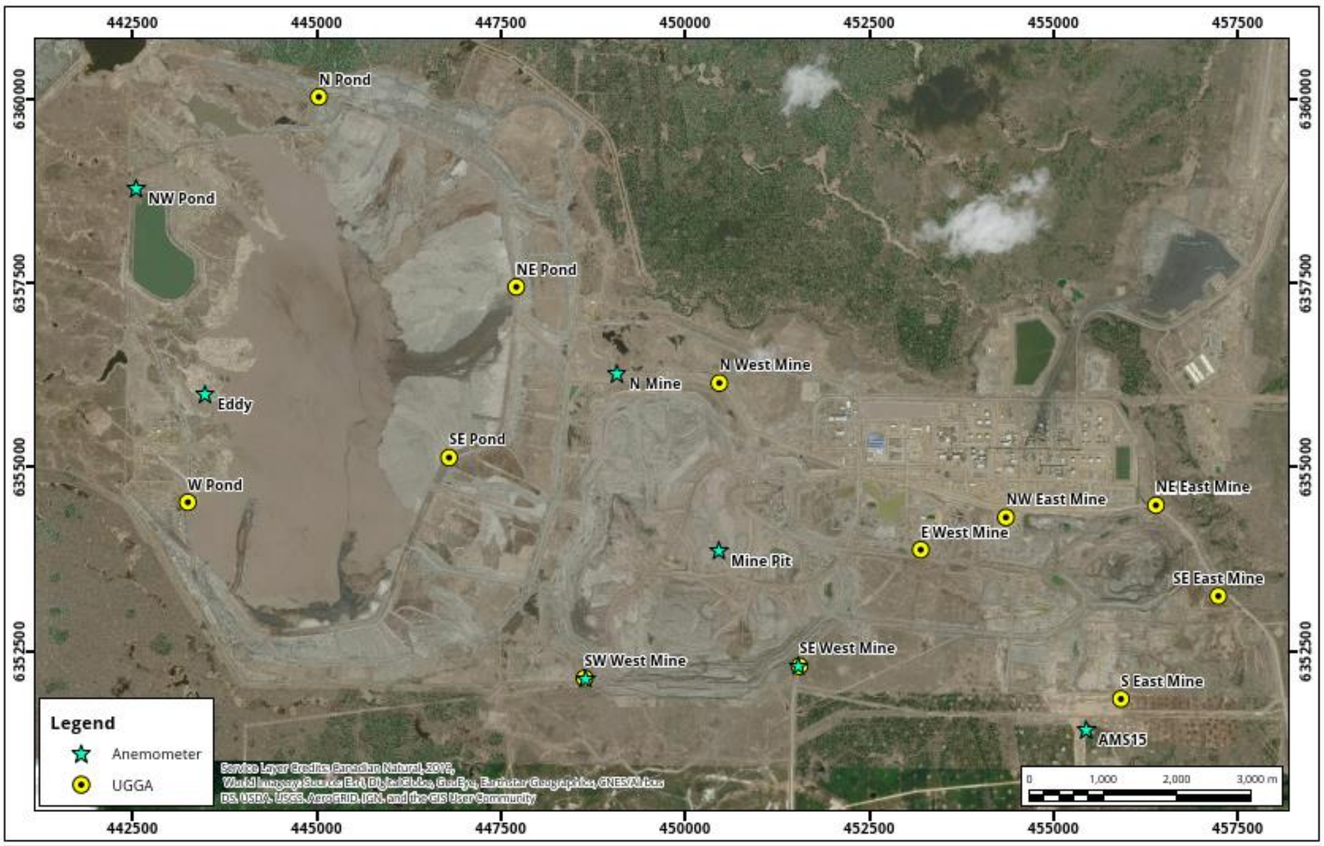

Figure 2: Location of Anemometers and LGR-UGGAs used in Fall 2019 at the Horizon Facility (as reported by RWDI in their GHG Fugitive Emission Quantification Via Inverse Dispersion Modelling Fall 2019 Survey Report)

Sources were delineated into subareas which were based on objective evaluation of location, activity level, anticipated similarity of the area's emission profile and qualitative assessment criteria anticipated to generate meaningful results. Qualitative criteria for the mine included active mining areas, prevailing meteorological conditions during the monitoring period and physical boundaries of both the tailings pond and the mine. For the pond, qualitative criteria included areas where bubbling had been observed and physical characteristics including open water vs sandy areas. Of note, sandy areas are not captured (due to safety concerns) by FC measurements. These subareas were assumed to have consistent emissions/emission profiles for the duration of each of the field campaigns (which typically lasted a few weeks at each of the given sources).

3.3.3 WindTrax IDM Modelling – University of Alberta

The “Backward” Lagrangian Stochastic (bLS) approach implemented by UofA uses concentration measurements measured upwind and downwind of the emitting surface, and the WindTrax model. The WindTrax model is a Lagrangian stochastic model that can be implemented in a “backward” fashion to enable the calculation of backward trajectories from a measurement point. These backward trajectories may then be used to calculate an emission rate based on the dispersion coefficient which is a function of the number of back trajectories reaching the emitting surface and the vertical velocity at “touchdown” at the surface.

At the core of the WindTrax approach is the assumption that Monin-Obukhov Similarity Theory (MOST) is valid. MOST states that for short intervals above a homogenous landscape the statistical properties of wind near ground are determined by a few key parameters that can be measured by a 3-D sonic anemometer: friction velocity (u*), Obukhov Length (L), Roughness Length ($z_{0)}$ and wind direction. MOST theory does not always hold true above homogenous landscapes and is less valid above non-homogenous landscapes (i.e., over complex terrain).

3.3.3.1 Sampling Program Design

Four Las Gatos Research (LGR) greenhouse gas analyzers that are based on cavity ring-down spectroscopy were used to obtain gas concentrations. These were the same LGR instruments setup by RWDI (See Section 3.3.2.1). An additional monitoring location was provided by the CH_4 and CO_2 monitoring equipment utilized by the Eddy Covariance (EC) system employed at the pond. Instrumentation employed provided 20 s data.

Wind data were obtained from two three-dimensional sonic anemometers, one of the two being the sonic anemometer employed by the EC system. The second sonic anemometer was placed just north of the mine. In both cases the sonic anemometers were needed to provide the wind parameters needed for WindTrax-IDM modelling:

- Friction velocity (u*)
- Obukhov Length (L)
- Roughness Length (z_0)

3.3.4 Eddy Covariance – University of Alberta

This is a well-established and well-regarded meteorological approach for measuring gas fluxes above an emitting surface.

A flux measurement relies on a high frequency (>5 Hz) time series of gas concentration and vertical wind velocity measured above the emitting surface, typically measured over a period of 30 minutes. The gas and wind sensors need to be located as close to one another as practical. Coupled to the need for a fast response, this eliminates the applicability of many measuring instrumentation.

Once a time series is obtained the EC analysis is then able to obtain the vertical flux of the measured gas (FEC) which can be related to the gas flux from the underlying emitting surface or the “flux footprint”. The flux footprint varies with wind conditions and needs to be computed in situations where the EC tower is not located directly above the source (e.g., offshore next to a tailings pond) prior to adjusting FEC and calculating area emission rates. The flux footprint is calculated using meteorological footprint models. These footprint models are unable to accurately model complex 2-D boundaries or complex terrain. Of note, the taller the tower the further the flux footprint extends upwind (up to the order of 10,000 m^2). Ideally, a large area source would have a large enough tower to capture the upwind extent of the pond. This is however not always practical due to the high cost associated with taller towers.

The technique assumes that average vertical velocity at the measurement location is spatially homogeneous (i.e., there is no flow divergence or convergence at the measurement site) an assumption which is only true for certain periods above flat and relatively gentle terrain.

3.3.4.1 Sampling Program Design

The sensors deployed during the Horizon pond field study included a three-axis sonic anemometer (Gill WindMaster, LI-COR Biosciences), an open-path CH_4 analyzer (Li-7700, LI-COR Biosciences) and a CO_2/H_2O analyzer (Li-7500DS, LI-COR Biosciences). The sensors were mounted 14.3 m above the ground on the western shore of the Horizon Pond. Of note, the laser CH_4 sensor optics needed manual cleaning despite the built-in cleaning system.

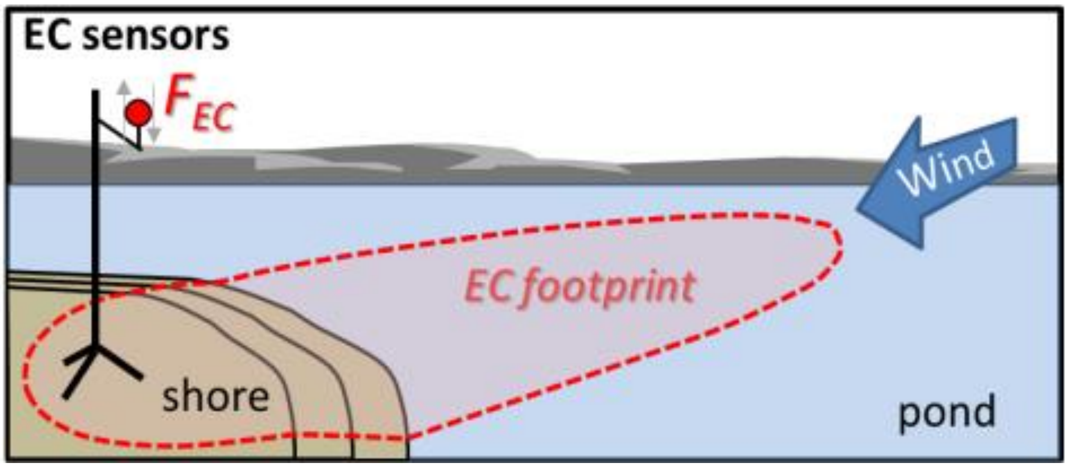

Figure 3: Illustration of the Flux Footprint at the Horizon Tailings Pond (Figure 2.1 in UofA 2020)

3.3.5 WRF Inverse Dispersion Modelling – University of Guelph

The Weather Research and Forecasting (WRF) 4.0 model with the advanced Research WRF (ARW) dynamical core and the passive tracer dispersion option was used as the University of Guelphs IDM model. A 5-tier nested modelling domain setup was used with the first tier covering much of North America and the fifth tier focused on the Canadian Natural site. Near-surface boundary conditions were provided to the model alongside field measured methane mixing ratios. The model provided a methane emission flux at the model's inner domain boundary.

As implemented the model required source code modification to enable updating boundary and methane mixing ratio conditions. This also required the model to be recompiled every four hours. Additionally, the model output was uncertain to the extent that the UofG did not report non-normalized emissions estimates.

3.3.5.1 Sampling Program Design

The UofG relied on instrumentation deployed by other project participants. In the case of the WRF IDM, the RWDI CRDS data was used. RWDI had deployed four CRDS instruments (LGR-UGGA, Los Gatos Research Inc., Mountain View, CA) which were positioned around the area source of interest (See Section 3.3.2.1 above). Instrument repeatability and precision were <0.6 ppb for CH_4 and <100 ppb for CO_2 (10 second averaging time). Instrumentation were field calibrated during the field campaign and cross calibration of instrumentation was performed before and after the field campaign.

The WRF model as implemented by the UofG did not require on site meteorological data.

3.3.6 GreenLITE Inverse Dispersion Modelling – S3

GreenLITE^{TM} is currently a pilot phase system. Laser absorption spectroscopy is combined with state-of-the-art radiative transfer retrieval methods to provide near-real-time concentrations. GreenLITE^{TM} can be coupled with high resolution meteorological data and an IDM to obtain emission estimates.

The GreenLITE^{TM} laser spectroscopy measurement is achieved using two transceivers and multiple reflectors to measure CO_2 and CH_4 path integrated concentrations over path lengths up to 5 km. The GreenLITE method can be configured to provide two-dimensional (2-D) mapping of gas concentrations and estimated emissions over large open areas up to ~25 km^2.

Once optical densities have been obtained and concentrations calculated the SCICHEM model is used to estimate emission rates via an iterative IDM process. SCICHEM is a SCIPUFF based modelling system capable of handling the complex photochemistry employed in CMAQ (The Community Multiscale Air Quality Modelling System). SCIPUFF is like CALPUFF in that both modelling systems are Lagrangian puff-based dispersion models. SCIPUFF however uses the second-order closure model of modern turbulence closure theory to approximate variances of wind, temperature and concentration. This is a more explicit approximation approach than the first-order closure model employed by CALPUFF that approximates gradient transport and mixing length.

3.3.6.1 Sampling Program Design

S3 deployed their system in two configurations, single transceiver or dual-transceiver (dual transceivers both measuring the same species across the area source) setups.

The single transceiver setup deployment consisted of placing a single transceiver for each measured gas on one edge of the measurement source and placing reflectors at various points across the area source of interest. For the single transceiver setup deployment at the Horizon pond a total of six chords (transceiver to reflector paths) were established, with four chords crossing over some portion of the pond and two chords on the east end of the pond acting as background chords. Chord lengths ranged from 1 km to 4.8 km. A meteorological measuring station capable of measuring vertical wind speed is also required. In the Horizon Pond deployment, S3 collocated a 3-D sonic anemometer with the transceivers (TX in **Figure 4** below). Two transceivers were collocated to measure CO_2 and CH_4, with both transceivers utilizing the same reflectors (R01 to R06 in **Figure 4**).

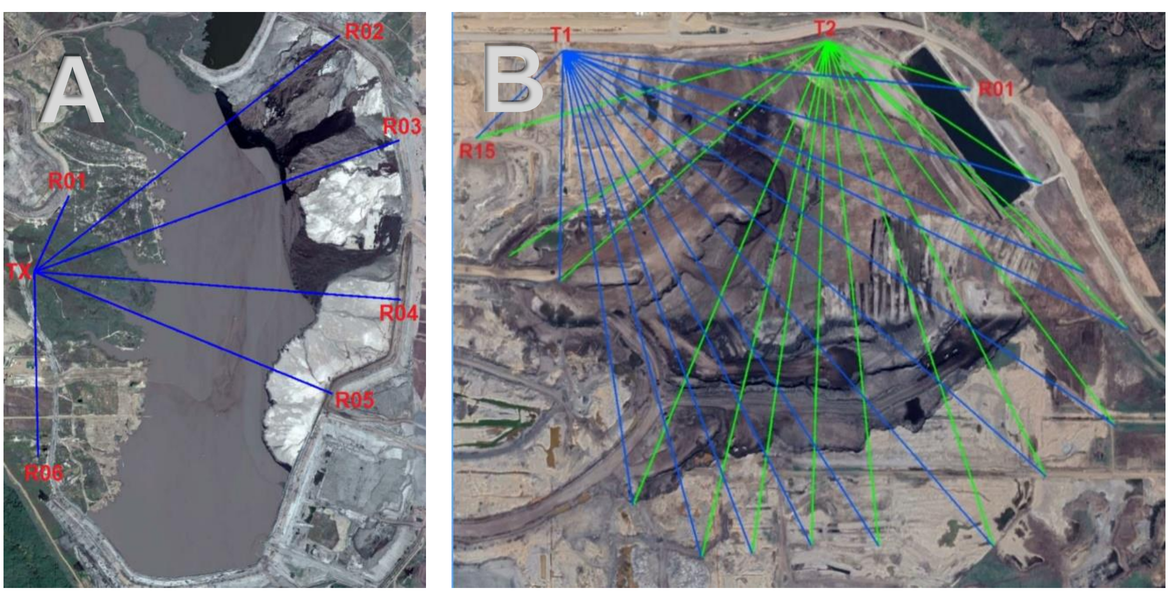

Figure 4: GreenLITE^{TM} Transceiver Configurations. A) Single transceiver configuration measuring methane across the pond. B) Dual-Transceiver setup to measure methane in the East Mine Pit (Adapted from S3 2019)

The dual transceiver configuration was deployed to estimate CH_4 emissions from the East Mine Pit. In the dual transceiver setup two separate transceivers measuring the same species were deployed (T1 and T2 in **Figure 4**), separated by 960 m, approximately half the width of the surface area being measured. Each of these two transceivers was setup with its own background and sampling reflector with sampling chords overlapping over the emission source being measured. In total fifteen reflectors were deployed in the East Mine, with 11 of the reflectors placed around the east and south edge of the mine and 4 reflectors in the mine itself. Chord lengths ranged from 440 m to 2.4 km with an average chord length of 1.6 km.

The single transceiver analysis consists of converting optical depths into path-integrated concentrations prior to applying an iterative SCICHEM IDM process to estimate emissions from rectangular release areas centred on the measured chords. The emission estimates from the area source chords are then converted to a normalized flux in $g/s/m^2$ prior to being scaled up to the total area of the emitting source.

In the dual transceiver setup, post analysis is somewhat more involved and requires computation of 2-D distributions of gas concentrations prior to IDM analysis. The 2-D computation estimates gas concentrations in the plane defined by the height of the chords and their intersecting horizontal areas after accounting for the impact of wind direction and speed on dispersion. The 2-D estimate of concentration can then form a more refined series of chords over which the iterative IDM analysis can be performed.

3.3.7 ARMS SmartPoles - Luxmux

Luxmux worked to develop their ARMS SmartPole system and went through three main concentration sensor prototype iterations. The final ARMS SmartPole system consists of a near-IR based concentration sensor capable of measuring CH_4, CO_2 and H_2O. This final ARMS smart pole variant utilized a Herriot cell configuration to enhance measurement path lengths, employed an improved photovoltaic based detector and was paired with a novel workup algorithm. Luxmux submitted a US patent application for this final sensor variant in February 2020.

In addition to the concentration sensors, the ARMS SmartPole systems each come equipped with a meteorological station which can measure wind speed, wind direction, air pressure, air temperature and relative humidity. The SmartPoles also have the ability to measure GPS location and elevation and are packaged in a NEMA 4 weatherproof enclosure. When deployed as a network with each SmartPole deployed alongside a solar panel and battery pack, the SmartPoles are intended to communicate data to a central location where data are backed up to an online hub and processed. The final version of the ARMS SmartPole system was not deployed at Canadian Natural and no emission estimates were obtained using the system.

3.4 Auxiliary Measurements Assessed

3.4.1 University of Guelph Meteorological Monitoring and Modelling

The work of the University of Guelph focused on understanding the Atmospheric Boundary Layer and accurately predicting and modelling the features of the surface boundary layer above a complex mine. UofG used a Tethered Air Blimp (TAB) to observe the microclimate and determine boundary layer structure. The TAB system was also used to infer land surface temperatures from thermal camera observations. The authors employed Computational Fluid Dynamics (CFD) to understand atmospheric transport above complex terrain (like what is encountered at the Horizon Mine). The UofG also assisted by assessing the impact of changes to topography, land use and grid spacing on WRF output. This WRF output was then used by project collaborators to assess diurnal, seasonal and annual variations in area-fugitive methane emission fluxes from the Horizon mine.

3.4.2 Air Mass Balance – University of Alberta

The UofA also attempted to assess the Air Mass Balance (AMB) emission estimation approach. AMB provides a fundamentally simple meteorological approach that estimates emissions by defining an imaginary control volume above the gas source and summing the gas fluxes crossing the volume boundaries. Fluxes at volume boundaries are calculated from the product of the wind velocity across the face and the gas concentration, an analysis that does not require computational modelling. Employing a large enough control volume above a source such that the upwind face is perpendicular to the wind, the across-wind span of the control volume is much larger than the source dimension and the box is suitably high enables the assumption that only measurements on the downwind face (and upwind face of a non-zero ambient background exists) are required.

The size requirements for a box to be large enough for AMB simplifications to hold true limit the applicability of ground based AMB measurement approaches to smaller area sources. Larger sources, such as the large industrial area sources of interest would require mobile sensors (e.g., mounted on drones).

The AMB method was not demonstrated at the Canadian Natural site due to a combination of the inability to get flight approval and difficult flight logistics associated with the Horizon Pond and Open-Mine Pits. A demonstration study at a feedlot indicated that the Horizon pond, which is approximately 2 x 7 km long would require a control volume with faces that are roughly 7 and 9 km wide and 300-400 m high. A larger control volume would be required for the larger West Mine Pit. These several-km faces would need to be sampled with aircraft-mounted sensors.

3.4.3 REVEAL – S3

S3 also deployed their Real-time Eye-safe Visualization, Evaluation and Analysis Lidar (REVEAL) system. REVEAL is an elastic backscatter lidar that uses an eye-safe micro-pulse laser (λ = 1.5 µm) to transmit laser pulses through the atmosphere. By precisely recording the time of returned particles, calculating the travel distance and plotting a histogram of the travel times/distances, a relative measurement of aerosol density as a function of distance can be computed. The laser is mounted on a mechanical scanner that scans a horizontal plane to create a 2-D map and identify aerosol features or plumes. A 2-D wind field can then be generated by comparing two successive scans (aerosol maps) and calculating the cross-correlation of the aerosol features in the aerosol maps.

The system has a maximum unambiguous distance that is dependent on the pulse repetition frequency (PRF) of the laser. The laser was operated at 15 kHz enabling an unambiguous fold-over range of 10 km and a range resolution of 7.67 m. At night the range distance is reduced to range of a few km due to the need to reduce system sensitivity to avoid interference from the solar background.

3.5 Comparison to Flux Chamber Measurement

3.5.1 *Quantitative Emission Estimate Comparison*

A quantitative comparison of FC results to those results obtained by alternative approaches was not fully possible. FC results for the Horizon Pond and Horizon West Mine Pit were available up until 2017 when the CALPUFF IDM approach was used at the Facility. FC data was also collected at the Mines during spring 2018, and Summer and Fall 2019 although these data was collected at a limited number of locations across the ponds and is not expected to be representative. This allowed little useful overlap with the alternate methods and did not provide enough data for meaningful statistical analysis. A qualitative comparison is presented in **Figures Figure** 5 through **Figure** 9 below. Data used to generate **Figures Figure** 5 through **Figure** 9 is also presented in **Table 1** below.

Table 1: Summary of Field Sampling Data Including Sampling Dates

Method	Year	Sampling Period	Season	Annual Emissions (t y^{-1})						
				Pond			Mine			Total
				CH_4	CO_2	CO_2-e	CH_4	CO_2	CO_2-e	CO_2-e
Flux Chamber[1]	2012	Late Aug	Summer	959	44,109	68,084	10,524	19,996	283,096	351,180
	2013	Mid Oct	Fall	187	37,937	42,612	34,684	38,152	905,252	947,864
	2014	Early Aug	Summer	727	34,898	53,073	22	14,605	15,155	68,236
	2016	Aug-Sept	Summer	1,799	24,394	69,369	81	19,403	21,428	90,797
	2017	Early Aug	Summer	1,905	23,227	70,852	273	23,626	30,451	101,303
	2019	Fall 2019	Fall				33	21,490	22,315	22,315
Eddy Covariance	2017	Mid Aug	Summer	1,945	15,841	64,466				
	2018	Jun-Aug	Summer	2,415	31,690	92,065				
	2019	Mar-April	Spring	1,867	2,546	46,671				
	2019	May-Jun	Summer	3,139	37,595	116,070				
	2019	Jul-Aug	Fall	1,862	71,905	117,895				
WindTrax-IDM[2]	2015	Sep-Oct	Fall	409	69,006	79,231	13,391	696,352	1,031,127	1,110,378
	2016	Aug-Sept	Summer	649	76,760	92,985	14,746	236,995	605,645	699,007
	2018	Apr-May	Spring	8,500	-21,000	191,500	9,500	-27,000	210,500	402,000
	2019	Feb-Mar	Winter	6,453	10,220	171,545	11,738	-28,470	264,980	436,540
	2019	July-Aug	Summer	6,383	396,865	556,440	12,077	-11,373	276,495	832,930
	2019	Oct-Nov	Fall	1,154	42,156	71,006	13,187	-57,108	272,567	343,590
CALPUFF-IDM	2015	Sep-Oct	Fall	2,712	33,523	101,323	3,093	95,885	173,210	274,533
	2016	Aug-Sept	Summer	1,052	69,797	96,097	12,552	21,268	335,068	431,165
	2017	Mid Aug	Summer	1,592		39,800	12,915		322,875	447,575
	2018	Apr-May	Spring	9,873	31,690	278,515	32,045	38,500	839,625	1,118,148
	2019	April	Winter	2,520		63,000	14,980	31,740	406,240	469,240
	2019	August	Summer	2,550		63,750	4,664	31,740	148,340	212,090
	2019	September	Fall	1,073		26,825	5,336	31,740	165,140	191,965
SCIPUFF-IDM (full)	2019[3]	Jul-Oct	Summer	2,628	-220,460	-154,760				-154,760
	2019[4]	Jul-Oct	Summer	5,001	-184,325	-59,313	21,900		547,500	488,188
	2020	Mar-May	Spring	1,935	33,580	81,943				81,943
SCIPUFF-IDM (Daytime)	2019	Jul-Oct	Summer		25,915	25,915				25,915
	2020	Mar-May	Spring		62,415	62,415				62,415
SCIPUFF-IDM (non-negative)	2019	Jul-Oct	Summer	3,541	115,340	203,853				203,853
	2020	Mar-May	Spring	2,446	65,335	126,473				126,473

Notes: 1. Flux chamber data excludes beach area inaccessible for flux chamber sampling
2. WindTrax-IDM analysis excludes crusher emissions.
3. SCIPUFF-IDM results as reported in S3's Ice Breakup Report (summarised Appendix A.7).
4. SCIPUFF-IDM results as reported in S3's 2019 Final Report (summarised in Appendix A.6).

Annual Facility CO_2 equivalent (CO_2-e) emissions show significant scattering among alternative methods (**Figure 5**), even without the negative fluxes. The overall observations are:

- FC emission estimates are factors of 4 to 8 (or more) lower than IDM emission estimates and less than the EC estimate which appears to reflect emissions from a portion of the Pond only.
- The Facility-wide emission estimates using CALPUFF-IDM generally match the trend in quarterly production. Measurements are about 400,000 t CO_2e/year, with some scatter and a spring 2018 spike.
- The trend with time in WindTrax-IDM emission estimates is less consistent with FC measurements and the trend in production.

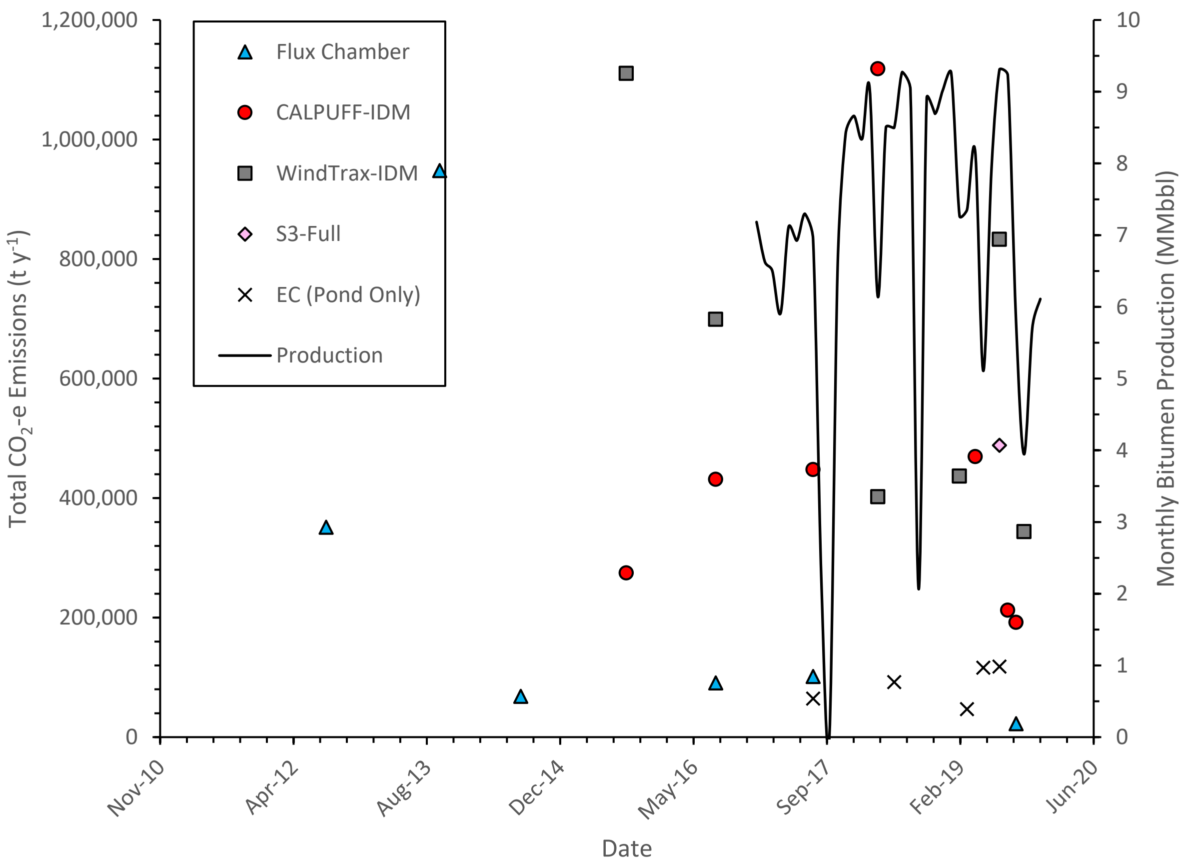

Figure 5: Annual Facility fugitive emissions in CO_2 equivalents (left axis) measured between 2012 and 2020. Methane was assumed to have a global warming potential of 25. Average Facility productions rates are also plotted as reported between 2015 and 2019.

The scatter observed in Figure 5 may be enhanced by the amplifications of uncertainties associated with mine emissions measurements after application of the 100-year CH_4 global warming potential of 25. The larger values estimated by IDM methods relative to FC are consistent with the greater spatial areas sampled by the IDM methods particularly in the pond where the beach is not safely accessible for measurement by FC. Larger values from IDM methods may also reflect other shortcomings of the FC method.

Pond CO_2 emission measurements (**Figure 6**) generally show better agreement among alternative measurement techniques and compared to FC measurements where available. The IDM methods resulted in emission estimates about three times higher than FC. Emission estimates among alternative methods are generally consistent beginning 2015, apart from a WindTrax-IDM spike in 2019[1].

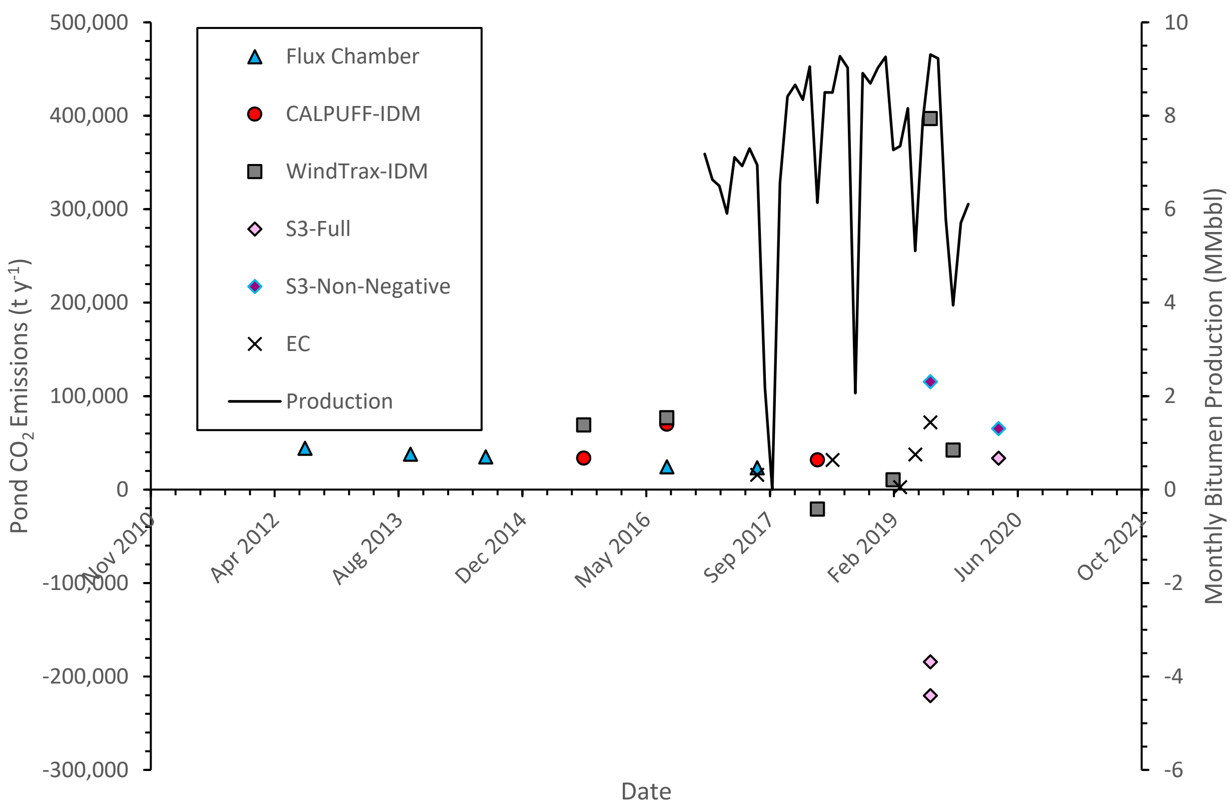

Figure 6: Annual Pond CO_2 emissions Measured between 2012 and 2020.

The CH_4 spike measured in spring 2018 (**Figure 7**), observed by CALPUFF and WindTrax IDM, appears to correlate with a slight increase in production; however, this spike was not observed by EC which measured in summer 2018 but did not fully sample the Pond area. The spring 2018 spike is discussed in a later section of this report.

Mine emission estimates from alternative flux measurement techniques correlated well with FC measurement data and to each other. For CO_2 (**Figure 8**), all were near zero, although WindTrax estimates varied more widely and were often negative. For CH_4 (**Figure 9**), FC measurements were near zero in all years (apart from a 2013 spike), WindTrax-IDM estimates were approximately constant with time, and CALPUFF-IDM estimates varied substantially and generally consistently with production.

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1. *According to the UofA, the summer 2019 rate was nearly 400,000 t CO2 /y. Two independent pieces of evidence corroborate the finding of historic levels of CO2 emissions. The first is eddy-covariance measurements taken at the tailings pond in the summer of 2017, 2018, and 2019 (the 2019 values were reported by the University of Alberta in a 31 March 2020 report to Canadian Natural by Trevor Coates). These measurements show that CO2 emissions in 2019 were more than double those from 2018, which in turn were more than double those from 2017. The second piece of evidence is the long-path laser measurements taken in August 2019 by the S3/AER group. An analysis of their data found that the pond plus beach emissions were equivalent to 145,000 t CO2 /y. This 2019 rate, although lower than the WindTrax-IDM estimate, is much higher than found in previous surveys.*

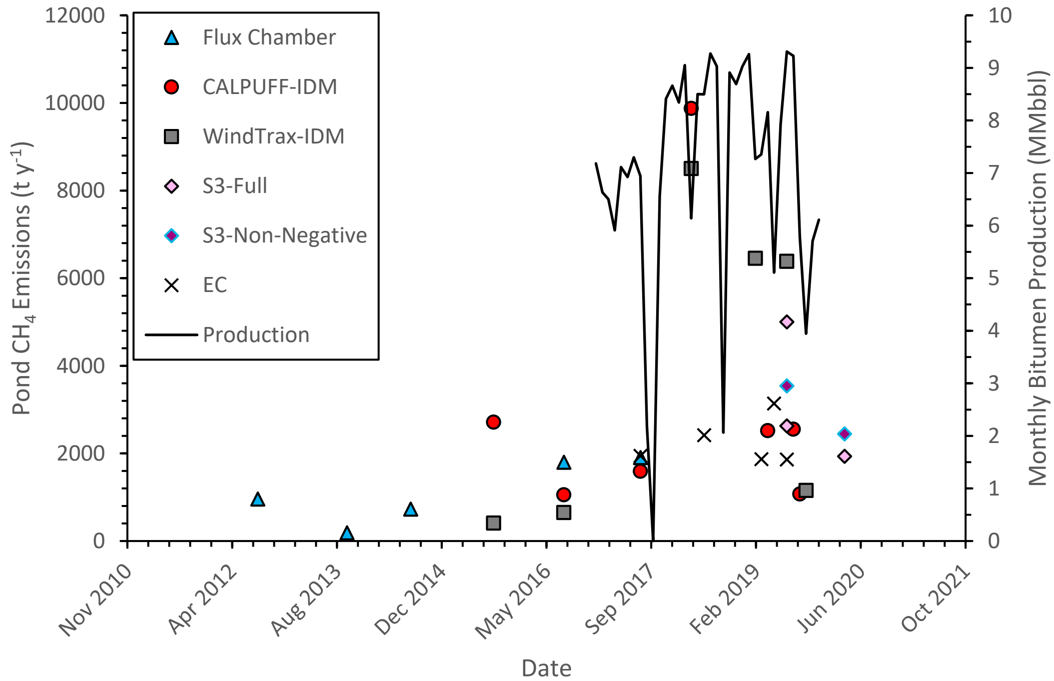

Figure 7: Annual Pond CH_4 emissions measured between 2012 and 2020

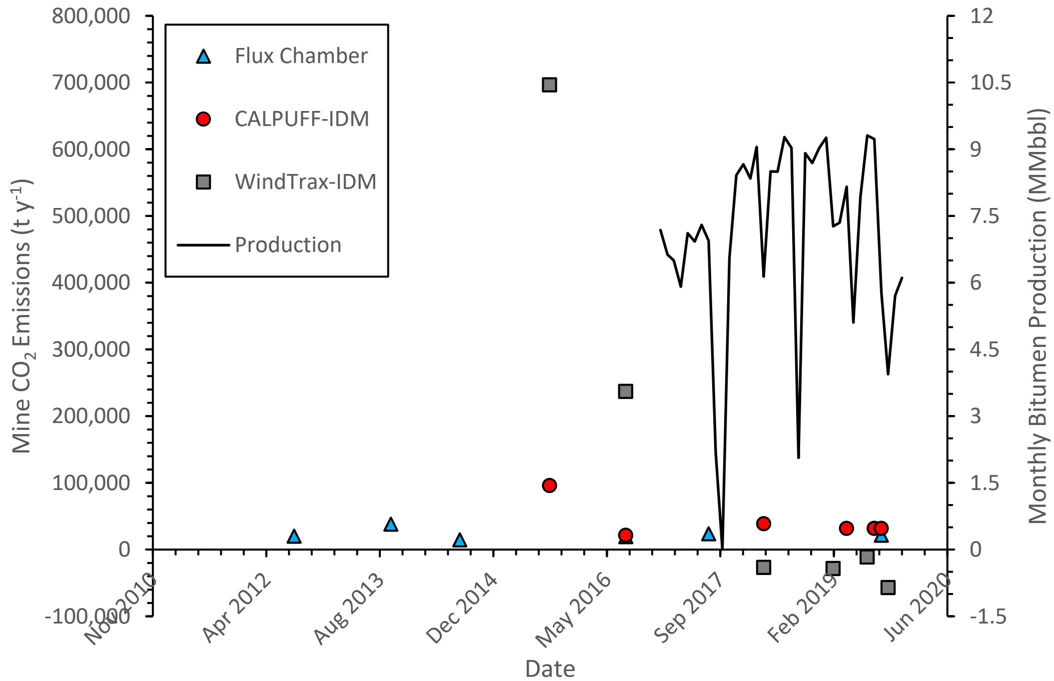

Figure 8: Annual Mine CO_2 emissions as measured between 2012 and 2020.

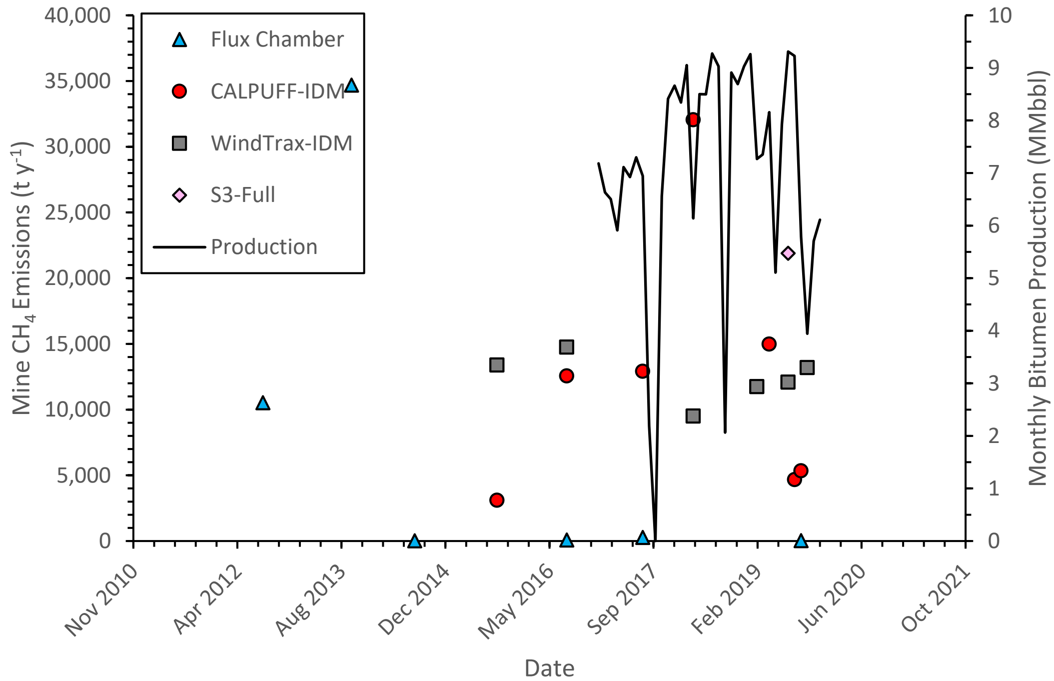

Figure 9: Annual Mine CH_4 emissions as measured between 2012 and 2020.

The non-zero IDM emission estimates were observed despite the CALPUFF IDM and WindTrax IDM methods estimating and subtracting the impact of mine equipment on CO_2 emissions observed downwind of the source. RWDI's approach to correcting for the mine fleet was to estimate concentrations due to the mine fleet at the sensors using a CALPUFF model run and subtracting these concentrations from field observations prior to carrying out the CALPUFF IDM analysis. The UofA computed average annual emission rates from the fleet and removed these from the computed mine surface fugitive emission rates. In both situations the mine fleet emission rate was based on fuel consumption rates from the fleet during the campaign period. WindTrax data indicated negative CO_2 fluxes in 2018 and 2019, inconsistent with estimates by FC and other alternate methods. CH_4 emission data from the Mine is less uncertain partially due to insignificant CH_4 emissions within the mine.

3.5.2 Qualitative Comparison to FC

The following subsections provide a broad comparison of the assessed methods abilities to meet the key assessment criteria relative to FC. The assessed methods will be discussed in three groups in relation to each of the assessment criteria: IDM, EC and AMB. The different IDM model implementations will be discussed relative to each of the assessment criteria. Although not successfully implemented at the Facility, the AMB method does provide a model free approach to assessing fluxes and was addressed in the comparison. Comparisons are summarized in Table 2.

Table 2: Comparison of Flux Measurement Techniques

	Flux Chamber	UofA Air Mass Balance	UofA Eddy Covariance	UofG WRF IDM	UofA WindTrax IDM	RWDI CALPUFF IDM	S3's GreenLITETM SCICHEM IDM
Direct Flux Measurement?	✓				×	×	×
Non-interference Technique?	×				✓	✓	✓
Continuous Monitoring /Ability to Monitor Temporal Trends?	×	✓				✓	✓
Deployable in Winter?	×	✓	×	×	×	✓	✓
Automated Field Collection	×	×	✓	✓	✓	✓	✓
Automated Real-Time Analysis	-	×	✓	×	×	×	×
Applicable in Complex Terrain (i.e., Mine)?	✓	✓	×	✓	×	✓	✓
Relative Cost* (per ERA project Proposal)	Low	High	Medium	Medium	Medium	Medium	Medium
Measurement Footprint	0.13 m^2	Drones: 1-2 km^2 Aircraft: >1-2 km^2	Up to 10,000 m^2 Dependent on tower size	> 10,000 m^2	> 10,000 m^2	> 10,000 m^2	> 10,000 m^2
Concentration Sensor Requirements	US EPA approved Flux Chamber	Ground based scanning equipment such as LIDAR. OR Fast response sensors for vehicle mounted equipment.	Adequate limits of detection Fast response (>10 Hz)	Adequate limits of detection (Minimum of two cross-calibrated instruments)	Adequate limits of detection (Minimum of two cross-calibrated instruments)	Adequate limits of detection (Minimum of two cross-calibrated instruments)	S3's GreenLite prototype laser absorption spectrometer (minimum one transceiver and one reflector)
Meteorological Sensor Requirements	-	-	3-D Wind Fast Response (>10 Hz)	-	3-D Wind	2-D Wind	3-D Wind

*Note: * Relative costs as calculated by project team and reported in Table 7 of the project Proposal.*

3.5.2.1 Inverse Dispersion Modelling

The strength of the IDM methods is their ability to provide an emission estimate, reflective of the average area source emissions, with a minimum of two concentration measurement sensors and one meteorological tower.

Choice of sensor is non-specific (unless implementing S3's proprietary approach) and concentration sensor requirements are limited to the need to differentiate between a non-zero background and the enhanced concentrations downwind of the source. Implementation of multiple sensors and/or reflectors adds the ability to monitor fluxes from different wind directions and reduces the time required to collect adequate field data. The multiple sensor approach though does drive up implementation costs and may not be needed if a predominant wind direction can be defined and/or sensors are to monitor for longer periods of time. The lack of specific sensor requirements also enables the possibility to implement weatherproofed instrumentation capable of continuously measuring throughout the year.

Emission estimates obtained with IDM models are highly uncertain and generally do not account for uncertainties associated with model implementation. A recent study by the Co-operative Institute for Research in the Environmental Sciences (CIRES) which implemented a HYSPLIT IDM approach to estimate emissions from a CEM monitored stack supported uncertainties on the range of 30-40% for IDM (Angevine 2020).

Nonetheless, all IDM models were able to provide spatially resolved emission estimates from subregions within the pond (including the beach area) and mine. CALPUFF and SCICHEM approaches to subregions were more sophisticated than those provided by WindTrax and substantially more sophisticated than the four subregions per area source treatment provided by WRF.

WRF IDM appeared to provide the least utility in that the demonstrated analysis was unable to provide accurate numbers to the extent that model results were only reported normalized. Normalized values were indeed able to track diurnal trends, but this appears to be of little utility for quantification if absolute values are not known. Additionally, the lack of appropriate background treatment in the model and need to recompile every four hours calls into question the value provided by the measurement in its current form.

WindTrax, CALPUFF and SCICHEM (S3) IDM all provided absolute emission rate estimates with generally reasonable agreement (considering inherent method uncertainties) for the Pond (Figures 5 and 6). Less certain is the agreement when considering the sum of fugitive emission sources (Figure 4) or mine emissions (Figures 7 and 8).

3.5.2.2 Eddy Covariance

EC is a well-established technique with fully automated commercial solutions available. The strength of the technique lies in the fact that a single tower of sufficient height (higher towers are required for higher area source) with fast response mounted within a flat area source could potentially achieve >80% pond coverage in its measurement. Once in operation the technique can ultimately provide an interference free measurement and the ability to monitor temporal trends.

Mounting a tower within a pond area source would however create logistical difficulties when regular maintenance and/or repairs are required. Additionally, if full area source coverage is required and/or mounting within the area source is not an option, multiple towers would need to be installed. Coupled with the necessity for fast response concentration and wind sensing instrumentation and the high cost of sufficiently high towers, technique implementation can be costly.

A major drawback to EC implementation relative to FC is fundamental assumptions that limit its implementation in complex terrains such as the mine. Additionally, the requirement for footprint modelling (if choice of tower siting is not ideal) can reduce the ability to automate the measurement and adds computational time constraints and uncertainty to the measurement.

3.5.2.3 Air Mass Balance

AMB was not fully implemented at the facility due to the inability to get clearance to fly drones or the capability to fly the long flight paths necessitated by the large size of the fugitive area source being studied. The size of the fugitive area sources makes implementing a ground based AMB method such as LIDAR extremely difficult. Nonetheless, AMB can provide a model-free direct assessment of fugitive area source emissions if implemented. The direct measurement would be fundamentally more accurate than EC or IDM; however, the longer flight paths necessitated by the size of the ponds (on the order of several kms long) would likely lead to issues with identifying a consistent and appropriate background and excluding other emissions sources (within the facility itself or at neighbouring facilities). The longer flight paths would also lead to considerably higher costs due to the necessity to implement larger planes or more sophisticated drones. The long flight paths with unmanned drones would also carry the drones far enough from the done operator and would require special flight clearances and considerations.

An additional factor limiting the utility of AMB for use with fugitive emissions sources is the inability to monitor continuously. By its nature, AMB provides snapshots similar to those provided by FC and would not enable diurnal and/or other temporal trends to be easily examined. Similarly, nighttime implementation of aircraft mounted AMB would be challenging to implement and is not typically feasible. The lack of the ability to monitor temporal trends and the high cost associated with AMB make currently implementations low value relative to other potential options.

4. Discussion

4.1 Technique Advantages and Disadvantages

4.1.1 Eddy Covariance Method

The Eddy Covariance Method is a well-established measurement method that has been used extensively for area source emissions studies, particularly from agricultural sources. The method was deployed by the University of Alberta at the Tailings Pond at the Horizon site from June to August 2018, and March to November 2019. The method utilizes a fast-response open-path methane analyzer, a CO_2/H_2O analyzer, and a 3-D sonic anemometer mounted on a pole approximately 14 m above the ground.

4.1.1.1 Advantages of the Method

The instrumentation utilized for the Eddy Covariance Method is robust, fast-response, and with minimal power requirements. The instrumentation is well-suited for long-term, continuous monitoring, as data can be collected unattended, and instrument status can be monitored remotely. Data are collected at one location, with no need for an upwind/background measurement. The Eddy Covariance calculation of flux values is straight-forward, with the University of Alberta reporting that this calculation was done in real-time using the system datalogger.

The method is appropriate for characterizing emissions from relatively large area sources, although the upwind footprint of the area contributing to pollutants measured is dependent upon the height of the instrumentation above the ground, among other factors.

4.1.1.2 Limitations of the Method

The main limitations of the Eddy Covariance Method are related to characterizing the upwind footprint contributing to the concentration of pollutants measured (e.g., which portion of the surface area of the pond is contributing to the concentration and subsequent emission flux values).

For a portion of the measurements at the Tailings Pond, the Eddy Covariance instrumentation was deployed some distance from the edge of the Tailings Pond (approximately 200 to 500 m from the shore of the pond). During this initial deployment, the footprint contributing to the flux included a large fraction of the land area (according to the University of Alberta, about 30% of the total emissions footprint). During later periods of the measurement campaign, the location of the Eddy Covariance measurements was moved much closer to the shore of the pond, so this issue was largely eliminated. However, the challenge of trying to determine the exact location and dimensions of the upwind footprint contributing to the pollutants measured remained. An analysis of the emissions footprint is done utilizing software available from the instrument manufacturer. By all indications, the software is easy to use in providing the location and dimensions of the upwind footprint. However, this analysis adds uncertainty to the final emissions flux values.

According to an analysis included in the final report from the University of Alberta, the Eddy Covariance footprint retrieved using the vendor software showed that only about 25% of the total pond surface area was sampled by the Eddy Covariance instrumentation deployed closest to the pond shore. Sampling such a small percentage of the total surface area of the pond brings into question the representativeness of the emissions calculated and adds additional uncertainty to the data results. As part of their final report, the University of Alberta team suggested an alternate measurement configuration for future measurement campaigns consisting of one or two Eddy Covariance stations deployed in the middle of the Tailings Pond. While this approach would certainly address the issues of surface area coverage and representativeness of emissions measurements from the pond, it seems that logistically, it would be extremely difficult to deploy and maintain the instrumentation in these locations.

Another consideration of the Eddy Covariance Method is that the flux calculation is not valid under complex wind flows. While the method is appropriate for deployment at sites such as the Tailings Pond with relatively flat and simple terrain, the method could not be utilized for emissions measurements at locations with complex topography (e.g., the mine sites where the complex topography affects the wind flow).

4.1.2 IDM Method with Point Sensors

An Inverse Dispersion Modelling (IDM) approach using portable, fixed-point analyzers (Los Gatos Research, Mountain View, CA) was utilized to perform emissions measurements at the Facility during four field campaigns conducted in 2018 and 2019. Upwind background concentration data were collected at each source. The concentration data and wind data collected onsite were input into an IDM model. The model was then used to generate an emission rate from the source that would result in the downwind concentration value observed by the analyzers. For the current study, the University of Alberta utilized the WindTrax model for the emission rate calculations.

4.1.2.1 Advantages of the Method

IDM approaches have been historically utilized for emissions surveys in several applications, so the method is mature and well-documented. The Greenhouse Gas analyzers used for the current study are robust and easy to use. IDM-based approaches are cost-effective, with modest labour requirements for deployment of instrumentation, especially considering that the instrumentation is capable of collecting data unattended for long periods of time.

IDM approaches can be used to characterize emissions from very large measurement footprints, such as the Tailings Pond and open-pit mine sources that were the focus of the current campaign. The accuracy of the emissions results from IDM approaches has been documented for sources with simple terrain subsequent wind flow patterns. It is likely that the IDM approach can be applied successfully to area sources with more complex topography and wind flow patterns; however, applications at these sites would certainly introduce additional uncertainty to the emissions results.

4.1.2.2 Limitations of the Method

One limitation of any IDM approach is that it requires a measurement upwind of the source (background), as well as a measurement downwind of the source. This can be problematic when trying to characterize a pollutant with a naturally occurring high background concentration, especially if the source of interest exhibits low emissions of the pollutant, with respect to background concentrations.

Another challenge when employing an IDM approach is attempting to isolate emissions from the source of interest, especially if there are additional potential sources located within the large measurement footprint.

As mentioned in the previous section, IDM has been well-documented as a viable approach for characterizing emissions from sources with simple terrain and simple wind flows in the vicinity of the source. However, the performance of IDM in accurately characterizing emissions from sources with complex terrain and resulting complex wind flows is less clear.

4.1.3 GreenLITE™ with SCICHEM Model

GreenLITE™ is a measurement system developed by Spectral Sensor Solutions (S3) that utilizes laser absorption spectroscopy to perform open-path measurements over large measurement paths. The measurement paths are defined by the laser transceiver (located at one end of the path) and a retroreflecting mirror (located at the other end of the path). The instrument yields a path-integrated concentration value of the pollutant of interest over each measurement path. For the current study, the GreenLITE™ system was deployed at both the Tailings Pond and the East Mine. The length of the measurement paths varied from approximately 450 m up to 5 km. Measurements were conducted at the Horizon site during the summer and fall of 2019. S3 utilized the SCICHEM coupled with concentration measurements from the GreenLITE™ system to calculate emission rates from the Tailings Pond and East Mine.

4.1.3.1 Advantages of the Method

The GreenLITE™ system is a robust system, that is based on well-established measurement technology, and is capable of continuous data collection. The measurement path lengths used in the current study were as long as 5 km, ensuring that a much larger portion of each source was sampled when compared to point sensor-based approaches.

The advantages of the SCICHEM dispersion model are similar to the IDM approach discussed in Section 5.2.1.

4.1.3.2 Limitations of the Method

Deployment of the GreenLITE™ system is more labour-intensive than the effort needed to deploy other instrumentation used in the current study. At the Tailings Pond, 2 transceivers and 6 retroreflectors on tripods were deployed. At the East Mine, a total of 2 transceivers and 15 retroreflectors were deployed. Each instrument /retroreflector was fastened to concrete blocks that had to be strategically placed by onsite contractors.

The limitations of the SCICHEM dispersion model are similar to those discussed previously in Section 5.2.2.

4.1.3.3 Air Mass Balance Method

The Air Mass Balance Method involves placing an imaginary volume over a pollutant source while conducting measurements at differing heights above the source. In simplified form, the flux is given by the product of the measured concentration and the wind flow across the downwind face of the imaginary volume. The measurement method is executed using a mobile platform (such as drone or aircraft) with a gas sensor and meteorological instrumentation attached. The mobile platform is flown along a flight path perpendicular to the prevailing wind direction. Flight paths are performed at varying heights above the downwind face of the area being surveyed. The product of the path-averaged concentration and wind velocity yield an emission flux for each height surveyed. The emission flux values are integrated vertically to yield the total site emissions.

4.1.3.4 Advantages of the Method

The Air Mass Balance Method is a viable technique for calculating emission flux values from an area source. The flux calculation is straightforward and simple, especially if the mobile sampling platform is flown perpendicular to the prevailing winds. The method requires measurements from only 2 instruments, the pollutant and meteorological sensors, and is capable of characterizing emissions from relatively large sources.

Another advantage of the Air Mass Balance approach is that it is a standoff measurement, so deployment of instrumentation within, or close to the emissions source is not necessary.

4.1.3.5 Limitations of the Method

One limitation of the Air Mass Balance Method deployed with a drone-based platform is that selection of instrumentation may be limited due to the payload capacity of the drone. In addition to the instrumentation, the user must consider the added weight from the power supply (e.g., batteries) or other ancillary equipment.

Data collection via drone flights is relatively easy if the wind conditions remain constant for the duration of the measurements. However, changes in wind conditions over time, or with height, would necessitate changes in the flight plans, which may need to be re-planned mid-survey.

Another major limitation of the drone-based measurement platform involves the horizontal and vertical extent of the measurement paths. This would not be an issue while surveying a relatively small source. However, the original plan for the current study was to utilize a drone-based measurement system to survey the Pond with dimensions 2 km by 7 km. The University of Alberta report estimates that in order to ensure sufficient horizontal plume capture, the measurement faces would have to be a minimum of 7 km to 9 km long, depending on the prevailing wind direction. Flight paths this long would exceed the current legal limits of basic drone operation and would necessitate seeking additional approval to fly the drones along flight paths with these dimensions. Similar limitations exist when considering the vertical extent of the flight paths needed to ensure sufficient vertical capture of the plume. The dimensions of the mine pits at the Horizon site are even larger than the Pond, so the drone flight limitations would be even more prohibitive to conducting measurement surveys in these areas.

4.2 Measurement Uncertainty

The Flux Chamber (FC) Method is currently the most commonly used regulatory method for characterizing fugitive emissions from area sources at oil and gas sites. The limitations of the method are well-documented, including the potential to alter the actual emissions from the source through the sampling procedure, and the very small footprint of the emissions measurement when compared to the area of the source being surveyed.

The overall goal of the current project was to demonstrate and evaluate alternative measurement methods for conducting emissions surveys at oil and gas sites. In performing the evaluation of the alternative methods, one of the elements that AECOM assessed was the standard error of the results from the alternative methods, when compared to the FC approach. With all of the methods used for estimating emissions from the Pond and mines, the uncertainty in the data results is from two primary sources: 1) the instrumentation used to perform the direct measurements in the field; and 2) the method used for calculating the emission flux values using the data collected.

AECOM reviewed several interim and final reports submitted by the study participants, a limited amount of FC emission results from the site (Section 1.2 of the University of Alberta Final Report). Figure 1.2 from the University of Alberta report presents a comparison of annual CH_4 emission results from the Pond determined with the FC and IDM methods. Not surprisingly, the standard error of the FC results was significantly larger than the error associated with the IDM approach. Figure 2.4 of the University of Alberta report presents CH_4 and CO_2 emissions results from the Eddy Covariance method. The standard error values shown in this figure are also significantly smaller when compared to the uncertainty in the FC results shown in their Figure 1.2.

The larger error shown in the FC results is most likely due to the extremely small percentage of the surface area of the pond actually sampled by the FC measurements (amplified by the fact that the Pond is a non-homogenous source), and the fact that the FC sampling represents a snapshot in time, unlike the continuous measurements collected with the IDM and EC methods.

4.3 Cost Considerations

AECOM performed a cost analysis of executing the FC method for emission measurements, as compared to the costs associated with the other alternative methods. In performing this analysis, we considered the costs of procurement of instrumentation, labour costs associated with onsite deployment of instrumentation, any potential outside laboratory costs, and data analysis costs. We then looked at the cost comparison from the standpoint of cost per data point.

Because AECOM does not have access to the actual costs of some of the instrumentation used in the current study, level of effort needed for field deployment and post-data analysis, or labour rates for staff members, this comparison should be considered a high-level analysis.

An estimated cost for an annual monitoring program at an oil and gas facility using the FC method is approximately $300,000 to $400,000 per year (based on approximately 250 flux measurements in ponds and mines). While the upfront capital costs for equipment expenditures necessary for the FC is certainly less than the other alternative methods, the labour costs for field personnel and laboratory analysis costs are significantly higher than the other methods. Scaling this cost estimate to the number of flux measurements conducted, the approximate cost of a flux measurement utilizing the FC method is approximately $1,400/flux measurement.

As mentioned above, the upfront capital costs associated with the instrumentation required to deploy the other alternative methods is almost certainly higher than the instrumentation needed for the FC method. However, after initial deployment, the alternative methods are each capable of collecting data continuously and largely unattended (with the exception of the drone-based approach). Additionally, the post analysis costs are almost certainly lower than the FC method, as there is no need for analysis of samples by an outside laboratory.

Without having access to information on the costs of instrumentation and level of effort associated with conducting measurements with the alternative methods, it is difficult to provide an estimate of cost per sample. However, the S3 report states that over 200,000 methane and CO_2 data points were collected with the GreenLITE™ system during the 2019 field campaigns, which is significantly larger than the number of flux measurements retrieved annually as part of a FC-based measurement program.
Cost is but one component of the assessment summarized in Table 2.

4.4 Are Any of the Techniques Better Than or Equivalent to Flux Chambers?

Fugitive GHG emissions from the oil sands region carry a large amount of uncertainty. For example, a study by Liggio et al. (2019) showed that area-fugitive CO_2 emissions from open-pit mines measured by an aircraft deviate by 13 to 123% of those estimated from emission inventory datasets (inventories are largely complied based on emission factors and activity data). Similarly, Baray et al. (2018) showed that the measured hourly CH_4 emission rate in the Athabasca Oil Sands Region, which was found to be largely due to fugitive emission sources (45% due to tailings ponds and 50% due to open pit surface mining), was 48 ± 8 % higher than emissions estimated from emission inventory datasets (datasets largely developed with FC data during the study period). Similarly, a study by You et al., (2020 – currently under review and in open discussion) which attempted to measure methane emission from an oil sands tailings pond using FC, EC and WindTrax IDM found that FC underestimated flux measurements by a factor of two relative to alternative methods in their assessment. Furthermore, Angevine et al. (2020) associate 30-40% uncertainty with IDM approaches, supporting the observation that all methods contain shortfalls in design, or execution, or analysis.

Although alternative flux emission measurement accuracy is uncertain, alternatives to the FC method are fundamentally better at estimating a flux rate more representative of the entire area source surface. Unless an unrealistically large number of FC measurements are made, the FC method's inherent small sampling area and need to extrapolate over the surface of the mine can be problematic. A well- documented case at Canadian Natural from 2013 was particularly striking as two outlier measurements by FCs in the mine accounted for 99% of emissions and was the impetus for this ERA-sponsored work. The larger area sampled by alternative IDM based methods may not suffer from such extrapolation issues.

Assuming relatively accurate estimates, the lack of ongoing flux measurements onsite during the project creates a lack of consistent long-term reference data for comparison, if one goal of the ERA-funded study was to provide a credible alternative to the AEP-approved method. For Pond emission rates, alternative methods appear to correlate well with flux chamber emission rates when they were present (2015-2017). The presence of flux chamber emission rates would have been particularly useful for validating the spring 2018 spike in Pond CH_4 emissions addressed in Section 4.5.1 below.

In the case of the Mine, FC data did not appear to trend well with alternative flux measurement techniques, possibly due to the additional uncertainty associated with IDM modelling over the complex terrain of the mine, and the inherent inability of WindTrax to address the complex terrain in the mine, Nonetheless, IDM has the advantage of providing emission estimates for large area sources without disturbing the measurement environment, allows the use of any number of gas monitoring equipment and the ability to choose safe and convenient measurement/sampling locations. Additionally, any number of atmospheric transport and dispersion model with appropriate capability to model the winds and turbulence downwind of an emission source may be utilized. This versatility in terms of instrumentation and model deployment alone makes adoption of IDM as an alternative flux measurement option attractive.

4.5 Did Emission Rates Exhibit a Seasonal Dependence?

One of the goals of the study was to measure emissions from the pond and mine surface during colder temperatures to note any observed temperature or seasonality related trends in emission rates. Emission rates from the study period were averaged by season (**Figure 10** and **Table 3**). No clear seasonality or temperature related trend was observed.

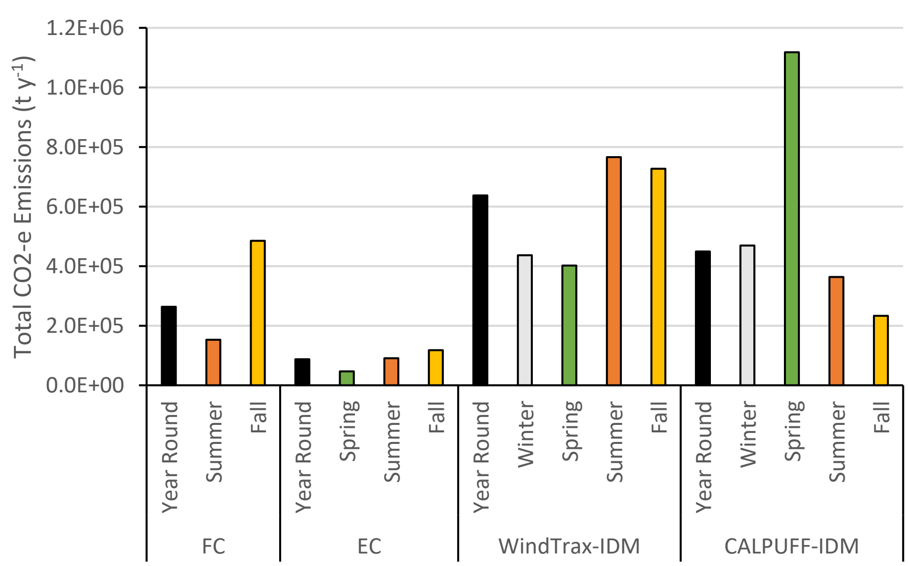

Figure 10: Annual Facility CO_2-e Emissions as Observed in Different Season by the Flux Chamber, Eddy Covariance, WindTrax-IDM and CALPUFF-IDM Methods

Table 3: Summary of Emission Estimation Data Averaged by Season

Method	Season	Number of Points Averaged	Annual Emissions (t y^{-1})						
			Pond			Mine			Total
			CH_4	CO_2	CO_2-e	CH_4	CO_2	CO_2-e	CO_2-e
Flux Chamber	Year Round	6	1,115	32,913	60,798	7,603	22,879	212,950	263,616
	Summer	4	1,348	31,657	65,345	2,725	19,408	87,533	152,879
	Fall	2	187	37,937	42,612	17,359	29,821	463,784	485,090
Eddy Covariance	Year Round	5	2,246	31,915	87,433				
	Spring	1	1,867	2,546	46,671				
	Summer	3	2,500	28,375	90,867				
	Fall	1	1,862	71,905	117,895				
WindTrax-IDM	Year Round	6	3,925	95,668	193,785	12,440	134,899	443,552	637,408
	Winter	1	6,453	10,220	171,545	11,738	-28,470	264,980	436,540
	Spring	1	8,500	-21,000	191,500	9,500	-27,000	210,500	402,000
	Summer	2	3,516	236,813	324,713	13,412	112,811	441,070	765,969
	Fall	2	782	55,581	75,119	13,289	319,622	651,847	726,984
CALPUFF-IDM	Year Round	7	3,053	45,003	95,616	12,226	41,812	341,500	449,245
	Winter	1	2,520		63,000	14,980	31,740	406,240	469,240
	Spring	1	9,873	31,690	278,515	32,045	38,500	839,625	1,118,148
	Summer	3	1,731	69,797	66,549	10,044	26,504	268,761	363,610
	Fall	2	1,893	33,523	64,074	4,215	63,813	169,175	233,249

Figure 10 presents annual facility CO_2-e emissions as estimated by FC, EC, WindTrax-IDM and CALPUFF-IDM in different seasons. The limited FC and EC data indicate maximum facility emission rates in the fall, noting the lack of spring observations by FC and the lack of winter observations by either EC or FC. WindTrax-IDM data shows the strongest emissions in the summer months with similarly strong emission rates in fall relative to lower emissions observed in winter and spring ((~50% of Summer). Conversely, CALPUFF-IDM appears to show a very strong springtime emission maxima that is three times the next highest emission rate observed by CALPUFF-IDM. The CALPUFF-IDM data are heavily skewed by a spring 2018 emission rate spike (discussed in greater detail in Section 4.5.1 below). If the spike is excluded, the spring emission would be similar to other seasons.

A consistent seasonality or observed temperature dependence across the various emission measurement techniques may be hidden by the high relative uncertainty in estimation. Each of the different emission estimation techniques offers an emission estimate that is highly uncertain, and which is compounded once pond and mine emissions are combined into a facility wide emission estimate. As such any seasonality or temperature dependent trends are likely lost in the scatter present in the data.

4.5.1 Spring 2018 Spike in Pond CH_4 Emissions

An anomaly in the data observations made during this study period was the spring 2018 spike in pond CH4 emissions. As measured by the CALPUFF-IDM method the spring 2018, CH_4 emissions were found to represent 8,500 t/year, a value nearly four times higher than the equivalent value measured in 2017 and three times higher than the previous pond maxima in 2015. Although no previous springtime data had been collected this spike was corroborated by high CH_4 emission rates as observed by WindTrax-IDM. The spike was not followed by elevated summer 2018 emission rates, as measured by EC, indicating that a more specific source caused the spring spike in emissions.

The spike was counterintuitive as warmer summer months and warmer pond waters are typically expected to be associated with higher emissions as a result of an expected increase in the activity of methanogenic bacteria along with a decreased ability to solubilize and contain dissolved gases. RWDI posited two potential ice breakup related causes at the time:

1. Ice breakup during spring opens up the effectively isolated pond to wind induced waves and solar heat gain. The result of this ice breakup is presumably rapid temperature increase and a well-documented "pond turnover" that leads to more effective release of dissolved CH_4 and nutrient cycling which can lead to a spike in methanogenic bacterial growth. Measurement would have to have occurred during or immediately after such a turnover event.
2. Cold water and ice inhibit the microbial break-down of bitumen and other organic substances during winter, allowing the buildup of substrate on the pond surface. Ice melt and the following rapid warming of the surface layer causes a burst of microbial activity to rapidly breakdown the built-up reservoir of substrate at the pond surface until the reservoir is depleted.

Although a combination of the two posited ice-breakup related explanations may have led to the spring 2018 spike in pond CH_4 emissions no such spike was observed in spring 2020 by S3's GreenLITE-IDM. This indicates emissions may have been caused by an alternative source, although Canadian Natural indicated that some of the activities in the mine during the spring field survey, such as melting of ice and snow, thawing of the surface, and pumping of basal water into injection wells in the northern area, were not abnormal events for that season. Tests with the IDM model did not identify basal water injection as a significant source.

A spring spike was not measured in 2020 even though S3 measured pond emissions for the full duration of the anticipated springtime ice breakup (March 13 - May 31). One potential reason for the discrepancy between spring 2018 and spring 2020 is a warmer April (coinciding with RWDI's spring 2018 measurements). Per Environment Canada's historical weather data for Fort McMurray April 2018 had an average temperature of -0.3°C, a maximum temperature of 25.3°C and a low of -24.8°C. This may have contributed to more rapid pond warming and ice breakup than spring 2020 where April temperatures averaged -1.1°C, had a high of 20.4°C and a low of -30.7°C.

What is clear from the pond methane spike in spring 2018 is the inability of a single measurement campaign to accurately reflect annual emission rates. The methane spike highlights the added uncertainty associated with extrapolating an emission rate measured by a single flux measurement campaign taking place over several days, regardless of emission estimation methodology, to accurately represent actual annual emissions once extrapolated to the entire year. To reduce the likelihood of anomalous data grossly skewing annual emissions multiple flux measurement campaigns within a given year could be conducted. Alternatively, when concentrations or emissions are seen to be anomalous in real time data, further investigation must be carried out immediately to ascertain the validity of the data, and if found to be valid, to determine the spatial and temporal extent of the anomaly.

4.6 Is There a Measurement That Can be Captured Easily and at Minimal Cost That is a Good Proxy to Direct Measurement?

Although no clear winner emerged from the project, two clear techniques appeared to offer the most value. For simple terrain applications and over small areas the EC method provides the most value and utility. Commercially available, fully automated EC solutions are available capable of providing defensible emission estimates. The changing spatial extent of emitting sources however, coupled with the potential need for EC footprint modelling complicates EC implementation. An IDM based solution (i.e., WindTrax or similar modelling systems adequate for simple terrain) appears to be the most promising.

At the complex terrain at the mine, IDM solutions that employ valid modelling frameworks that can accommodate complex terrain (i.e., CALPUFF or SCICHEM) appear to be the most promising. Unlike EC though, IDM approaches are less mature, slowly undergoing iterative progress and refinement (as was the case for the models in this study) and have yet to be optimized nor automated. Where instrumentation costs are of concern, the placement of a limited number of point measurement sources in upwind and downwind location appears to be the most cost-effective method of applying IDM.

In short, there appear to be no measurements, and none of those in the current ERA-funded project, that meet this criterion.

4.7 Is More Instrumentation Needed to Provide Sufficiently Accurate Measurements (and How do We Determine Sufficiency?)?

IDMs main limitations are in the instrumentation required to provide a truly continuous measurement. Unsuitable wind directions that carry the gas plume away from monitoring instrumentation or insufficient wind such that the plume spread cannot be reliably modelled lead to exclusion of certain measurement periods from analysis. Low winds create conditions which are inherently more uncertain to assess with IDM models however wind directions can be addressed with additional instrumentation placed strategically around the mine. Strategic instrumentation placement, be it point source or path integration, in such a manner to capture simultaneous background and downwind conditions during winds from multiple directions would greatly improve usable data capture and would reduce the length of a fully representative field campaign. The exact number of additional sensor locations and the effectiveness of additional sensors is a function of a given area sources terrain complexity, the likelihood of unusable calm winds and the presence, or lack thereof, of predominant wind direction. Nonetheless, where longer term monitoring is of interest, two sensors placed in the predominant downwind and upwind directions would be more than sufficient. Such a two-sensor deployment could be chosen if year-round monitoring were implemented. Alternatively, as technology evolves to improve detection levels, a number of inexpensive continuous methane or CO_2 sensors operating on solar power and ringing the sources of interest could significantly improve spatial coverage to support IDM approaches.

Path integrated techniques, such as S3, do not require additional transceivers but simply reflectors placed at various locations along the mine site. Additionally, the information contained within path integrated chords across the surface of the emissions source is inherently more representative of emission conditions than a measurement collected at a point source downwind. Furthermore, the ability to deploy two transceivers and create chord/path length overlaps, further increasing knowledge of emission profiles above the emitting surface is not possible with point source measurements. Ultimately the need for such a complicated setup would need to be demonstrated and insufficient data has been presented yet to indicate the need for the additional instrumentation.

For IDM in general, where REVEAL, or a similar system is not implemented, collocation of meteorological monitoring equipment with background collections sensors is non-ideal. Winds measured over the source itself or downwind are more representative of conditions at the emitting surface. This is particularly important when dealing with the complex terrain of the mine or potential effects of the pond.

As mentioned in preceding sections, the inability for the EC method to accurately account for the complex terrain such as that present in the mine greatly limits its utility. Nonetheless, relatively flat area sources such as that provided by the surface of the Pond can be appropriately addressed by EC. Per the UofA's Dr. Flesch's estimation, the placement of a single EC tower of sufficient height in the centre of the pond could potentially lead to sufficient coverage of the entire pond and would be deployable for both short term and long term accurate monitoring of Pond emissions. Where shorter towers are warranted, and more complete pond coverage is required, Dr. Flesch's recommendation is for two equally spaced towers centred on the north south centre line of the pond. The main drawback to implementation of EC within the Pond's footprint are logistical; however, automation reduces the need to service the EC towers on a regular basis.

In the case of AMB, the method would be able to accurately measure emissions from source characterized by both simple and complex terrains however this measurement would be a snapshot measurement. The snapshot nature of the measurement would mean that much of the diurnal and seasonal variability would go unnoticed. To identify whether AMB deployments are representative would require additional AMB deployments which are inherently costly at the scale of the Horizon Pond or Mine Pits.

4.8 Background Correction

Background correction was required for all flux measurement techniques assessed. In the case of EC, the need for such correction may be reduced by choice of location removing the need for flux footprint computation. AMB requires that the upwind flux be calculated and subtracted from the downwind flux. IDM requires background concentrations be measured and subtracted from downwind measurements prior to emission rate assessment.

The ability to assess and correct for background concentrations appeared to be a major hurdle and source of uncertainty for the IDM flux measurement techniques whose ability to distinguish between background and area source enhanced concentrations is fundamental. For IDM this is generally tied to the instrumentation's ability in terms of both limits of detection and precision to pick up on small enhancement above a variable background. As indicated in Section 3.2 RWDI reported the CH_4 background was found to be ~2 ppm with ΔC up to 0.2 ppm. In the case of CO_2, the background ranged from 400-500 ppm, with a diurnal variation as large as 140 ppm, and a ΔC up to 30 ppm. Instrumentation options capable of tracking the small concentration enhancement are available but the subtraction in itself adds substantial uncertainty to modelled results. This was apparent in the data presented by the UofA (Table 3.1 of the final report) that showed that in some cases sensor precision limits (when subtracting data) were not sufficient to resolve the enhancement above background. This may be augmented by the limited capability of ponds with algae to absorb CO_2 and adds uncertainty to emission rates computed with such data.

Additionally, data impacted by nearby emission sources (not sampled by background measuring instrumentation) need to be removed from data prior to application of any post processing. This can generally take the form of data filtration (typically by wind direction) but is less trivial when the impacting sources on the surface of the area source itself as is the case with mine equipment emissions. In the case of these mine emissions fuel consumption numbers were used to compute average emissions rates which were used to correct final area source emission rates. The correction process further adds uncertainty to emission estimates.

4.8.1 CO_2 Background Correction

In the case of CO_2 background correction was particularly non-trivial. Diurnal variability in CO_2 concentrations was caused by natural activity occurring in the heavily forested areas west of the site (in the predominant upwind direction). The natural fluxes, which themselves are expected to exhibit diurnal and seasonal variability created large regional concentration gradients. RWDI reported situations where nighttime enhancement of the CO_2 background caused downwind instrumentation to measure lower concentrations than upwind stations. Conversely, the concentration gradient during the day would be expected to bias downwind concentrations upward.

The natural fluxes add considerable uncertainly and make true background concentration measurements of CO_2 difficult. This would especially be problematic in AMB implementation where the virtual bounding box needs to extend well beyond the extent of the assessed area source. The fluxes also call into question the ability of a single upwind station, particularly one employing a point source, to measure the true background upwind of area sources the size of the Horizon Pond or Mines.

4.9 Is the Mine Face Under-sampled? If Yes, How Can This be Practically Improved?

IDM approaches applied to the mine did not appear to under sample the mine surface. All IDM applications, with the exception of WRF IDM, did a reasonable job in estimating emissions from various sub regions within the Pond (including the beach) and Mine Pits. Comparison of regions with the highest emission rates in both the Pond and Mine indicated reasonable agreement although exact agreement of highly emitting regions was not possible due to the different size, shape and distribution of subregions between the models.

Of note, the extrapolation back to surface emissions from a point source measurement downwind of the area source to the surface of the area source (as was the case with CALPUFF and WindTrax IDM in the reviewed work) is inherently more uncertain than extrapolation to an above surface chord. Additionally, the chord above the surface provides additional spatial data for more refined regional analysis of the area source without solely relying on the ability of the employed model to accurately model dispersion from the various subregions of the area source.

5. Summary and Recommendations

In preparing this evaluation report, AECOM reviewed several interim and final reports submitted by participants in Canadian Natural's greenhouse gas emissions measurement project. The reports summarized the measurement techniques employed by each participant, the measurement configurations utilized in the field, the method used for emission rate calculations, data, results, and assumptions and challenges encountered.

While performing the reviews, AECOM considered the following for each measurement approach:

- The applicability and performance of the instrumentation used for the measurements
- The applicability of the emission rate calculation method for the source being monitored
- Assumptions made in emission rate calculations
- Uncertainty associated with the emission rate calculation
- Cost associated with each method, including instrumentation, deployment, and data analysis
- Logistical considerations related to instrument deployment
- Overall technical soundness of the measurement approach

In assessing each of these elements, AECOM performed an inter-comparison of each method utilized in the current study for emissions calculations. AECOM also compared each method to the FC approach, which is the current regulatory standard for characterizing fugitive greenhouse gas emissions from large sources at oil and gas facilities.

The following sections present a discussion of recommendations for performing future source emissions measurement campaigns for regulatory purposes.

5.1 Recommendations for Future Regulatory Emission Measurements

After completing the assessment of the alternative methods that were applied to conduct CO_2 and CH_4 emissions measurements at the Facility, AECOM concludes all approaches described were technically sound and an improvement over the currently widely used FC method for regulatory reporting. We further conclude each alternative method is superior to the FC method in generating a more representative picture of the true emissions from the sources at the Facility (due to a larger measurement footprint and a larger number of data points collected), and each is more cost effective than FC when considering labour costs and the number of flux measurement generated per field campaign. The following subsections present our recommendations for conducting future regulatory emissions measurements at the Facility.

5.1.1 Monitoring of CO_2 Emissions

The monitoring of CO_2 emissions at both the Tailings Pond and mine sites proved to be a challenge for each study participant due to a number of factors, including highly variable background concentrations due to plant photosynthesis and respiration, insufficient instrument sensitivity in some cases, and low emissions from the sources when compared to background concentrations and potential nearby external sources (e.g., vehicles in the mine area). These issues sometimes resulted in negative CO_2 emission results being calculated.

Despite these challenges, we consider it feasible to successfully monitor CO_2 emissions by applying filters to the CO_2 emission results, similar to the approach taken by S3 in their analysis of CO_2 emissions from the Pond. The group calculated the average CO_2 emission values including any negative results and the average CO_2 emission values when removing the negative emission values. The group then calculated CO_2 emissions only between the hours of 1 PM and 9 PM when both photosynthesis and respiration are active, and the height of the planetary boundary layer is greatest, thereby providing a well-mixed atmosphere. Emission values calculated between 1 PM and 9 PM were then averaged to provide a “daytime” emissions value. The three average CO_2 emission values were then presented, providing a reasonable range of the true CO_2 emissions from the pond.

5.1.2 Emission Measurements at the Tailings Pond

While we agree the EC method is an attractive method for fugitive emissions characterization, we think this method is better suited for relatively small area sources. As discussed previously, deployment of this method at the Pond showed an emissions footprint that covered approximately 25% of the surface of the pond. While this issue could potentially be mitigated by deployment of one or more instrument towers in the middle of the pond, logistically, we found this approach to be infeasible.

After reviewing each of the alternative methods, we consider the IDM method with the LGR Greenhouse Gas Analyzers to be the most favourable method for conducting emissions measurements at the Pond. The LGR analyzers used for performing the concentration measurements were shown to be easy to deploy, robust, and capable of collecting continuous data, unattended, for long periods of time. In general, an approach including IDM has a sufficiently large footprint, appropriate for large area sources such as the Pond. The WindTrax model has been well-documented as an effective model for characterizing emissions from sources with simple terrain and subsequent wind flow patterns such as the Pond. This recommendation does not preclude the use of models like CALPUFF that are better formulated to handle complicated terrain features throughout the Facility.

5.1.3 Emission Measurements at the Mine Areas

The University of Alberta report recommends an Air Mass Balance approach for conducting emissions surveys at the mine areas. While this approach would be straightforward due to the simplicity of the method emission calculation, it would introduce logistical and cost challenges. Based on the results of the drone-based Air Mass Balance demonstration conducted at the animal feedlot in southern Alberta, the measurement face for this method must be significantly longer than the horizontal dimensions of the source being surveyed, and the vertical height of the measurement faces must be sufficiently high enough to capture the vertical extent of the plume. As discussed in a previous section, these factors preclude the use of a drone-based measurement platform. While an aircraft-based platform could be utilized to execute an Air Mass Balance measurement campaign at the mine locations, it is certain an aircraft could not safely fly low enough above the source area (perhaps 100 m above ground) to collect the necessary measurements. Aside from these logistical considerations, the use of an aircraft to perform the measurements would seem to be cost-prohibitive.

We consider the most favourable approach for conducting emissions measurements from the mine areas is the IDM Method with the LGR Greenhouse Gas Analyzers. As discussed in the previous section, the instrumentation is robust and capable of collecting continuous data unattended.

While IDM-based approaches exhibit additional uncertainty when applied to sources with complex topography and wind flows such as the mine areas, the Computational Fluid Dynamics studies conducted by the University of Alberta and the University of Guelph provided interesting and relevant results. The simulations showed a wide range of virtual emission results when compared to the simulated “true” emissions values (e.g., large underestimation of true emissions at some sensor locations and large overestimation of true emissions at other sensor locations). However, the report from the University of Alberta showed that when a group of results from sensor locations directly downwind of the source were averaged, the average emission result calculated with the WindTrax model returned an emission result that was within 12% of the simulated “true” emission rate. This suggests that over the course of several days of measurements with varying wind conditions, the true source emission rate is reasonably represented by the average emission flux values calculated by the IDM model.

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Appendix A

Review Summaries

A.1 University of Alberta – Final Report

Topic/Element	Comments/Critique
Report Title/ Authors/Date	Emission Measurements: Meteorological Approaches for Oil & Gas Facilities University of Alberta: Thomas Flesch September 2, 2020
Theoretical/Conceptual Framework/General Approach	This report provides a summary of measurement techniques available for estimating emissions from large oil and gas emission sources. The report divides the measurement techniques into four basic categories: **The Flux-Chamber (FC)** – The flux chamber method provides a direct emission measurement by applying a mass balance approach to a control volume of air above the emitting source. **Eddy-Covariance (EC)** – A flexible and mature method of flux measurement which requires high-frequency wind and concentration data as typically measured from an EC tower. **Inverse dispersion modelling (IDM)** – A flexible emission estimation technique where a variety of concentration measuring instrumentation may be implemented upwind and downwind of the emission source. Atmospheric dispersion models, of varying complexities, may then be implemented to estimate source emissions. **Air Mass Balance (AMB)** – a fundamentally simple meteorological approach that estimates emissions by defining an imaginary control volume above the gas source and summing the gas fluxes crossing the volume boundaries. Fluxes at volume boundaries are calculated from the product of the wind velocity across the face and the gas concentration.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	**The Flux-Chamber (FC) Method** – The FC method works by applying mass balance to a control volume of air over the emission source. This can be done using a static chamber where the volume of air is sealed, and the emission rate is determined by the time rate-of-change of concentration inside the chamber. Alternatively, a dynamic chamber where “clean” air is used to continually flush the chamber. In the case of the dynamic chamber method the emission rate is given by the gas concentration in the exhaust multiplied by the exhaust rate. The EPA approved approach is to use the dynamic FC method. This method is the regulatory standard for emission measurements. The method is simple, repeatable, inexpensive, and accessible by non-experts. However, the method provides an emission measurement over a small footprint (US EPA FC chambers cover 0.13 m^2) requiring many measurements to fully characterize a large source, particularly when this source may not have spatially uniform emissions. The method also disturbs the surface being monitored and has the potential to interfere with the emissions from the source being monitored. This translates into the method being more ideal for comparative studies and less than ideal for measure absolute emissions. Finally, the FC method is not one that lends itself well to continuous measurements and is not appropriate for assessing temporally variable emission rates. **Eddy-Covariance (EC)** – A flux measurement relies on a high frequency (>5 Hz) time series of gas concentration and vertical wind velocity measured above the emitting surface, typically measured over a period of 30 minutes. The gas and wind sensors need to be located as close to one another as practical. Coupled to the need for a fast response, this eliminates the applicability of many measuring instrumentation. The sensors deployed during the Horizon pond field study included a three-axis sonic anemometer (Gill WindMaster, LI-COR Biosciences), an open-path CH_4 analyzer (Li-7700, LI-COR Biosciences) and a CO_2/H_2O analyzer (Li-7500DS, LI-COR Biosciences). The sensors were mounted 14.3 m above the ground. Of note, the laser CH_4 sensor optics needed manual cleaning despite the built-in cleaning system.

Topic/Element	Comments/Critique

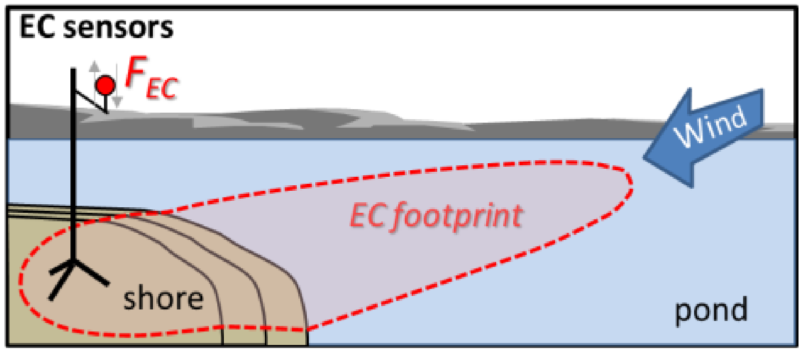


Fig. 2.1. *Illustration of the flux footprint at the Horizon tailings pond.*

Once a time series is obtained the EC analysis is then able to obtain the vertical flux of the measured gas (F_{EC}) which can be related to the gas flux from the underlying emitting surface or the "flux footprint". The flux footprint varies with wind conditions and needs to be computed in situations where the EC tower is not located directly above the source (i.e., offshore next to a tailings pond) prior to adjusting F_{EC} and calculating area emission rates. The flux footprint is calculated using meteorological footprint models. These footprint models are unable to accurately model complex 2-D boundaries or complex terrain. Of note, the taller the tower the further the flux footprint extends upwind (up to the order of 10,000 m^2). Ideally, a large area source would have a large enough tower to capture the upwind extent of the pond. This is however not always practical due to the high cost associated with taller towers.

The EC method provides a non-interference emission measurement method capable of semi continuous emission measurements that is applicable to larger measurement footprints relative to flux chambers. The method is also well suited for continuous, long-term emission measurements and can capture temporal variability in emissions. The method does require that the EC measurement is conducted within or near the emission source and that the emitting source or nearby terrain do not have any complex terrain features.

Inverse Dispersion Modelling (IDM) – Inverse dispersion modelling requires a concentration measurement (C) downwind of an emission source. Where a non-zero background exists for the emitted species an upwind background concentration (C_b) must also be measured. The concentration increase downwind of an emission source is proportional to the emission rate Q. IDM calculates this emission rate by applying an atmospheric dispersion model to account for the dispersion of gases emitted from the source.

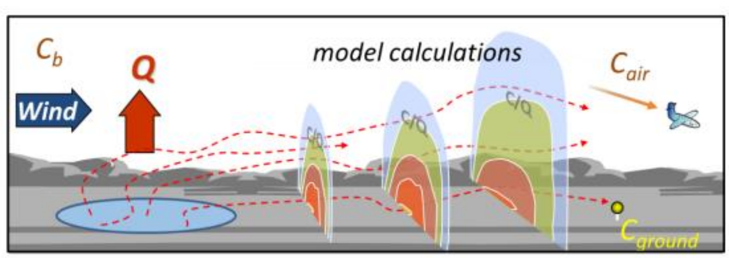
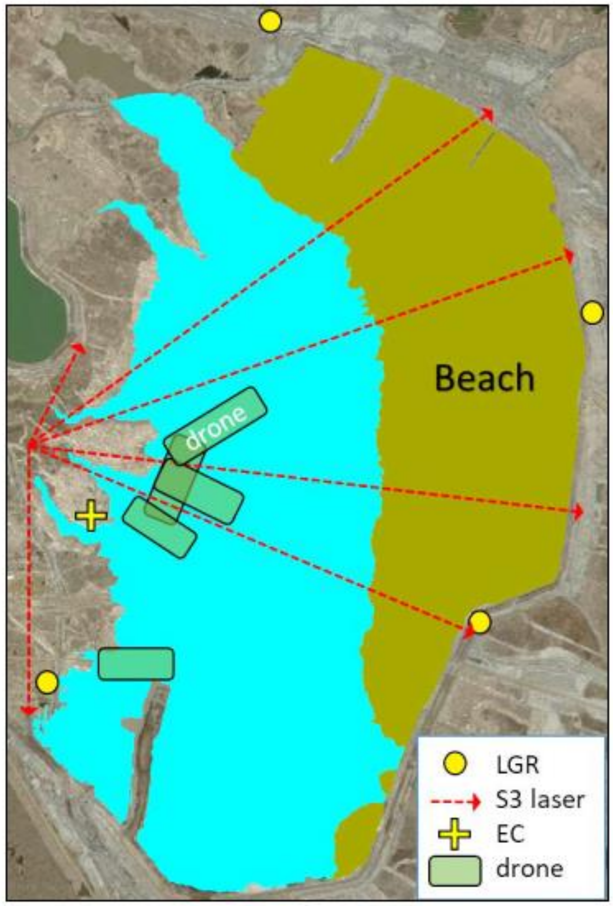


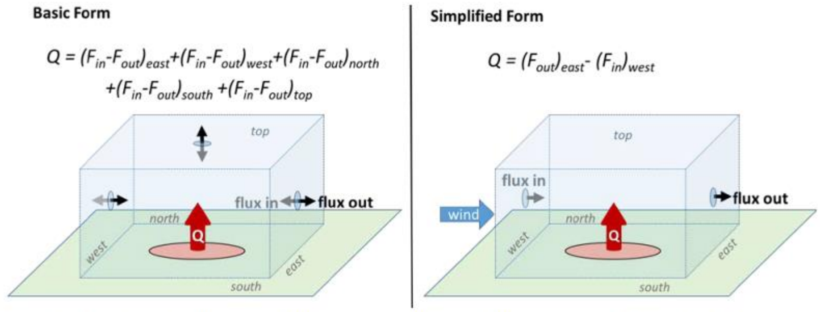
Fig. 3.1. *Illustration of an IDM measurement: 1) tailings pond emits gas at rate Q; 2) gas concentration C is measured downwind of the pond; 3) dispersion model predicts normalized concentration C/Q at the downwind location; 4) the pond emission rate is determined by dividing the measured C by the predicted C/Q. For most gases a background concentration C_b needs to be subtracted from the observations.*

The four main requirements for applying IDM to predict emissions are:

1. Gas concentration downwind of the source of interest;
2. Gas concentration upwind of the source;
3. Wind information for the dispersion model calculation (the met data requirement is highly dependent on the specific dispersion model employed); and
4. Map of the source and sensor locations.

Topic/Element	Comments/Critique
	IDM – Measurement requirements: Concentration Sensors: Concentration sensor requirements for IDM are quite limited with the main requirement being the need for adequate sensitivity to differentiate between C and C_b. Differentiating between C and C_b is particularly difficult when the ambient background is high relative to the downwind enhancement (as is the case with CO_2). Nonetheless, any number of concentration sensors may be employed regardless of their response time or measurement platform (as in fixed-point sensors, mobile sensors on vehicle or aircraft, or line-averaging sensors). Another consideration for concentration sensors is their placement. In particularly the dispersion model being employed needs to be able to resolve winds along the path between sensors measuring C_b and C. Complex terrain features should be avoided as they would add uncertainty even in situations where models can resolve winds. Drone application in these cases can reduce these uncertainties by measuring further away from the complex features. As winds change, instrumentation mounted on mobile platforms can provide C and C_b measurement under different wind conditions. Alternatively, a network of sensors in fixed location can provide different C and C_b pairs under different wind conditions. Wind Sensors: The need for specific meteorological measurements is highly dependent on the specific dispersion model employed but at minimum dispersion models require accurate wind speed and wind direction. Some models may also require turbulence measurements (typically provided by sonic anemometers) or upper air wind information (typically obtained from weather stations nearby or weather models). Regardless, measured winds should reflect the winds above the emitting surface and the winds between the emitted surface and the concentration sensors. Dispersion Model: The choice of dispersion model is critical as it dictates the spatial scale at which the model can be applied, the atmospheric and/or terrain conditions under which the dispersion model is applicable, and meteorological information required for performing IDM model runs. Of note, all dispersion models have high uncertainty at low wind speeds. The author notes that several important questions need to be posed when deciding on the appropriateness of a dispersion model for IDM application: 1. Is the model relatively easy to use? 2. Are model inputs directly measurable (e.g., avoiding subjective inputs such as fractional cloud cover)? 3. Is there flexibility in handling arbitrarily shaped and sized emission sources? 4. Does the model scale match the scale of the IDM problem? 5. Is there guidance on using the model with IDM? The authors approach was to use the WindTrax dispersion model for IDM calculations. The model is a short range Lagrangian stochastic model that has been extensively used with IDM. The model is limited as it is not appropriate for implementation where complex terrain is encountered. The UofA applied the WindTrax model to data collected by fixed point Las Gator Research (LGR) Sensors (operated by RWDI), by GreenLITE long-path sensors (operated by S3) and by Drones (operated by the UofA).

Topic/Element	Comments/Critique
	 **Fig. 3.4.** *Location of IDM sensors at the Horizon tailings pond (for the fall of 2019). The eddy-covariance (EC) system is also shown.* The UofA drone flights were complicated by the Horizon flight-approval process which limited the flight time. The drone flights consisted of the drone flying 20 m above the pond surface with flights beginning near the west shore and travelling ~ 1 km above the pond (as far as good visual contact could be maintained). The gas sampling portion of the flights ranged from 1.5 to 3.5 km in length, generally involving multiple passes over a line of flight. During the gas sampling portion of the flight and while over the pond, a pump would be remotely activated and sample air into a Tedlar sampling bag. After landing, triplicate gas samples were extracted from the Tedlar bag and analyzer later in the laboratory using gas chromatography. Measurement of C_b were made before and after the flights. Wind information was obtained by on the two 3-D sonic anemometers in place for the EC measurement. **Air Mass Balance (AMB)** – A control "box" is placed over the gas source and the emission rate is calculated by the gas fluxes in and out of the five open box faces. Flux across a face is calculated from the product of the wind velocity across the face and the gas concentration:

Topic/Element	Comments/Critique
	 *Fig. 4.1. Conceptual illustration of the air mass balance (AMB) technique. In its basic form (left), an imaginary volume is defined over the source and the emission rate (Q) is determined by summing the gas fluxes (F) across the five open volume faces. The AMB calculation can be simplified (right) when there is a wind and the box is large enough that no fluxes occur across three of the five faces.* For large control volumes, wind and gas concentrations are measured at many locations across each face. AMB can be implemented in a manner that simplifies the measurement approach. This simplification relies on the presence of wind and is described as follows: • If the box is oriented such that the upwind face is perpendicular to the wind, and the across-wind span of the box is much larger than the source dimension, there are no fluxes across the north and south faces. • If the box is suitably high, there will be no fluxes out of the top of the box. • If the gas of interest has no significant background concentration (C_b), then there is no flux across the upwind face. • If the gas of interest has a large Cb, and if the wind on the west and east faces is equivalent (over a 30 min measurement period) and Cb is spatially uniform, then measurements are not needed on the upwind face of the box. The simplifications as such require that only the downwind face of the box be sampled. This can be achieved via ground-based sensors (such as differential absorption lidar (DIAL) but is only applicable to smaller sources. Large sources (which require very large box faces due to the simplification) require mobile sensors. AMB was not demonstrated at the CANADIAN NATURAL site due to the inability to get flying approval to fly at Horizon and due to the difficult flight logistics created by the large size of the tailings pond. The approach was demonstrated at a cattle feedlot containing ~25,000 head of cattle confined in pens. This feedlot was a more intensive CH_4 source (emissions per unit area) and only 1 km^2. The feedlot demonstration suggests that a similar measurement at the Tailings pond, which is approximately 2 x 7 km long, would require box faces that are roughly 7 and 9 km wide and 300 – 400 m high. A larger box face would be needed for the mine.
Additional Methodology Considerations	**Flux Chamber (FC)** – In terms of Applicability to CANADIAN NATURAL flux chamber application cannot capture the identified temporal variability in emissions. When applied at a specific time the area measured is incredibly small relative to the large size of the area sources (<0.000001% of the pond area in the case of the Chadder and Dawson 2017 measurements). Nonetheless, the method is able to track increases in bitumen production as evidenced by the following historical comparison of FC to IDM:

Topic/Element	Comments/Critique

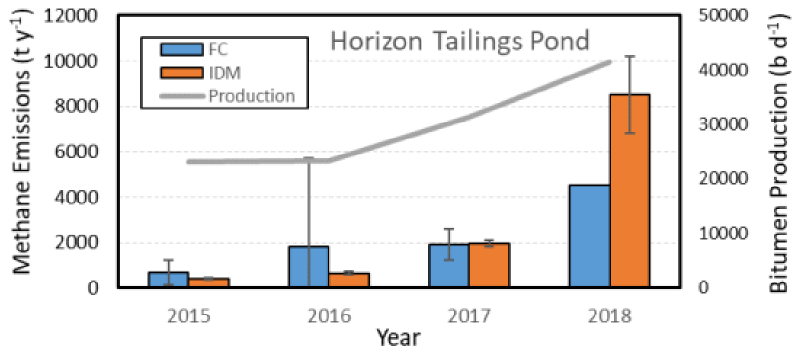


Fig. 1.2. *Methane emission rates from the Horizon tailings pond as measured by the FC and IDM techniques in annual measurement surveys from 2015 to 2018. Standard errors are shown as error bars (missing for FC in 2018). Annual bitumen production from the Horizon mine is also shown.*

Eddy-Covariance (EC) – In terms of applicability to CANADIAN NATURAL the EC technique lends itself well to measuring emissions from the pond, but technique assumptions are not valid at the mine. Deployment at the Horizon tailings pond would be most ideal if the EC tower was placed on top of the pond itself removing the need to calculate a flux footprint. However, this would add complexity to tower setup and any needed tower or sensor maintenance. One offshore sensor placed centrally or two distributed centrally such that they capture the north and south sides of the pond locations can directly measure much larger portions of the pond and provide a measurement regardless of wind direction.

The western shoreline of the pond which was used provides the most ideal on shore tower placement as berms on other sides of the pond make for complex terrain and challenge EC assumptions. (Complex terrain as defined by the author are "location where topographic effects on the winds are significant, through aerodynamic wakes, density driven slope flows, channeling, flow acceleration over hill crests, etc.") However, placement of the EC tower as close as possible to the pond waters would ensure that more of the flux footprint is above the pond itself. This is non-trivial considering the pond shoreline changes seasonally. Additionally, the onshore placement not only added the need for a flux footprint calculation but meant that the centre of the pond, which has higher emissions (as measured by flux chambers) than the western portion of the pond, was not captured within the flux footprint. This is evident from comparison of the EC and IDM data.

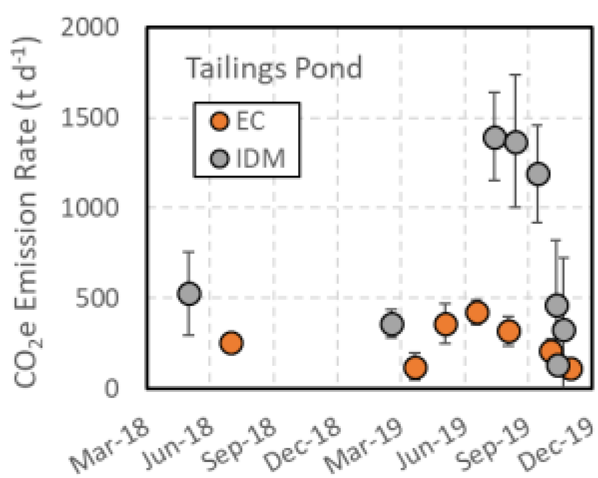


Fig 2.7. *CO_2e emissions from the Horizon tailings pond as measured by EC and IDM techniques.*

Topic/Element	Comments/Critique

EC is most appropriate under the following three conditions:

- The landscape setting is characterized by simple terrain.
- The use can demonstrate that the EC footprint covers a large and representative portion of the source area (this can be adjusted by system placement, height of the EC system and additional EC systems).
- The EC system is sited so as to not require footprint calculations to determine emissions.

Inverse Dispersion Modelling (IDM) – Instrument sensitivity has been problematic particularly for CO_2 as instrument precision can be fairly close to measured $C\text{-}C_b$:

Table 3.1. *The average magnitude of ($C\text{-}C_b$) measured during four IDM campaigns at the Horizon tailings pond (for both CO_2 and CH_4). The precision of the gas measurement system is shown for comparison.*

Survey Year	CO_2 Measured $\|C\text{-}C_b\|$	CO_2 Sensor Precision[a]	CH_4 Measured $\|C\text{-}C_b\|$	CH_4 Sensor Precision[a]	Sensor Type
	ppm	ppm	ppm	ppm	
2015	8.0	14.1	0.14	0.071	Open-path lasers
2016	15.3	14.1	0.10	0.071	Open-path lasers
2017	3.0	1.7	0.11	0.003	Point Sensor
2019	6.4	1.7	0.04	0.003	Point Sensor

[a] *Standard deviation when measuring a concentration difference.*

WindTrax IDM produced identical results regardless of sensors employed and was able to successfully track seasonal changes in emission rates:

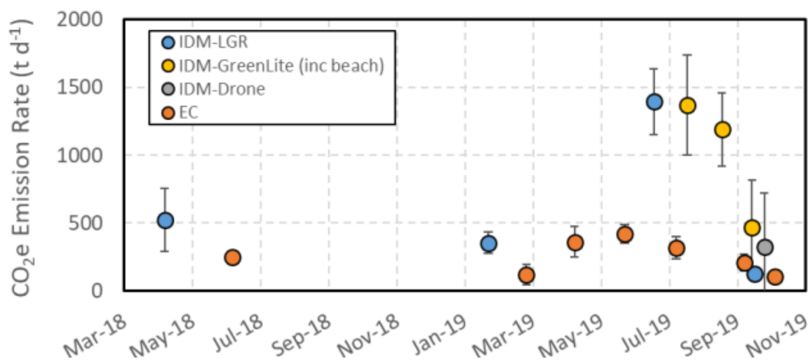


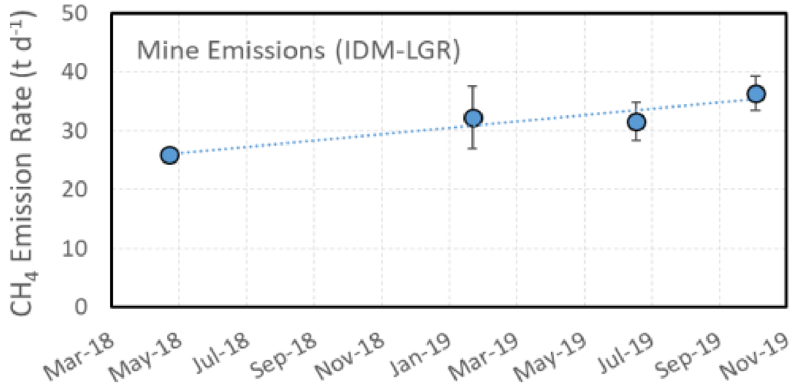
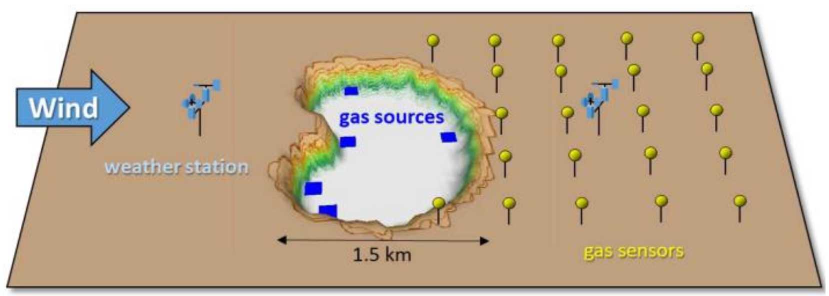
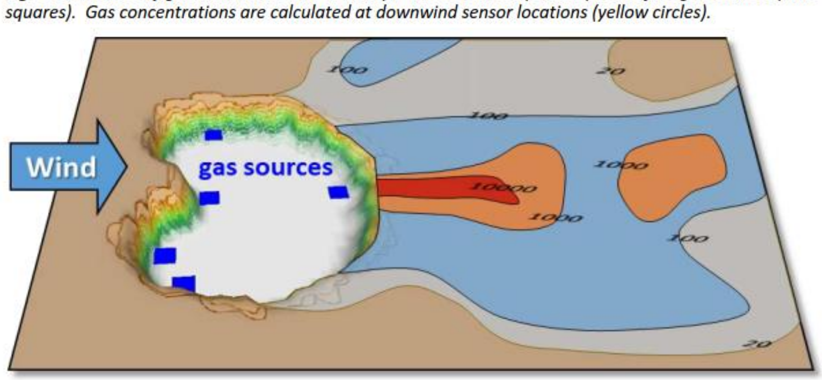
Fig. 3.6. *GHG emissions from the Horizon tailings pond (tonnes of CO_2 equivalents per day) as measured by the three IDM variants and EC. The IDM-GreenLITE measurements include beach emissions, while the others do not[6]. Error bars show the standard error.*

Table 3.2. *CO_2e emitted from the Horizon tailings pond (in tonnes per day ± standard error) calculated from three IDM variants in 2019.*

Period	IDM Sensor LGR[a]	IDM Sensor GreenLite[b]	IDM Sensor Drone[a]
July / August	1,395 ± 245	1,370 ± 367	
October	130 ± 30	465 ± 355	328 ± 395

[a] Only pond (liquid) area emissions
[b] Includes pond (liquid) and beach (sand) area emissions

The issue of a stable C_b was discussed by the authors with large biogenic CO_2 fluxes interfering with otherwise valid sampling periods. Positive (due to plant respiration and/or organic decomposition) or

Topic/Element	Comments/Critique
	negative (photosynthesis) fluxes alter CO_2 concentrations that reach the C_b measurement point either depleted or enriched and cannot provide a spatially consistent C_b for the IDM calculation. WindTrax IDM application at the mine pit tracked well with bitumen production but these results may not be accurate as the complex terrain of the mine do not conform to the assumptions of the WindTrax model:  ***Fig. 3.7.*** *GHG emissions from the Horizon mine-pits (tonnes of CO_2e per day) as measured by IDM-LGR. Values do not include vehicles and equipment emissions. Error bars indicate the standard error.* A follow-up modelling study attempted to shed light on the appropriateness of IDM application to mine surfaces that have complex terrain. A synthetic Mine CFD simulation was performed where a kidney shaped mine pit (2 x 1.5 km, 100 m deep) containing five-point sources was modelled.  ***Fig. 3.8.*** *Mine configuration in the CFD-LS study. The 100 m deep mine-pit has five gas sources (blue squares). Gas concentrations are calculated at downwind sensor locations (yellow circles).*  ***Fig. 3.9.*** *Gas concentration (ug m^{-3}) contours downwind of the mine in a daytime case (unstable atmosphere). The concentrations are at 10 m above ground. Each mine source is releasing gas at a rate of 1 kg s^{-1}.*

Topic/Element	Comments/Critique

IDM model runs using WindTrax were performed using a weather station located outside of the mine (on a CFD model grid point) and using "gas sensor" information positioned downwind of the mine. The model attempted to calculate emission rates from the five area sources (a more realistic area source analysis was performed but wasn't reported on in this work). For 13 of the 22 sensors the modelled emission rate is more than factor of two different from the actual rate. On average however WindTrax provided an emission rate that was 88% of the actual emission rate which could explain the reasonableness of IDM results at the CANADIAN NATURAL mine and calls for long-term IDM-averages.

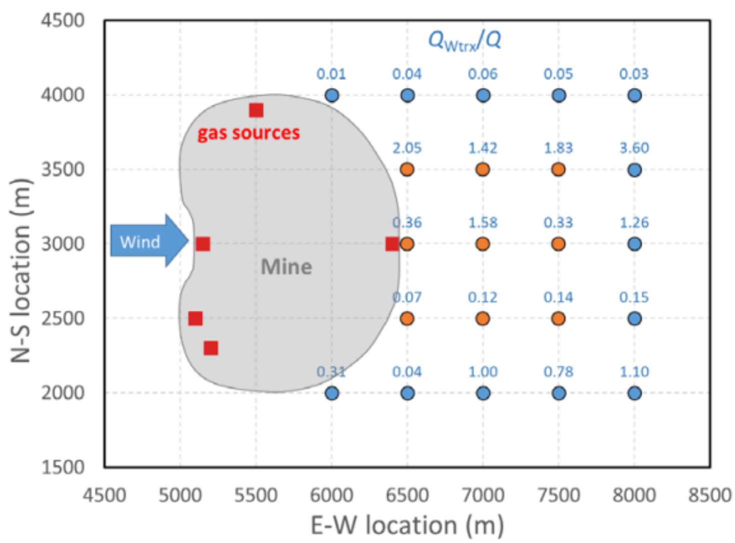


***Fig. 3.10.** Ratio of the IDM-WindTrax calculated emission rate (Q_{Wtrx}) to the actual mine emission rate (Q) for different downwind sensors. In this example, an upwind weather station was used for the IDM-WindTrax. Sensors indicated by orange circles are identified in the text.*

A similar study examined the use of CALPUFF (which can consider complex winds) and representing mine topography using a horizontal resolution of 200 m and vertical resolution of 20 m. Five "weather stations" were used with four located outside the mine and one within. Two upper-air locations also provided wind speed and wind direction. Once again five surface area sources were used. CALPUFF generated a mine plume over a 24 hr period using constant wind conditions and the concentration predictions for the las hour were used in the IDM analysis.

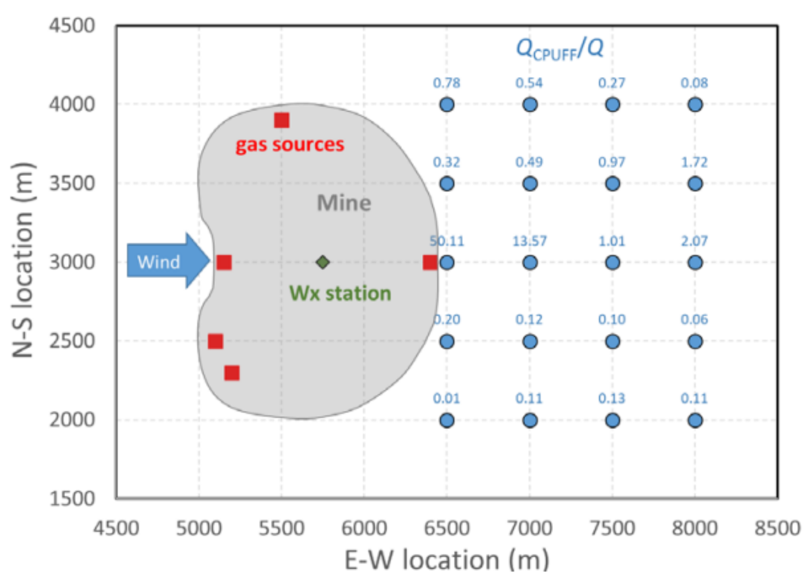


***Fig. 3.11.** Ratio of the IDM-CALPUFF calculated emission rate (Q_{CPUFF}) to the actual mine emission rate (Q) for different downwind sensors.*

<table>
<tr><th>Topic/Element</th><th>Comments/Critique</th></tr>
<tr><td></td><td>For 15 of the 20 sensor locations the modelled emission rate was more than a factor of two different from the actual rate. This is not much better than the simpler WindTrax approach. Due to the questionable results with complex winds the author concludes that EC, which is capable of handling simple terrain, is more appropriate. EC requires only one measurement location and analysis is more straightforward (if no footprint correction is needed). IDM is however recommended over EC when:

• Fast response sensors are not available for the gas species of interest,
• When the EC footprint does not sufficiently cover the source, or
• When the EC footprint falls extensively outside the source such that footprint corrections are required.

Air Mass Balance (AMB) – The AMB-Drone approach should be capable of handling smaller emission sources (1-2 km^2) but is not appropriate for the Horizon Pond of the CANADIAN NATURAL mines. For the Horizon pond and Mines on site a larger aircraft capable of further and higher travel is required. The single face measurement approach assumes the source being monitored is isolated. Due to the large size of the box and the nature of the CANADIAN NATURAL site this might not be the case and multiple box faces would need to be measured for background correction.

The AMB approach is simplest when sampling flights are made at constant height above the ground which requires relatively simple terrain (complex terrain within the source does not matter in this case as the bounding box face is downwind of the source). Finally, the AMB approach provides a snapshot measurement and is not appropriate for tracking temporal tends. Despite the lack of an onsite demonstration the author recommends AMB be used at the mine and for topographically complex area sources due to the limitations of other techniques.</td></tr>
<tr><td>Analysis/Results</td><td>The Flux-Chamber (FC) Method – Analysis is straightforward in principle and limited to mass balance calculations of emissions rates.

Eddy-Covariance (EC) – EC analysis is complicated requiring sophisticated analysis steps to account for co-ordinate rotation for title correction, spectral corrections for low frequency signal losses, spectra corrections for high frequency sensor response, time lag co-ordination between the sensors and accounting for density effects on the concentration measurements. Specialized software are however available (e.g., EddyPro open source software, LI-COR Biosciences) that can perform much of the analysis in real-time using on-board datalogging modules. As such, where flux footprint processing is not required the process can be fully automated

Inverse Dispersion Modelling (IDM) – The first step in the analysis requires calculating the emission enhancement due to the source (i.e., calculating $C\text{-}C_b$). This fairly straightforward measurement step is followed by application of the inverse dispersion model of choice. Depending on the model this can be a fairly complex step.

Air Mass Balance (AMB) – Not Demonstrated at the site.</td></tr>
<tr><td>Comparison to Flux Measurements</td><td>The Flux-Chamber (FC) Method –

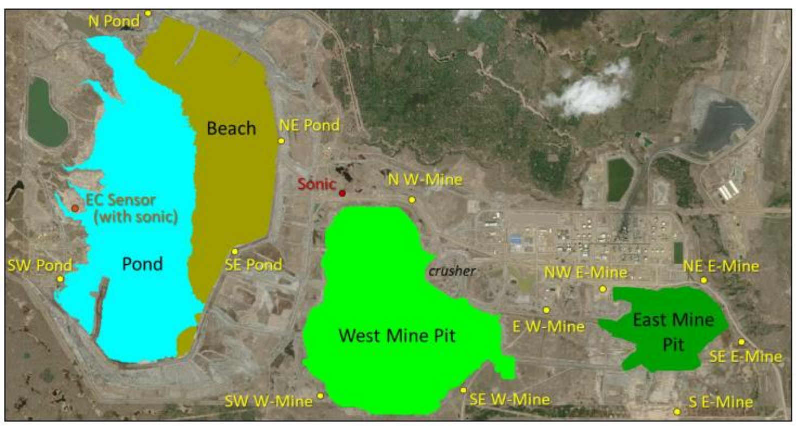
• Technique interferes with the emission source
• Very specific requirements for accepted US EPA approved instrumentation
• Not capable of continuous monitoring - not capable of monitoring temporal trends
• Applicable in complex terrain
• Small measurement footprint (0.13 m^2)
• Need hundreds of samples to fully assess Horizon pond

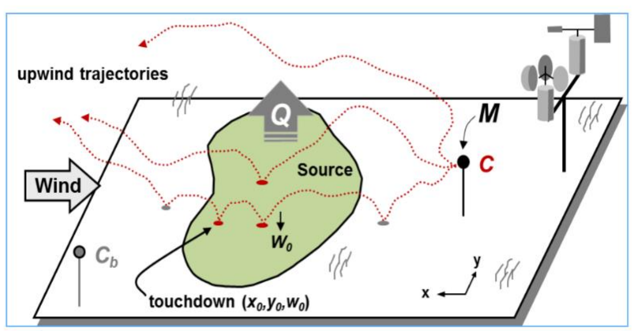
Eddy-Covariance (EC) –
• Non-interference technique
• Requires instrumentation with fast instrument response
• Semi-continuous (dependent on wind direction if a single on shore EC tower is used) long-term monitoring - capable of monitoring temporal emission trends
• Not applicable in complex terrain
• Large measurement footprint (on the order of 10,000 m^2) – flux footprint dependent on tower height.</td></tr>
</table>

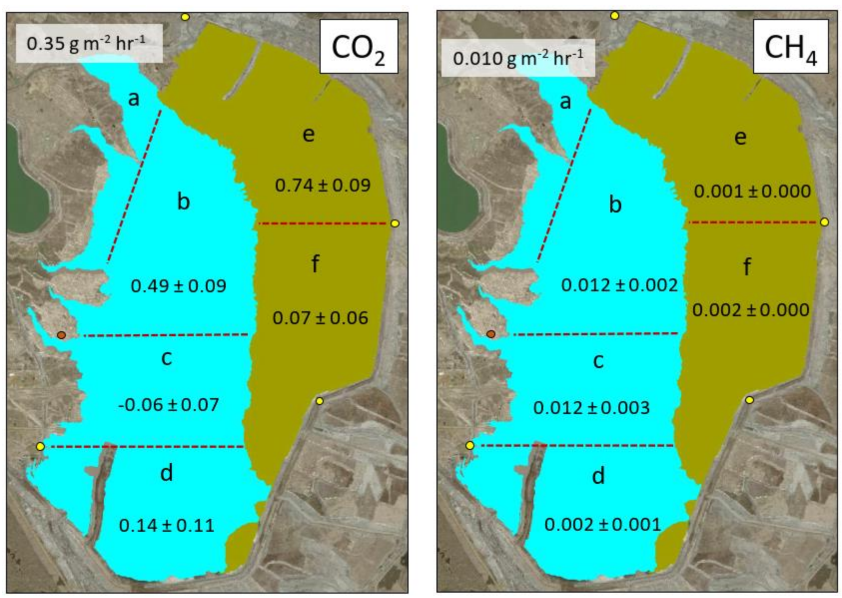
Topic/Element	Comments/Critique
	• Potential for real-time on-board analysis of emission rates (if complex flux footprint modelling isn't required) **Inverse Dispersion Modelling (IDM) –** • Non-interference technique • Semi-continuous (dependent on wind direction if a single on shore EC tower is used) long-term monitoring - capable of monitoring temporal emission trends • Applicable in complex terrain – if specific dispersion model used is appropriate (this has yet to be demonstrated). • Large measurement footprint • Complexity of dispersion modelling • Dispersion model inaccuracy particularly during light winds • Requires at least two measurement locations. ($C-C_b$) **Air Mass Balance (ABM) –** • Non-interference technique • Snapshot measurement (if using mobile drone mounted sensor) • Applicable in complex terrain • <1-2 km^2 measurement footprint (using drone platform); Larger measurement footprint (using larger aircraft and longer flight paths) • Direct measurement with relatively simple model free analysis • Requires very large "box" faces for large emission sources.
Gaps/Limitations in Measurement or Analysis	**The Flux-Chamber (FC) Method –** Measures over a very small emission footprint and cannot track temporal trends. **Eddy-Covariance (EC)** – EC tower needs to be placed within the emitting source to avoid the added complexity of footprint modelling and the associated additional modelled uncertainty. Not applicable over complex terrain. **Inverse Dispersion Modelling (IDM) –** Technique is limited by the model employed and is limited by model assumptions. The WindTrax model cannot deal with complex terrain and as such WindTrax IDM is not applicable to emission sources that are associated with complex terrain. IDM is also largely unproven over complex terrain. **Air Mass Balance (Air Mass Balance) –** Not demonstrated to work at CANADIAN NATURAL. Would require km long flight paths that are currently not permitted without special flight permits and that would require larger drones or aircraft. Snapshot measurement that is unable to provide insight into temporal trends.
Compensation for Background Concentrations?	**The Flux-Chamber (FC) Method –** A direct measure of emission rate so does not require background correction. **Eddy-Covariance (EC)** – Does not require background compensation unless a portion of the flux footprint contains a second source/sink for species of interest. **Inverse Dispersion Modelling (IDM) –** Background compensation achieved via subtraction of an upwind background concentration (C_b). **Air Mass Balance (Air Mass Balance) –** Air mass balance can require background compensation (if the bounding box has contributions for other non-stable sources). This can be achieved by sampling box faces both upwind and downwind of the source but complicates the analysis.
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	**The Flux-Chamber (FC) Method –** Requires a very large number of deployments to fully elucidate emission from large sources such as the Horizon Pond or the mine. **Inverse Dispersion Modelling (IDM) –** Conceptually requires at least two measurement stations/locations. A network of measuring instrumentation is more ideal.
Is there a lower-cost alternative measurement approach?	

Topic/Element	Comments/Critique
Recommendations for Improvement	**EC –** locate the EC tower within the footprint of the pond to avoid complex footprint calculation and to be able to interpret data from additional wind directions. **IDM – WindTrax (using Drone) –** Drone mounted gas sensors could be used instead of the Tedlar bag. This would remove the necessity to measure gaseous concentrations offline after field deployment. This would also allow C and C_b to be measured in a single flight pass. **AMB** – Drone mounted gas concentration and wind velocity sensors would be ideal. Gas concentration sensors onboard could help speed up the analysis and ensure the "box" is fully scanned. Mounted wind sensors could also more precisely define wind velocity at the box "face".

A2. U of A Fall 2019

Topic/Element	Comments/Critique
Report Title/ Authors/Date	Greenhouse Gas Emissions from the CANADIAN NATURAL Horizon Tailings Pond and Open-pit Mine: WindTrax-IDM Analysis (Fall 2019), UofA, Thomas K. Flesch, 5 June 2020
Theoretical/Conceptual Framework/General Approach	Inverse Dispersion Modelling (IDM) using the WindTrax dispersion model. The method relies on measuring gas concentrations upwind and downwind of the emitting source. The enhancement of concentrations downwind of the emitting source is proportional to the emission rate out of the source. Dispersion modelling, in this case the WindTrax dispersion model, is then used to calculate the numerical connection between the emission rate and the concentration enhancement downwind of the source. IDM has the advantage of providing emission estimates for large area sources without interfering with the measurement environment, allows the use of any number of gas monitoring equipment and the ability to choose safe and convenient measurement/sampling locations. Unsuitable wind directions that carry the gas plume away from monitoring instrumentation or insufficient wind such that the plume spread cannot be reliably modelled lead to exclusion of certain measurement periods from analysis.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	Four gas sensors were placed around the tailings pond and each of mine pits enabling them to provide downwind and upwind concentrations for different wind directions. Sensors were setup at fives sites around the tailings pond from 24 October to 8 November 2019. Sensors were position around the east-pit October 9-19, and then moved around the west pit November 10-17.  ***Fig 1.** Map of the Horizon site showing the tailings pond and mine pits. The tailings pond was divided into "pond" (liquid) and "beach" (sand) surfaces. There were 13 gas measurement locations in total: 12 LGR locations shown by yellow dots, and an EC system shown by the orange dot. The location of two sonic anemometers ("sonics") are given by red and orange dots.* Four Las Gatos Research (LGR) greenhouse gas analyzers that are based on cavity ring-down spectroscopy were used to obtain gas concentrations. An additional monitoring location was provided by the CH_4 and CO_2 monitoring equipment utilized by the Eddy Covariance (EC) system employed at the pond. Instrumentation employed provided 20 s data. Wind data were obtained from two three-dimensional sonic anemometers, one of the two being the sonic anemometer employed by the EC system. The second sonic anemometer was placed just north of the mine. In both cases the sonic anemometers were needed to provide the wind parameters needed for WindTrax-IDM modelling: • Friction velocity (u*) • Obukhov Length (L) • Roughness Length (z_0)

Topic/Element	Comments/Critique
Additional Methodology Considerations	Although nearly 1000 hours of concentration data was collected filtering of the data leads to far fewer IDM-WindTrax usable observations. In the case of the pond, which was divided into liquid surface and beach for this analysis, there were a total of 57.5 usable hours (10.5 hours from the pond and 56 hours from the beach). This was due to the lack of inability to calculate pond emissions during westerly winds as well as due to issues with solar power on the EC system (which limited the number of wind observations usable for pond calculations). For the east-pit there were a total of 50 hours of usable observations for CO_2 and 47 hours of usable observations for CH_4. The west pit was had only 19 hours of usable CO_2 observations and 24 hours of usable CH_4 observations. WindTrax is a Lagrangian stochastic (LS) model that calculations dispersion by mimicking the trajectories of thousands of tracer "particles" as they move in the atmosphere. Each trajectory is made up of a series of small changes in particle position and velocity that reflect the wind and turbulent conditions. WindTrax uses a "backward" LS approach (bLS) to calculate the trajectories of tracer particles upwind of a measurement point (M). For the WindTrax model the important back trajectory information is the location where trajectories impact the ground ("touchdowns") which is a function of the given location and a vertical velocity at touchdown (w_0). Only those touchdown points within the source boundary (the ground area where emissions influence the ambient concentration relative the background concentrations) are relevant. The source emission rate may then be calculated as: $$Q = \frac{\Delta C}{\frac{1}{n}\Sigma \lvert \frac{2}{w_0} \rvert} = \Delta C * K$$ Where n is the total number of particles released from M, ΔC is the difference between the concentration measured downwind of the mind and that measured at background locations, and K is the WindTrax dispersion coefficient. The above analysis depends on wind properties, which are spatially variable but for short time intervals in a homogenous landscape, Monin-Obukhov Similarity Theory (MOST) states that the statistical properties of wind near ground are determined by a few key parameters that can be measured with a 3-D sonic anemometer: u*, L, z_0 and wind direction. The study author indicates that this limits the WindTrax application, which has different consequences for the tailings pond and mine calculations. In the case of the pond, which is a near-ideal MOST environment, WindTrax model is appropriate and has been shown to be accurate to better than 10% (Harper et al., 2010). The complex terrain of the mine on the other hand does not allow simple MOST wind profiles. The long distance between touchdown points and the downwind concentration sensor (up to ~4 km in the case of this study) creates additional uncertainty. Furthermore, gas emitted above the mine may travel high above the mine before being sampled by the downwind concentrations. MOST does not describe winds aloft and as such this transport is not well modelled by the WindTrax IDM model.  ***Fig. B1.** Illustration of the WindTrax (bLS) technique for estimating the emission rate (Q) from the concentration enhancement (C-C_b) at location M. The relationship between (C-C_b) and Q is calculated from trajectory "touchdowns" inside the source (w_0 is the vertical velocity at touchdown).* Uncertainty in the calculated emission rate is a function of the uncertainties in determining ΔC (largely driven by instrumentation error), uncertainties in determining the dispersion coefficient, K (typically 20% for bLS per the work of Harper et al. (2010) but assumed to be 40% for the less than

Topic/Element	Comments/Critique
	idea WindTrax implementation at the mine), and uncertainty in the background concentration measured (as the single background point measurement may not be representative i.e. the background is not necessarily spatially or temporally uniform).
Analysis/Results	Concentration and wind data were also averaged to 15-minute prior to IDM analysis. IDM data filtering also takes place where data are filtered for: • Low winds (windspeed <= 2.0 m/s, friction velocity u* <= 0.1 m/s, • Strongly stable/unstable atmospheric stratification (Obukhov Length |L| <= 10 m), • Periods when the inferred surface roughness length z_0 > 1.0 m. Exceeding this threshold indicates the wind flow does not conform to the underlying WindTrax assumptions (i.e., z_0 is unrealistic for the surface cover at the sonic sites). Additionally, care was taken to only consider periods when the downwind concentration footprint had to cover a minimum of 1% of the source area of interest (i.e., the pond), while covering less than 0.1% of the other source areas (e.g., the beach, the mine pits, the crusher, etc.). In the case of the mine, equipment emissions were subtracted from the measurement prior to application of IDM based on the estimated daily fuel consumption. Background data may then be subtracted from downwind data. The concentration enhancement is then modelled using WindTrax-IDM to determine an emission factor. This emission factor applies to the region of the pond/mine in between the measurement site used for background and the measurement site used as a downwind measurement point. The pond and mine can as such be broken into section between various sensors and each of these can be associated with an independent emission factor.  ***Fig. 3.*** *The CO_2 and CH_4 emissions per m^2 of surface (g m^{-2} h^{-1} ± standard error) for different zones (labeled a-f, delineated by the dashed lines).* A final check of the WindTrax "footprint" map was also done visually of each 15-min observation to remove observations potentially impacted by either the crusher area or the horizon processing facilities. CO_2 emission results from the mine had very large uncertainties and were found to be less than zero (a CO_2 sink) albeit not statistically different from zero.

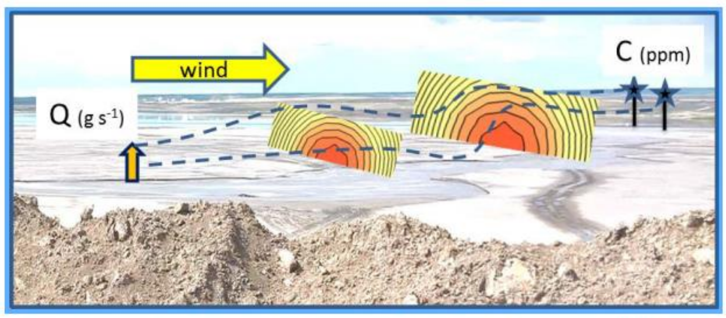
Topic/Element	Comments/Critique
	The analysis indicated that the pond was a small contributor to GHG emissions relative to the mine (195 ± 41 vs. 747 ± 319 CO2e). This was unlike the summer 2019 WindTrax analysis which found the pond to be contributing nearly two thirds of GHG emissions.
Comparison to Flux Measurements	
Gaps/Limitations in Measurement or Analysis	The Author notes that CO_2 instrumentation not sensitive enough to capture the small enhancement of CO_2 caused by the pond above the large ambient background. Although not discussed in the reviewed paper instruments used to calculate ΔC are assumed to track ambient air concentrations identically. Instruments that may be prone to interference, particularly from species that may be emitted from the source area, are not ideal for this analysis. Interference from water or a relative humidity dependence of instrument response for instance, might act to introduce additional uncertainty or even erroneously amplify concentrations measured downwind of a pond. This problem can be compounded by the fact that instrumentation being used for the ΔC calculation are located kilometres apart where small differences in external parameters (e.g., temperature, pressure, etc.) may lead to minor differences in instrument response. A rigorous field calibration program is required to ensure the subtraction is valid – such a field calibration system may have been implemented but calibration details were not provided. Complex (non-MOST and/or vertical) wind flow in the mine is unaccounted for by the WindTrax-IDM method.
Compensation for Background Concentrations?	Upwind stations provide a background concentration for background subtraction.
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	More sensitive CO_2 instrumentation could help capture the small CO_2 enhancement relative to the large ambient background.
Is there a lower-cost alternative measurement approach?	Costs of application are dependent on instrumentation employed and instrumentation needs are such that cheaper instrumentation options are potentially available.
Recommendations for Improvement	Implementation of a sufficiently rigorous field calibration program to ensure upwind and downwind instrumentation employed for ΔC calculation are responding accurately. Author Recommended improvements: • Application of additional computation fluid dynamics of wind flow can help overcome the issue of complex wind flow over the emitting area.

A3. RWDI Fall 2019

Topic/Element	Comments/Critique
Report Title/Authors/Date	GHG Fugitive Emission Quantification Via Inverse Dispersion Modelling Fall 2019 Survey – Draft (April 27, 2020) RWDI, Michelle Seguin, Francoise Robe, Matt Endsin
Theoretical/Conceptual Framework/General Approach	Inverse Dispersion Modelling (IDM) – a non-intrusive method relying on measurement of ambient GHG concentrations around the perimeter of area sources, followed by inverse modelling to estimate are source emissions. Four seasonal studies – this report highlights the 4th study completed October - November (fall) 2019. Flux chamber measurements were also taken to supplement the fall IDM measurements.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	Refer to GHG Fugitive Emissions Quantification via Inverse Dispersion Modelling 2018 Survey: Version 3.0 or GHG Fugitive Quantification via Inverse Dispersion Modelling 2019 Survey for more details. Ambient air concentrations of CO_2 and CH_4 were measured at four sites around the pond (Oct. 24- Nov. 9), east mine (Oct. 7 – 24), west mine (Nov. 9 – 21), and ? (blank in draft). GHG measurements were performed with Los Gatos Research Ultraportable Greenhouse Gas Analyzers (Cavity Enhanced Absorption – CEAS). Temperature, wind direction and wind speed were also collected at several (6) meteorological stations strategically located throughout the Horizon site during the campaign. Only 1 anemometer collocated with ambient air measurement instrumentation.
Additional Methodology Considerations	IDM was "centred" on the subset of data taken prior to the pond icing over on November 4th as "such a significant and durable change in emissions led to non-unique inversion solutions with the whole dataset." Because CO_2 spatial gradients are more pronounced at night (RWDI, 2018), only daytime values were inverted, this leads to conservative IDM emission estimate for the pond, as the pond was observed (by eddy covariance) to absorb CO_2 at night. Large uncertainty in CO_2 emissions calculated by IDM due to the large background and small/negligible emission from the pond and mines.
Analysis/Results	Provide spatial distribution of pond pit emissions (map with emissions from area source). Time series of emission rates based on IDM emission rate estimates. Comparison to Flux measurement results only visual up to this point.
Comparison to Flux Measurements	Comparison to Flux measurement results only visual up to this point. More complete analysis should follow in the final report – we might be able to pull the data ourselves as well.
Gaps/Limitations in Measurement or Analysis	CO_2! Requires a network of instrumentation. Unable to perform inverse IDM during change from open water to ice capped pond. Meteorology needs to co-operate, or spatial coverage of ambient samplers be wide enough, to ensure adequate number of upwind/downwind datapoints are present for proper IDM analysis to be possible. IDM requires significant post-processing of data prior to obtaining emission rates.
Compensation for Background Concentrations?	Difficulty with CO_2 due to high background.

Topic/Element	Comments/Critique
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	No specific instrumentation needs - any ambient and met instrumentation, with sufficient enough limits of detection, precision and stability could be deployed.
Is there a lower-cost alternative measurement approach?	Lower cost ambient/met instrumentation potentially available
Recommendations for Improvement	Online or semi real-time IDM analysis would bring this in line with other reviewed methods. Might lead to issues but breaking up the data into shorter time steps prior to running IDM might enable the extraction of emission rates during emission change events (i.e., pond icing).

A.4 RWDI Final Report

Topic/Element	Comments/Critique
Report Title/ Authors/Date	Final Report – Area Measurements of Methane & Carbon Dioxide – Final Report RWDI: Francoise R. Robe, A. Michelle Seguin, Christian Reuten, David S. Chadder, Matthew Endsin, Travis Tokarek, Eric Christensen August 25, 2020
Theoretical/Conceptual Framework/General Approach	The RWDI approach relies upon combining concentration measurements with a CALPUFF based inverse dispersion modelling (IDM) approach. IDM is considered a “top-down” approach, in that it captures emissions emission information from the site and apportions emission rates based on site knowledge. “IDM essentially answers the question, what would be the emission rates have to be to cause the observed increase in downwind concentrations?” IDM is characterized by the ability to use non-disturbance measurements and micrometeorological-based modelling methods to calculate emissions. IDM relies on ambient concentration measurements taken downwind of an emission source (C) and dispersion modelling to estimate source emission rates based on the prevailing winds and the turbulence regime at the time of the measurement. An upwind measurement (C_b) is also required to account for non-zero background concentrations upwind of a source. As such IDM is concerned with the increase in concentration downwind of an emissions source, ΔC ($\Delta C = C - C_b$).  *Figure 2: IDM Conceptual Picture, where Q is the source emission rate and C the ambient concentration measured downwind of the source.* Concentration measurements may be conducted with any valid ambient measurement technique. Measurement may be conducted using either point sampling or open path concentration measuring systems although measurement systems are ideally identical during a single deployment for optimal performance. Any atmospheric transport and dispersion model with appropriate capability to model the winds and turbulence downwind of an emission source is appropriate. CALMET/CALPUFF were used by RWDI. CALMET/CALPUFF simulate the movement and dispersion of individual puffs emitted in each time step and overlay the puffs for each pre-selected receptor location. When the CALMET/CALPUFF modelling system is sufficiently accurate, the prediction should agree with synchronous observation at the same location modelled within a range of uncertainties in time without substantial bias. Inverse dispersion modelling works by taking observed data and finding an emission rate that best explains the observation. The RWDI CALPUFF IDM approach has been employed at the CANADIAN NATURAL site and over several years and has been permitted by the regulator as an alternative method to flux chamber measurements.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	Regional meteorological stations run by the Wood Buffalo Environmental Association and Meteorological data from the eddy covariance system were used as inputs the CALMET meteorological mode. Additional meteorological stations within the mine were also used to account for the influence of topography on meteorological parameters measured. Up to six meteorological stations were stations around the site during each campaign with each station measuring wind speed and wind direction and in some cases temperature. Pressure and Relative humidity, which are also required as inputs into CALMET were obtained from a single station.

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Two-dimensional (2D) (WINDSONIC1, Campbell Sci.) and 3D (CSAT-3, Campbell Sci.) sonic anemometers were used at the monitoring stations deployed. These stations were setup at a height of 10 m (per the Air Monitoring Directive (AMD) guideline) and measured at 10 Hz. Air data was also used form the nearby local air shed which operated a three-cup anemometer (Met One 010C/020C). 2D wind measurements are adequate as CALMET does not require the 3D component of wind direction as an input.
Typically, four cavity ring-down spectrometers (CRDS) (LGR-UGGA, Los Gatos Research Inc., Mountain View, CA) were position around the area source of interest. Instrument repeatability and precision were <0.6 ppb for CH_4 and <100 ppb for CO_2 (10 second averaging time).
Sources were delineated into subareas which were based on objective evaluation of location, activity level, anticipated similarity of the area's emission profile and qualitative assessment criteria anticipated to generate meaningful results. Qualitative criteria for the mine included active mining areas; prevailing meteorological conditions during the monitoring period and physical boundaries of both the tailings pond and the mine. For the pond qualitative criteria included areas where bubbling had been observed and physical characteristics including open water vs sandy areas. Of note Sandy areas are not captured (due to safety concerns) by Flux Chamber measurements. These subareas were assumed to have consistent emissions/emission profiles for the duration of each of the field campaigns (which typically lasted a few weeks at each of the given sources).
During RWDI's field deployment they performed cross calibration of field instruments before and after the field campaign and performed field calibration during the field campaign.
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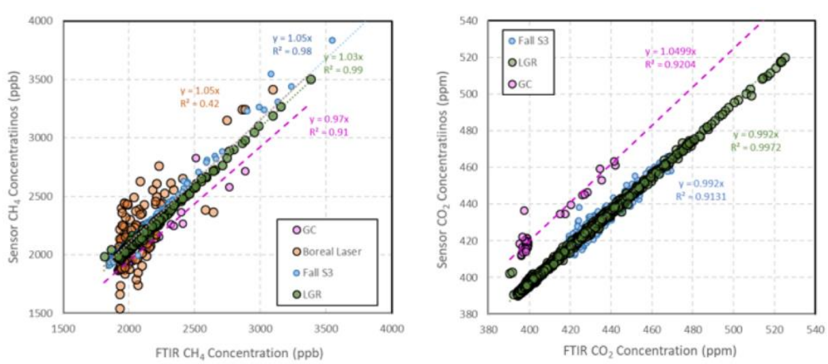
<tr><td>Additional Methodology Considerations</td><td>
IDM is well documented and has been used successfully in regulatory decision making but needs to be tailored to each use case for results to be representative. This CANADIAN NATURAL campaign appears to be the first attempt to tailor IDM to estimating GHG emissions from the Oil Sands.
Comparison of Measurement Techniques
A comparison of point and pathway measurement techniques was performed during summer and fall 2019 field campaigns. Instruments compared included the UofA FTIR (which was assumed to be the standard in figured below) as well as the RWDI operated LGR-UGGA, S3's Long Path Spectrometers, Boreal Laser spectrometers, and the U of A's laboratory GC analysis of Tedlar bags.
In this experiment a good correlation was observed between the RWDI LGR-UGGA point measurements which were placed in the mid-point of the 85 m UofA FTIR pathway. It was concluded by RWDI that over short distances (~100 m) that concentrations do not change (This may not be a valid assumption when closer to an emission source/sink). Of note, the boreal laser system appeared noisier at lower CH4 concentrations and was much less correlated with the UofA FTIR.
A comparison to the LI-COR instrument was not shown. Comparison to the LUXMUX sensor could not be conducted to as it was not collocated during the comparison experiment.


Figure 1: Comparison of different techniques to measure concentration measurements for methane and CO2. Comparison was compiled in Summer and Fall 2019 field surveys. Data was compiled by Dr. Flesch (U of A) and additional information can be found in his report.
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Topic/Element	Comments/Critique
	Although the LGR-UGGA and FTIR correlated quite well (within 3% for CH_4) other instruments correlations were less than ideal. Even though most instruments were within 10% of the UofA FTIR some instruments were found to be noisier. RWDI concluded that although either point or long path would work for IDM implementation that single measurement technique should be used. Their reasoning for this includes: • Ease in the field with only one type of instrument, parts and instruments could be swapped at different sites if need be; • External influences are assumed to act the same on all instruments; and • Biases on the instruments are assumed to be similar. **Table 3 of the Final Report provides a good summary of different techniques and their potential for future use with IDM.** **Meteorological Data Comparison** The Weather Research and Forecasting (WRF) model was to provide input for meteorological values aloft to supplement surface meteorological measurements. A comparison of 1 km by 1 km and 3 km by 3 km spacing for WRF did not change CALMET results greatly and indicated that the lower resolution could be used to save computation time. A U of G led peer reviewed peer reviewed paper was published to present these findings: Complex Meteorology over a Complex Mining Facility: Assessment of Topography, Land Use and Grid Spacing Modifications in WRF (Nahian 2020). **Spatial Comparison** IDM offers spatial analysis of emissions. The spatial analysis was supported by the ability to accurately reflect elevated emissions from the middle of the tailings pond which was also observed by Flux Chamber data. Drone flights by SAIT, which are limited to flights in good weather and daytime periods and have limited range and limited time of flight were also assessed for their ability to provide spatial analysis as well as insight into vertical mixing. SAIT drone results did not always agree with IDM results but it was unclear whether this was due to operational changes at the site or due to the snapshot nature of the measurement. Scientific Aviation also carried out aerial measurements albeit at higher elevations. These results showed clearer disagreement with IDM results but were conducted at > 150 m above the site so perhaps were not capturing the correct sources. The S3 measurement was also able to provide spatially integrated concentrations. Results from the S3 and Atmospheric and Environment Research (AER USA) generally agreed with IDM results. S3 does however have variation in temporal emission rates and concentrations within the S3 databased on individual hours. It is uncertain if this variation is due to meteorological conditions at the time of measurements or if other factors contribute. A more detailed comparison reveals that S3 did however predict higher emission than IDM at the perimeter and the south and west sides of the mine. This extended beyond the sub-area source that RWDI predicted. The reason for this discrepancy is unclear but may be a result of the RWDI modelled area extending further to the southwest than the region covered by the S3 sensors. Lowest emissions were also found by both S3/AER USA and RWDI to be the mid-north of the mine although the two regions as defined by the different techniques do not align perfectly. **Field Monitoring Optimization** **Optimizing Campaign Length and Averaging Periods** Regulatory guidance (Specific Gas Emitters Regulation (SGER) and Specified Gas Reporting Regulation (SGRR)) stipulates that alternative emission measurement techniques require a monitoring period of no less than 72 hours. In practice RWDI found the true minimum campaign length to vary for IDM based on the number of sub-sources being examined and the averaging period of GHG monitoring equipment. This would also depend on environmental conditions such as rain that may alter emissions during sampling (particularly important as the data set is interpolated from a daily emission rate to an annual emission rate).

Topic/Element	Comments/Critique
	RWDI indicates that ten times the number of sub-sources is the minimum required number of valid data points. This allows for a statistical Markov Chain Monte Carlo (MCM) algorithm to be used in the inversion calculation and allows results to converge on a more realistic bulk average. Shortening the averaging period could reduce the minimum length required for field measurements but models used would need to be able to model these shorter timesteps. RWDI deemed a 15-minute average reasonable for a campaign that included four GHG monitoring stations. Assuming 15-minute averaging is used for measurement data this and 20 sub-areas would require a minimum of 50.5 hours. However, even though 72 hours would be adequate RWDI indicates that five to seven days (120 – 168 hours) would be optimal as this provides for more representative conditions and would meet the 72-hour minimum after invalidating data due to instrument failure and /or operational activity.

Optimizing Meteorological measurements
CALMET requires wind speed, wind direction, temperature, relative humidity, pressure, ceiling height and cloud cover to run. A global model (Weather Research and Forecasting (WRF)) was used to obtain ceiling heights and cloud cover. Temperature and Relative humidity were deemed stable across the site and as such only required a single measurement on site. Wind speed (WS) and wind direction (WD) do need to be measured to account for topography. Ideally, WD and WS would be measured at stations placed between the source and each surrounding terrain features (e.g., elevated terrain, river valley, etc.) likely to effect winds at or near the source. The optimal number of Met Measurements required is 1 more than the number of terrain features effecting wind fields at the source.

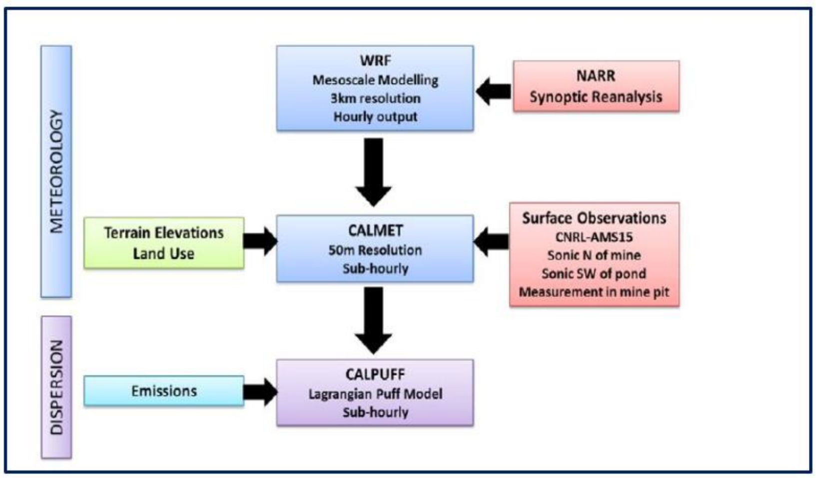


Figure 6. Meteorological Modelling Flowchart

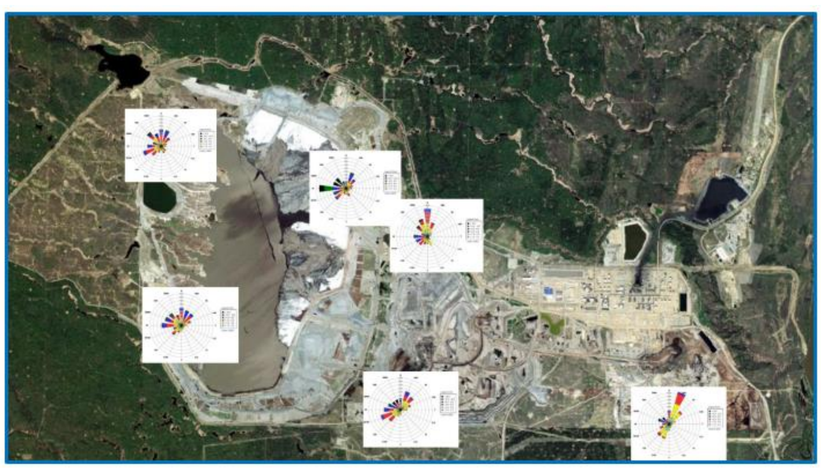
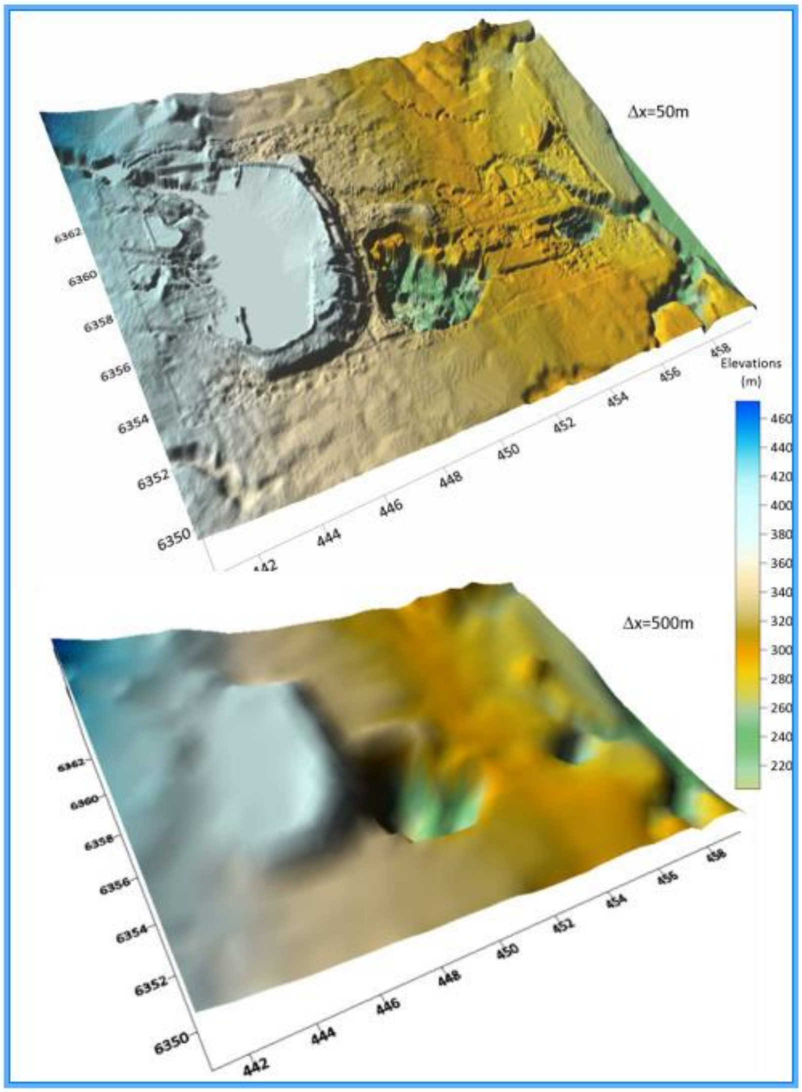


Figure 4. Wind roses observed around the pond and the mines from April 28 to May 10, 2018 (From RWDI, 2019)

Topic/Element	Comments/Critique
	The sheer scale of the Canadian Natural site with each area source being several kms wide and the complexity of the terrain causes winds to vary both vertically and horizontally. This complexity as such precludes those models that assume horizontally homogenous wind fields, such as gaussian plume models (AERMOD, US EPA 2019), as the forward model in IDM or a backward Lagrangian Stochastic (bLS) model, such as WindTrax (Flesch et al. 1994). CALPUFF provides the 3-D modelling approach required to resolve the landscape features and resulting 3D boundary layer meteorology. Other 3-D models could be used but would come with their own drawbacks. Computational Fluid Dynamics (CFD) for instance would require each terrain feature to be represented explicitly and would be prohibitively costly and time consuming to use. The WRF model could also be used but would also be very time consuming to run at the high resolution required to fully define site features. A hybrid model which combines WRF prognostic model data at a resolution of 1 to 3 km (both provided adequate results), CALMET at 50 m along with measured on site meteorology was ultimately used by RWDI.  *Figure 5. Terrain elevations over the Horizon facility at 50m and 500m resolution* RWDI put a meteorological station within the mine and modelled the wind fields within and compared model to measurement. CALMET was initialized with surface observations supplemented with WRF for meteorological values Results indicated good agreement between modelled meteorology and measurement despite the complex terrain of the mine regardless of whether 1 km × 1 km or 3 km × 3 km WRF data was used.

Topic/Element	Comments/Critique
	Logistics with Concentration Measurements **Siting Monitoring Stations** Four monitoring stations/sensors were deemed optimal as a compromise between the need for necessary data and budget, availability and logistics. Sensors should be placed in a manner such that at any given time (i.e., under any expected wind conditions) one or two sensors are downwind of the source while the remaining sensors can be used to monitor for background. Sensors should be placed away from terrain features and far enough from the source to avoid picking up on discrete events impacting the source (e.g., wind gusts, recirculation, etc.). Sensors should also be located close enough to the source to be able to distinguish ΔC above background and to avoid picking up on other nearby sources. Ideally, RWDI deemed the optimal range for GHG sensors to be 150-400 m for the site but sensors were placed between 50 and 900 m away from the area sources due to accessibility issues and the need to not interfere with site operations. The 50 m spacing required CALMET to run with 50 m resolution. **External/interfering Sources** Mine emissions from the mine itself makes it impossible to place sensors in such a manner that would allow no interference from mine emissions. Although sensors should be placed as far away from high emission sources (e.g., the haul road) these still need to be removed from the dataset. To account for these in mine emissions, GPS co-ordinates and fuel consumption data were used alongside emission factors to populate a CALPUFF run to generate concentrations at sensor locations. These concentrations were then removed from the measurements at the station prior to running IDM. **Considerations for sensors** The CH4 background, as measured by RWDI was found to be ~2 ppm with ΔC up to 0.2 ppm. The CO2 background was between 400 and 500 ppm, with a diurnal variation as large as 140 ppm, and a ΔC up to 30 ppm. Instrumentation employed need to be able to track these concentrations accurately and precisely. The LGR-UGGA employed can operate between 5-40 ˚C and required heated shelters during winter. Multipoint cross calibration is required but RWDI noted this was easier with the LGR-UGGA than with previously employed open path instrumentation. Sensors also did not require any post campaign corrections for pressure, temperature and path length as was the case with open path instrumentation previously deployed. **Background Considerations** For use as a background RWDI calculated a 15-minute background time series based on a weighted running-average (centred, ±30 min). This was done to average data from multiple stations that may act as background stations at a given point in time and to fill in gaps where no adequate background could be obtained. In the case of CO_2 background subtraction is not straightforward largely due to the natural variability induced by the landscape and vegetation (particularly west of the pond). This was evidence by the diurnal trend observed at night that increased by >100 ppm relative to daytime measurements. This led to a concentration gradient above the source with the downwind stations measuring lower concentrations than the background. During the day this is also anticipated to occur with a concentration gradient increasing across the pond and potentially biasing the measured emission rates upward. A combination of the prementioned effects also meant that a background station placed 1.5 km west of the site was not able to provide a “workable” background.
Analysis/Results	The four analysis steps to carry out the IDM method include: 1. Ambient GHG Monitoring 2. Calculation of Net Measured Impact caused by area source (including background subtraction, subtraction of interfering sources, and filtering of data effected by other external interference) 3. Forward modelling after dividing area sources in subunits assigning unit emission rates 4. Inversion using a statistical approach which allows the retrieval of best estimates and associated uncertainties.

Topic/Element	Comments/Critique

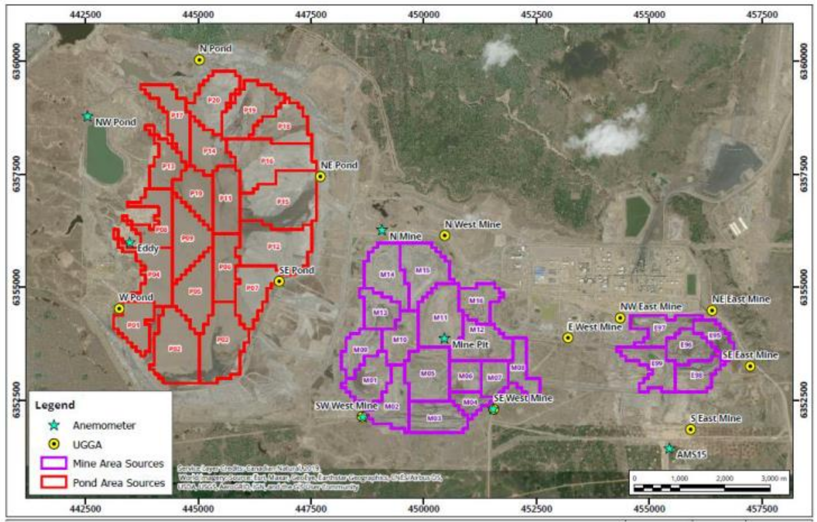


Figure 2. Sub-areas and monitoring locations for CALPUFF-IDM IDM (Fall 2019 campaign)

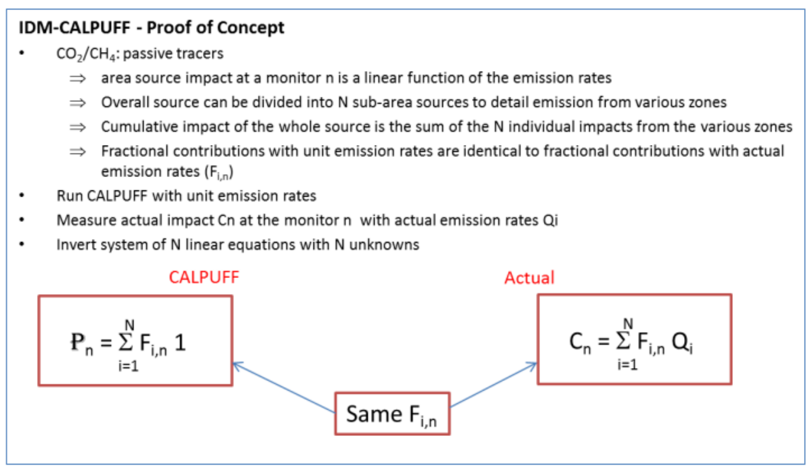


Figure 3. Inverse Dispersion Modelling – Concept Diagram (from RWDI, 2017) for N sub-areas sources with emission rate Qi, leading to a cumulative observed concentration Cn at monitoring site n. Pn is the modelled concentration assuming unit emission rate.

The CALMET modelling domain extended over a 19 km by 15 km area which was centred on the horizon facility and contained the tailings pond and mine. The modelling domain was setup with 380 x 300 grid points (50 m horizontal resolution). Canadian Natural provided updated terrain and high-resolution satellite imagery (process to generate land use datasets) including an accurate outline of the tailings pond were provided prior to each campaign. Albedo, Bowen ratio, and surface roughness were assigned according to the AEP and BC MOE air dispersion modelling guidelines. Roughness over the pond was increased to match observed values (derived from 3-D anemometers on site). Additionally, a "rough" barren land category was also created to depict the nature of the mine pit.

Topic/Element	Comments/Critique

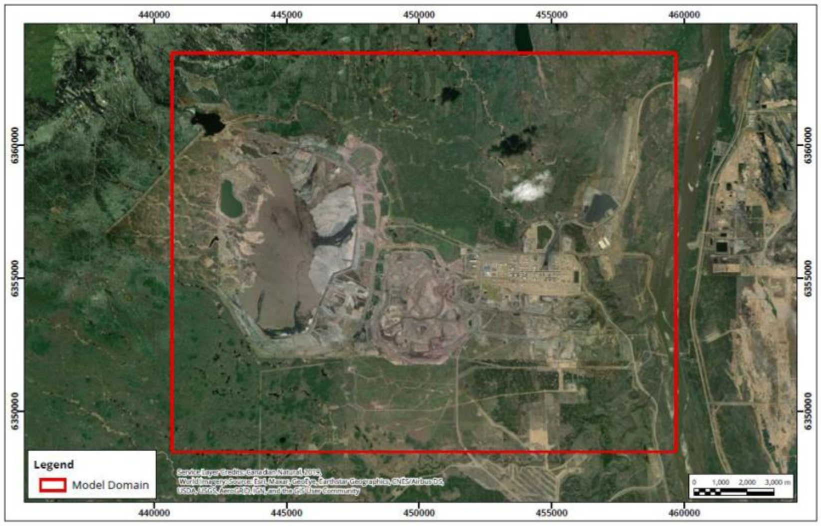


Figure 7. Extent of the CALMET-CALPUFF modelling domain, overlaying a satellite picture of the site (Fall 2019 campaign.

CALMET was run with 15-minute time steps and run in full observational model. Prognostic WRF data was reformatted as upper air soundings using UAMAKE. This non-default method of using WRF in CALMET was done to reduce the impact of WRF relative to the better surface observation data and to account for the finer scale terrain effects (particularly in the mine).

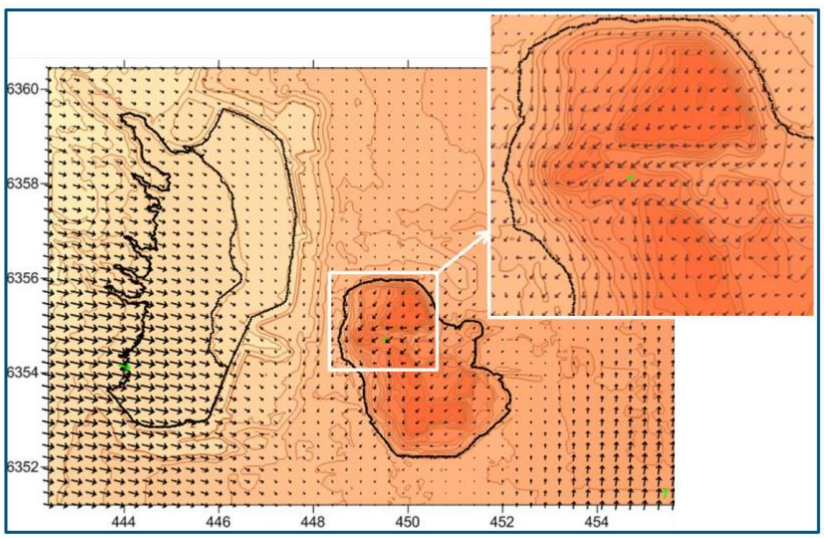
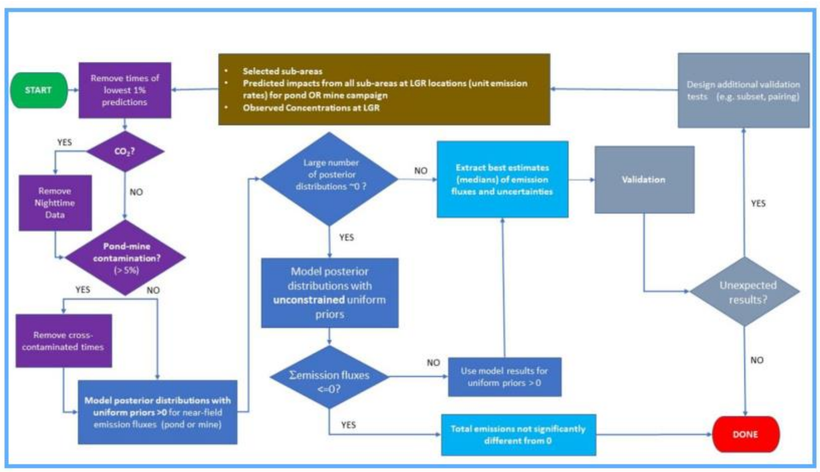
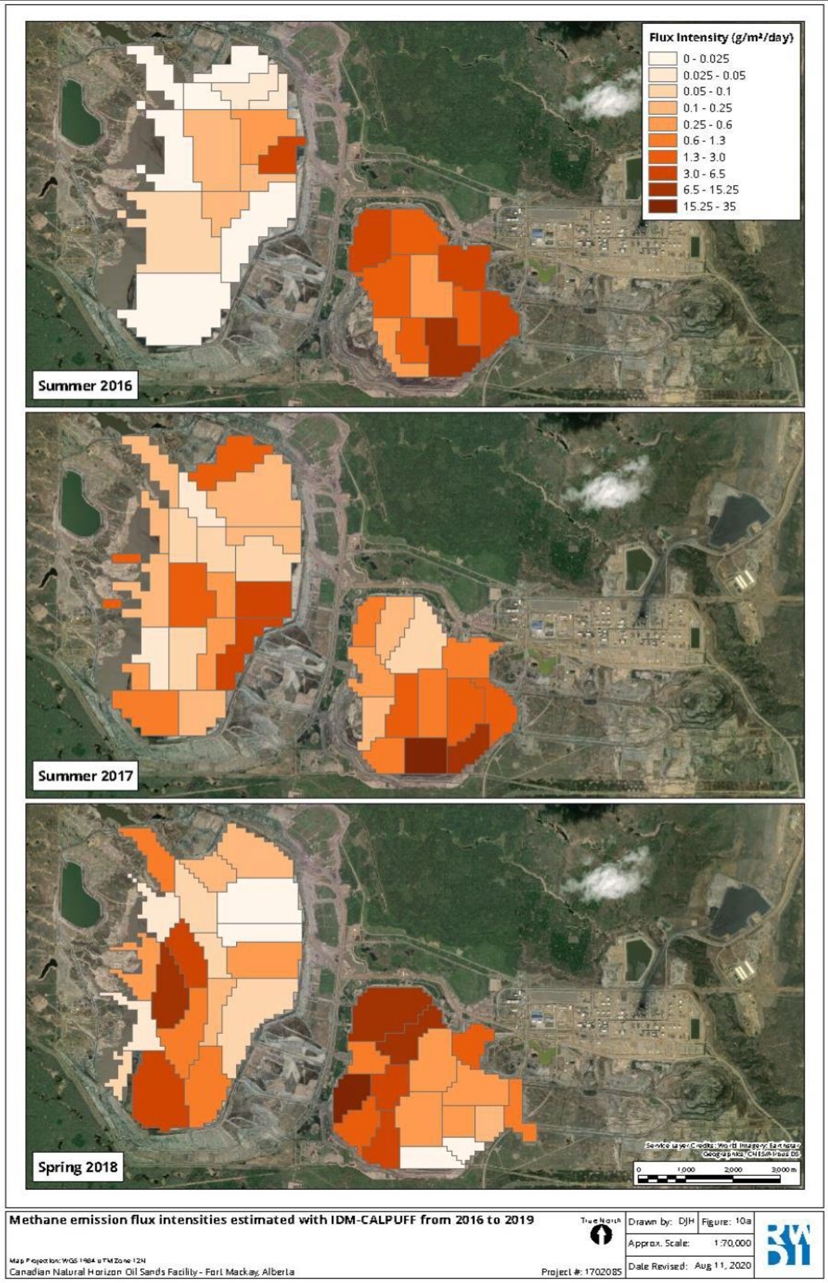
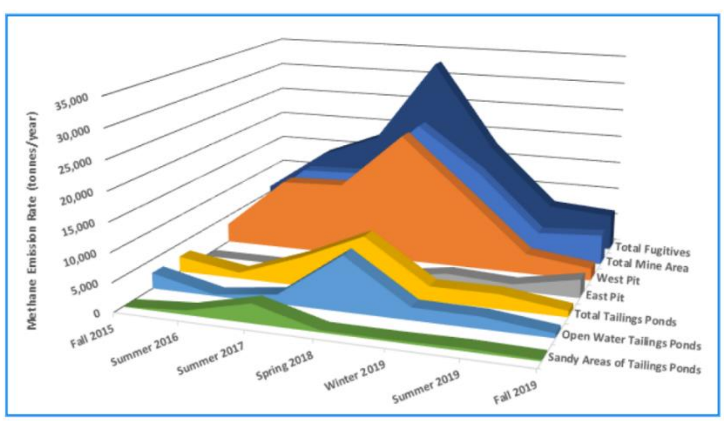


Figure 8. Vector plot of the CALMET 10 m wind on September 8, 2016 at 1AM. The whole domain winds are plotted every few grid points for clarity and winds (inset, west mine pit) are plotted every other grid point. Observed winds are plotted in green (RWDI, 2017).

CALPUFF (model version 7.0) was run with 15-minute timesteps, using regulatory model options as per the Alberta Air Quality Modelling Guidelines. The more computationally expensive SLUG mode was used and CALPUFF was driven by sub-hourly wind fields (generated by CALMET) with dispersion coefficients internally calculating with CALMET. For the forward dispersion modelling each source sub-area was further divided into 100 m by 100 m cells which were each modelled as an area source set at ground height with a unit emission rate (1 $g/s/m^2$) and an initial sigma-z of 0.2 m (experiments on modelling bias indicate this should be increased to 2). This further division was required to appropriately account for terrain features (particularly within the mine emissions source). The modelled contributions of all of these small sources were then summed up into the larger sub areas (20 for the pond, 16 for the main pit and 5 for the east pit) prior to performing the inversion.

Topic/Element	Comments/Critique
	The inversion performed was then based on a Bayesian statistical approach. This was done as a simple matrix inversion (which would have required 1 data point (i.e., time step) for each sub area (or 1 equation per sub area) cannot be applied due to the number of zeros present in the model (these occur when the model predicts no contribution form a specific area source to a specific site at a specific time step. Instead of a simple matrix inversion the system can be solved by framing the solution as a regression problem by aggregating all observations prediction over all time steps. The Bayesian approach that was ultimately employed and refined accounts for uncertainties in both measurements and model predictions and allows the imposition of prior limits on unknown parameters (e.g., limiting methane flux to non-negative values for instance). The Bayesian approach is also more efficient and more accurately characterizes uncertainties associated with the analysis by calculating complete probability distributions (which can be non-gaussian as opposed to the gaussian distributions assumed by multilinear regression analysis). The Bayesian model runs require a Markov Chain Monte Carlo (MCMC) Algorithm to solve for multiple parameters of the Bayesian expression prior to conversion onto an optimized value. Although this process can be semi-automated in R or other statistical software it typically required 10 reruns to arrive at optimal parameter ranges and 20-40 reruns prior to finally conversion on parameters. Parameters are typically modified by the user prior to reruns and final reruns are typically performed with 300,000 iterations. The entire process takes ~1-2 hours.  **Figure 2: Procedure applied for the pre-processing of Bayesian model input (purple), statistical inversion (dark blue), summary statistics (light blue), assessment (grey), and preparation of additional tests (brown).**

Topic/Element	Comments/Critique
	

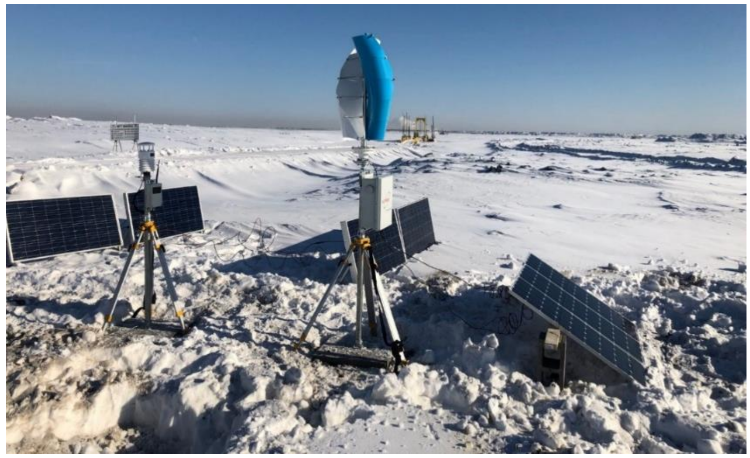
Topic/Element	Comments/Critique
	  ***Figure 2.*** *Methane Emissions Quantified by IDM-CALPUFF since 2015*

Topic/Element	Comments/Critique
	Spatial variation was observed at the pond with higher emissions observed at the centre of the pond (the deepest part of the pond) and, in more recent campaigns, the southern part of the pond. This is consistent with observed bubbling in the centre of the pond and increased bubbling at the south end of the pond. Mine spatial variability tracked freshly disturbed areas including near the vertical mine faces in the freshly mined area. An additional hot spot was identified by RWDI (as well as S3) in the northwestern part of the pit that could not be associated with mine activities and remains unexplained. Temporal variability at the site was not seasonally correlated (beyond the short period following ice breakup) nor correlated well with production at the facility. This was particularly the case with the mine emissions which presumably tracked well with specific mining activities during measurement campaigns. The results indicate that although year-round measurements would be ideal, short seasonal measurements are not likely to provide a much-improved emission estimate over a single summer measurement campaign.
Comparison to Flux Measurements	IDM using CALMET/CALPUFF vs. Flux Measurement Flux measurements • bottom-up approach • 30-minute snapshot of emissions • small area (i.e., 0.13 m^2). This is inadequate as many fugitive emissions sources such as open pit mines and tailings ponds have surface areas on the order of square kilometres. • Disturbs surface IDM using CALMET/CALPUFF • Top-down approach • Can monitor temporal trends • Large emission source • Non-disturbance measurement • Safer deployment of instrumentation (no need to place flux chambers over the pond) • Reduced operational disruption • Ability to identify additional source areas (e.g., identification of the beach as a source of CH_4) • Ability to track vertical mine faces emissions.
Gaps/Limitations in Measurement or Analysis	In addition to measurement systems being identical a rigorous cross calibration should be performed on deployed instrumentation.
Compensation for Background Concentrations?	Background compensation is achieved by upwind monitoring stations. In the case of CO_2, whose background measurement was more problematic (due to natural sources/sinks) every combination of time step and site that was predicted to have no impact from the mine was considered to provide a background measurement of CO_2. RWDI employed a 1 hour rolling weighted average (centred, ± 30 min) to generate a 15-minute timeseries of background data. A background station previously implemented and placed hundreds of meters away from the source was unable to provide an adequate background for CO_2. This is largely due to the interference from natural sources and sinks that led to diurnal variability of up to 170 ppm (an order of magnitude larger than ΔC). Although less pronounced CH_4 from the sources also impacted the background site. Upwind stations, as defined by local meteorology as such provide more adequate backgrounds.
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	
Is there a lower-cost alternative measurement approach?	
Recommendations for Improvement	Authors Recommend: • A standardized IDM model be identified along with a standardized statistical treatment approach to allow for future use and further characterization of the IDM approach. This may be achieved by a dedicated application which is under regulator control.

A.5 Luxmux Final Report

Topic/Element	Comments/Critique
Report Title/ Authors/Date	Area Fugitive Emissions Measurements of Methane & Carbon Dioxide – Emissions Reductions Alberta Final Report, Luxmux Technology Corporation, Rick Nelson, October 30, 2020
Theoretical/Conceptual Framework/General Approach	The Luxmux approach is largely based on the ARMS SmartPole system. The system couples an infrared based sensor measuring CH_4, CO_2 and H_2O with a meteorological station. Each Meteorological station measures wind speed, wind direction, air pressure, air temperature, and relative humidity and has a GPS for location and elevation information. SmartPoles are placed around and within the area source of interest. The measurement from the fixed ARMS Smartpole systems is coupled to a cloud-based flux model to estimate emission fluxes. The proprietary ARMS SmartPole system was being developed by Luxmux during the project and went through several prototype variants advancing to what Luxmux deemed a commercial ready instrument. Luxmux filed a US patent on February 7, 2020 for the device.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	The Luxmux concentration sensor works by drawing in ambient gases into a gas cell. The concentration sensor initially employed a Herriott cell which relies on spherical mirrors that allow a single beam of light to make multiple passes across the measurement cell in doing so increasing the effective path length. In the gas cell the gas is irradiated with different wavelengths of light with each wavelength tuned to the absorption of a specific gas. The Luxmux sensor uses light of 7.6, 4.26 and 2.9 µm wavelengths to measure CH_4, CO_2 and H_2O, respectively. Each SmartPole is equipped with a solar panel and batteries and communicated with a central pole. Data are automatically backed up to the central pole and to the cloud. Every pole has GPS/elevation and a meteorological station. The met data are used alongside the concentration data to feed into Luxmux's air dispersion model. The flux measurement is based on comparison of the concentration data observed coming out of the zone of interest relative to the concentration data coming out of the zone of interest. Luxmux did not provide any additional detail related to the air dispersion model used to estimate fluxes. The Herriot cell which was 37.4 cm in length was capable of achieving effective path lengths of 35.9 m but this was not sufficient to detect ppb concentrations of either CH_4 or CO_2. Luxmux then moved to an intracavity laser absorption spectroscopy approach. The Luxmux approach put the gas cell within the laser cavity with fibre optics used as the propagating media thus removing the need for alignment. The approach allowed enhanced pathlength amplification and allowed increased instrument sensitivity (500 ppb for CO_2). The technique is however highly sensitive to temperature changes and the cell was stabilized via the use of a thermal electric cooler or TEC (alpha prototype). The alpha prototype (pictured in Figure 1 from the final report and included below) was deployed in Spring 2018 alongside LGR CRDS instrumentation for comparison.  *Luxmux Alpha Prototype ARMS SmartPole in tailings pond measuring CH4, CO2, wind speed and wind direction*

Topic/Element	Comments/Critique
	The TEC was found to be too power hungry and Luxmux opted to instead adjust laser injection currents to compensate of ambient temperature fluctuations (beta prototype). This beta prototype current compensation method required too frequent current compensation during wintertime testing and was unable to provide a usable measurement. Five beta prototype instruments (pictured in Figure 5 from the final report and included below) were deployed around the pond in Winter 2019.



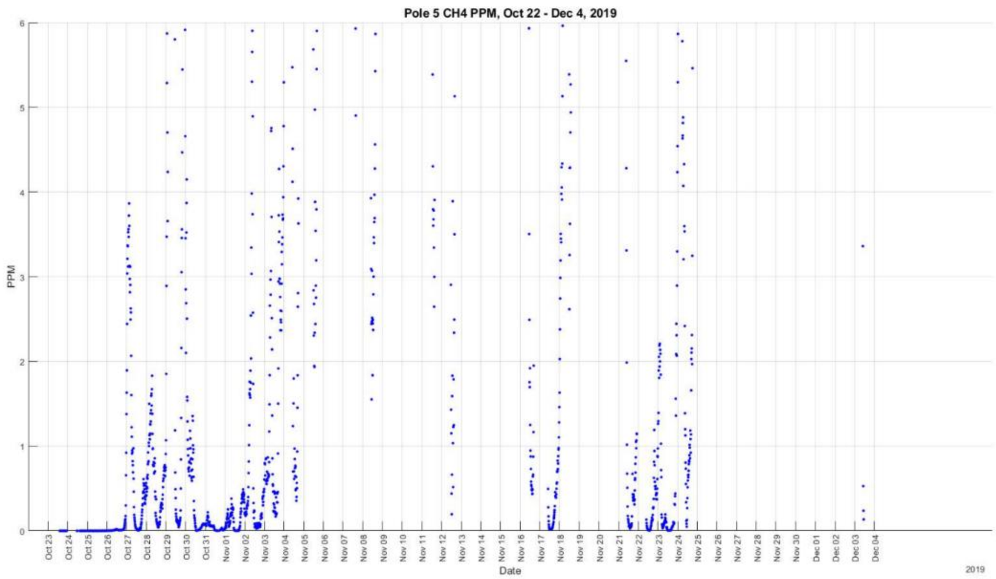
ARMS SMartoile deployment location #1, measurement near Las Gatos deployed by RWDI

Luxmux moved away from the intracavity approach and back to a Herriott cell type configuration. To achieve the necessary sensitivity, they attempted a variant with a mid IR laser tuned (all variants up to this point had used Near-IR wavelengths). Absorption of CH4 and CO2 in the mid-IR is 100 times stronger than in the near-IR. The detector, detection method and workup algorithm were updated at this point as well. The detection works by comparing the detector signal with laser on and sampling the gases to a dark value measured when the laser is off. Measuring these in succession in the field allows the two to be matched in terms of temperature and allows the system to be deployed without temperature controlling the gas cell. Employing a reference wavelength not absorbed by any gases allows normalization of detected signal. Concentration values are then obtained by comparison of normalized signal to calibration curves. The method offers a 10s measurement.

Three sensors of this variant, dubbed TRL9, were deployed at the pond in November 2019. The solar panel and battery pack assembly (which had come about as a result of several prototypes) was able to keep the instruments running without interruption throughout the campaign.

ARMS SmartPole TRL9 deployment

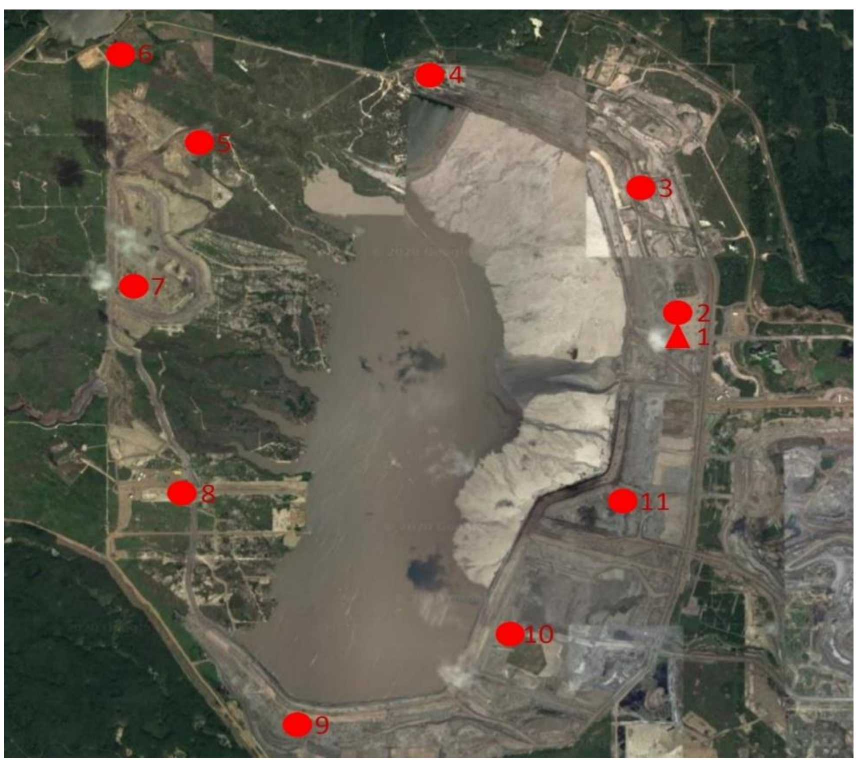
<table>
<tr><th>Topic/Element</th><th>Comments/Critique</th></tr>
<tr><td></td><td>



Pole 5 CH4 Measurements

The final variant of the instrument was based on the TRL9 prototype but with an improved photovoltaic based detector (previous prototype used a photoconductive detector).

A planned spring 2019 field deployment was cancelled due to COVID 19. The proposed study layout (pictured below) consisted of 10 sensors deployed around the Horizon Pond.



Planned deployment sites

</td></tr>
<tr><td>Additional Methodology Considerations</td><td>A concentration measurement was prototyped and developed into a commercial ready instrument housed in a weatherproof NEMA 4 enclosure.</td></tr>
</table>

<table>
<tr><th>Topic/Element</th><th>Comments/Critique</th></tr>
<tr><td></td><td>
<table>
<tr><th>Success Metric</th><th>Commercialization Target* (Lost Gatos Ultraportable Methane & Carbon Dioxide Specifications)</th><th>Project Target</th><th>Achievements to Date (At project startup)</th><th>Achievements to Date (December 2019)</th></tr>
<tr><td>Repeatability / Precision CO_2</td><td><300 ppb</td><td><10 ppb</td><td>1 ppm</td><td>100 ppb</td></tr>
<tr><td>Repeatability / Precision CH_4</td><td><2 ppb</td><td><100 ppb</td><td>10 ppm</td><td>5 ppb</td></tr>
<tr><td>Response Time</td><td>1 second</td><td>1 second</td><td>30 second</td><td>10s</td></tr>
<tr><td>Measurement Range CO_2</td><td>1 - 2000 ppm</td><td>1ppm - 100,000 ppm</td><td>1000 ppm – 10,000 ppm</td><td>0.1ppm - 100%</td></tr>
<tr><td>Measurement Range CH_4</td><td>0.01 - 100 ppm</td><td>10ppm - 10,000 ppm</td><td>1 ppm – 10,000 ppm</td><td>0.01ppm - 20%</td></tr>
<tr><td>Ambient Humidity</td><td><98% non-condensing</td><td><98% non-condensing</td><td>Have not measured</td><td><98% non-condensing</td></tr>
<tr><td>Operating Temperature</td><td>5 to 45C</td><td>-40C to +40C</td><td>10C – 30C</td><td>-40C to +40C</td></tr>
<tr><td>Power Requirements</td><td>Battery / Solar</td><td>Battery / Solar/Generator</td><td>Battery / Solar/Generator</td><td>Battery / Solar/ Generator</td></tr>
</table>

The SmartPole package incorporation of auxiliary meteorological parameter measurement may help the Luxmux sensor ultimately provide a better instrumentation package for flux measurements although no details were provided as to how the sensors would ultimately be used to obtain emission fluxes. Air dispersion modelling was mentioned and Luxmux indicated they had been developing a model but no further details were provided.</td></tr>
<tr><td>Analysis/Results</td><td>No data analysis beyond the initial algorithm required to obtain concentration measurement data was outlined. Dispersion modelling was said to take place in the cloud, but no specific details were provided beyond this.</td></tr>
<tr><td>Comparison to Flux Measurements</td><td>Although not demonstrated in the final report a network of Luxmux SmatPole sensors could be coupled with inverse dispersion modelling to provide a flux measurement. In this case:

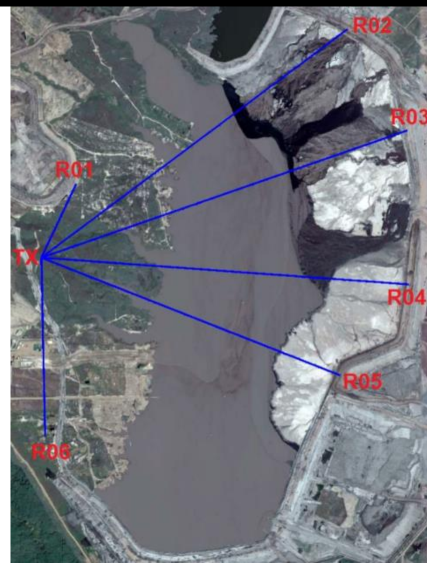
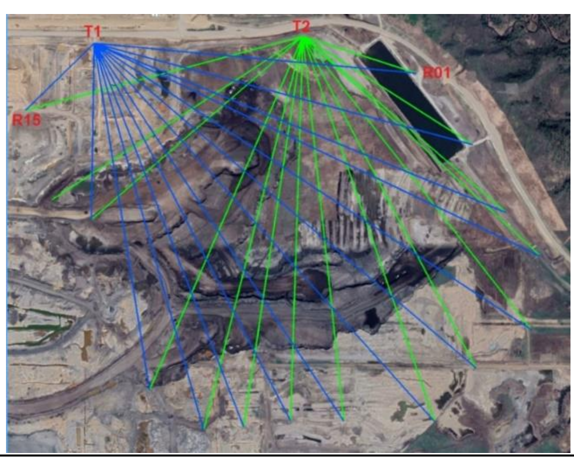
Flux chamber measurements
• bottom-up approach
• 30-minute snapshot of emissions
• small area (i.e., 0.13 m^2). This is inadequate as many fugitive emissions sources such as open pit mines and tailings ponds have surface areas on the order of square kilometres.
• Disturbs surface

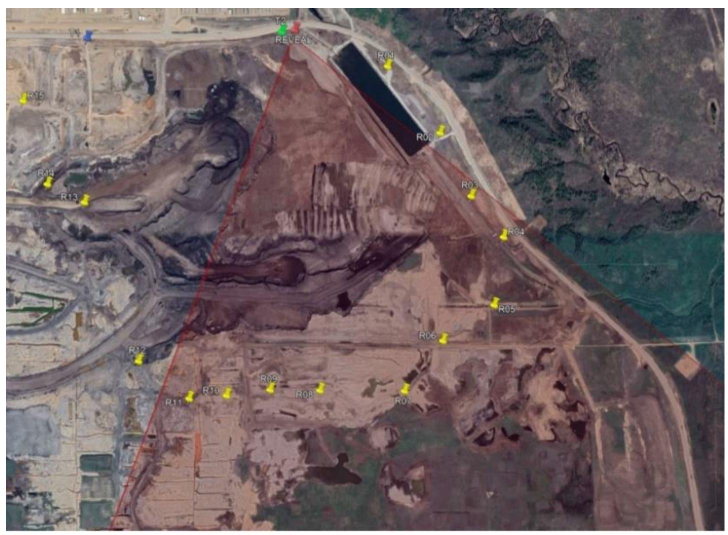
Luxmux SmartPoles when coupled to IDM using CALMET/CALPUFF
• Top-down approach
• Can monitor temporal trends
• Large emission source
• Non-disturbance measurement
• Safer deployment of instrumentation (no need to place flux chambers over the pond)
• Reduced operational disruption</td></tr>
<tr><td>Gaps/Limitations in Measurement or Analysis</td><td>A network of SmartPole sensors has yet to be deployed successfully to measure are emission fluxes.

The long-term stability, durability and longevity of the instrument is unknown/unproven.</td></tr>
<tr><td>Compensation for Background Concentrations?</td><td>N/A – an area flux estimate using the ARMS SmartPole sensors has yet to be demonstrated.</td></tr>
<tr><td>Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?</td><td></td></tr>
<tr><td>Is there a lower-cost alternative measurement approach?</td><td>The SmartPoles offer a fixed-point measurement that is offered by several other manufacturers including the Los Gatos Research sensors that were deployed by other project participants. Due to the prototype nature of the Luxmux sensor it is as of yet unclear what the cost of the instrument will ultimately be a lower-cost option.</td></tr>
<tr><td>Recommendations for Improvement</td><td>It is unclear if the sensor has been characterized with respect to interference from other ambient species that may be present in ambient air.</td></tr>
</table>

A.6 S3 Final Report

Topic/Element	Comments/Critique
Report Title/ Authors/Date	GreenLITE CO_2 & CH_4 Concentration Measurement, 2-D Mapping, and Emissions Estimation Demonstration with REVEAL 2-D Wind Field Mapping Spectral Sensor Solutions and Atmospheric and Environmental Research Jeremy Dobler (Point of Contact) December 24, 2019
Theoretical/ Conceptual Framework/ General Approach	GreenLITE™ is currently in the pilot phase system: Laser absorption spectroscopy is combined with state-of-the-art radiative transfer retrieval methods to provide near-real-time concentrations. Once coupled with high resolution meteorological data GreenLITE can be used to provide emissions estimates. The GreenLITE system consists of one or more optical transceivers and some number of retroreflectors arranged such that a clear line of sight exits between each transceiver and the reflector. A transceiver consists of a climate-controlled equipment cabinet with an optical head that is mounted on a two-axis mechanical scanner. Intensity modulated continuous wave (IMCW) laser absorption spectroscopy (LAS) is used. Two laser sources are selected such that one is absorbed by the gas of interest and one is not. The differential absorption of these two wavelengths by the gas can be directly converted to an optical depth which can be integrated to obtain a concentration. The system's use of IMCW makes it immune to scintillation and other noise associated with long-path laser techniques. Once optical densities have been obtained and concentrations calculated the SCHICHEM model is used to estimate emission rates. REVEAL - 2-D vector mapping was performed with a Real-time Eye-safe Visualization, Evaluation and Analysis Lidar (REVEAL). REVEAL is capable of detecting, mapping, and tracking aerosol plumes at distances up to 15 km and provides the capability to derive wide-area 2-D horizontal vector wind field information by applying an advanced algorithm to the motion of aerosol features in the plumes and the surrounding atmosphere. REVEAL is an elastic backscatter lidar that uses an eye-safe micro-pulse laser (λ = 1.5 µm) to transmit laser pulses through the atmosphere. By precisely recording the time of returned particles, calculating the travel distance and plotting a histogram of the travel times/distances a relative measurement of aerosol density as a function of distance can be computed. The laser is mounted on a mechanical scanner than scans a horizontal plane to create 2-D map. Processing algorithms are then able to identify aerosol features or plumes. A 2-D wind field can then be generated by comparing two successive scans (aerosol maps) and calculating the cross-correlation of the aerosol features in the aerosol maps. The system has a maximum unambiguous distance that is dependent on the pulse repetition frequency (PRF) of the laser. The laser was operated at 15 kHz enabling an unambiguous fold-over range of 10 km and a range resolution of 7.67 m. At night this distance is reduced to range of a few km due to the need to reduce system sensitivity to avoid interference from the solar background.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	S3 and AER deployed two GreenLITE systems and a REVEAL system at the CNRL Horizon site. **GreenLITE Pond (June 17 – October 27):** GreenLITE was installed over the tailings pond in June 2019 to measure path-integrated CO_2 and CH_4 concentrations for a continuous period of approximately 13 weeks. A single transceiver setup was used. The objective here was to demonstrate the conversion of raw concentration data into estimates of total emissions.

Topic/Element	Comments/Critique
	 Instrumentation were deployed such that one edge of the pond had two collocated transceivers with the reflectors placed at various points across the area source. Each of the collocated transceivers measured a different gas in a single transceiver non-mapping arrangement. A total of six chords were established, with four crossing over some portion of the pond and two serving as background chords (assuming winds are predominantly from the west). Chord lengths ranged from 1 km to 4.8 km. A weather station which provided met data and a 3-D sonic anemometer (for vertical wind data) were collocated to the transceiver. Transceivers were each installed on a set of four concrete blocks and powered by a single diesel-powered generator. Each of the reflectors and the weather station were mounted on two concrete blocks. An additional 300 m chord was also deployed to roughly coincide with the measurement path being monitoring by the UofA FTIR and two Boreal Laser GasFinder systems (operated by UofA). This chord is much shorter than other chords and shorter than what the GreenLITE instrument was optimized for but used as the FTIR is limited to a maximum measurement distance of ~ 350 m. **GreenLITE Mine (September 11 – October 26):** GreenLITE was installed over the east mine pit in a dual-transceiver configuration to map CH_4 concentration. A shorter range 2.5 km system was used here as the 5 km system was still in place at the pond. For mapping the two transceivers were separated by 960 m and must be separated by a distance on the order of half the width of the area to be measured. Fifteen reflectors were deployed, 11 reflectors around the east and south edge of the mine and four reflectors in the mine. Chord lengths ranged from 440 m to 2.4 km with an average chord length of 1.6 km. 

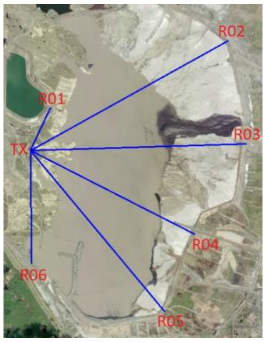
Topic/Element	Comments/Critique
	Transceivers were mounted as described for the pond, but reflectors and the weather station were each mounted on a single concrete block. Mining and S3 had trouble coming up with mine placement options for reflectors that were acceptable to both parties. One reflector, R12, was relocated twice during the deployment period to accommodate mining operations. These moves were performed by mining and S3 was able to remotely adjust operations for measurements to continue. Installation at the mine was performed by S3 personnel over four days. **REVEAL (October 19 – October 26):** REVEAL was installed to overlap a portion of the east mine and provide 2-D emission distribution – proof-of-concept trial. Due to the newer generation REVEAL instruments being deployed elsewhere the first GEN non-weatherproof reveal was used for this work. It was mounted in the back of a cube van and situated next to the T2 transceiver overlooking the East Mine. This limited the scanning capability of the instrument, but it was still able to scan 70˚ in azimuth and cover ~60% of the area contained within the GreenLITE footprint.  Installation took half a day. “REVEAL scans were performed at a fixed elevation angle chosen to capture as much of the air flow at the opening of the mine as possible while attempting to minimize interference from hard targets such as towers, poles, and trees.”
Additional Methodology Considerations	GreenLITE utilizes all-fibre laser components which enables it to operate without precise optical alignment as is often required with other lidar systems. Finally, laser wavelengths chosen are useful at wavelengths up to 5 km while remaining below the eye-safety limit. The strength of the technique is realized when multiple chords, or transceiver to reflector paths, are setup across a measured surface. If two transceivers are employed and their optical paths intersect a 2-D reconstruction of the distribution of gas concentrations can be obtained. This is possible for area sources up to 25 km^2. The GreenLITE system is internet connected and data are uploaded to a cloud-based processing, storage and display framework where emissions are computed. A web-based interface provides near-real-time display of the data and can send alerts if user set thresholds are reached. GreenLITE pond: Chord samples are 30-second average concentrations measurements.

Topic/Element	Comments/Critique
	Loss of generator power at the two pond transceivers led to loss of two weeks of data. CH4 measuring transceiver did not automatically come back online after power failure and remained offline for two weeks until S3 came out to site to restart sampling. Pond Reflectors were rinsed with distilled water on July 24. Reflector R05 was found to be damaged and was replaced on September 7. GreenLITE Mine: Each sample is a 10-second average concentration measurement. Brief data interruptions due to generator maintenance. Reflectors were cleaned with distilled water on October 18th. R12-R14 were particularly dusty due to proximity to mine haul roads. (how did this effect sensitivity?) REVEAL: Prototype used was not designed for remote continuous operation leading to some data gaps.
Analysis/Results	The GreenLITE data processing and analytics system works to “convert observed differential transmission/optical depth values into xCH_4 or xCO_2 chord concentrations, compute 2-D distributions of gas concentrations, estimate flow rates/fluxes, and distribute these products via standard open-source network-based protocols”. Analysis generally follows a multistep process: 1) Conversion of observed optical depths into path-integrated concentration values of xCH_4/xCO_2 along individual chords. This is done by incorporating collocated weather information (e.g., temperature, relative humidity, surface pressure) in an iterative basis scheme for computing dry-air mixing ratio. The scheme employs a line-by-line radiative transfer (RT) model to minimize the differences between observed optical depths and those computed using the embedded RT model, along with local temperature, moisture and pressure measurements. 2) Computation of 2-D distributions of xCH_4 concentrations (mine only). This was done by combining the local wind information to create a 2-D estimate of the concentration that lies within the plane defined by the height of the chords and their intersecting horizontal area. This is done using a sparse tomographic approach (or sectioning) that attempts to minimize error between a model of the field and the observed chord values. Wind speed and direction are used to constrain the direction and strength of dispersion, and the chord intersect values aid in initial parameter estimates. 3) Off-line estimation of xCH_4 and xCO_2 using an iterative SCICHEM modelling approach (other approaches are also currently under consideration. Briefly, SCICHEM is run using continuous area source release scenarios with the input being the integrated measurements that span the release area after background correction. SCICHEM utilizes rectangular release areas so these are centred on the measured chords. The model then runs with an initial emission rate with the difference between modelled and measured values being used to adjust the emission rate in an iterative process until the measured and modelled concentrations converged within a threshold value (e.g., 0.0005 ppm). This leads to an emission rate that can then be converted to a normalized flux (in g/s/m^2) based on the area of the rectangle modelled. The flux can then be averaged hourly and scaled by the estimated total area of the emitting source. 4) Construction of system- and application-specific analytics to enable remote access via a web portal.

Topic/Element	Comments/Critique
	GreenLITE pond: The onshore chords were used to estimate and correct for the varying background concentrations primarily driven by biogenic sources and global atmospheric background. Data was filtered and no emission estimates were calculated when winds were blowing outside of the acceptable wind range of 190° to 350°. Outside this range the pond is expected to contaminate the background chords. Method provides hourly data that was used to examine the expected diurnal trend in the CO_2 flux and lack of a defined diurnal trend for CH4. CO_2 concentrations seem to track the biogenic background well with the exception of specific instances, primarily at night, and during nominal depletion events. Tried to assess the effect of pond water temperature on fluxes and found little correlation with the exception of a specific event between 8/16-8/19 that showed a distinct enhancement in CO_2 fluxes associated with a distinct decrease in maximum pond temperature. Emission changes are potentially more strongly associated with process changes. CH_4 emission rates over the pond are more consistent. They appear to be moderated by the planetary boundary layer and wafting from outside sources that contaminate the background chords. There also appears to be a weak correlation between CH_4 emissions and periods of enhanced CO_2 concentrations. GreenLITE mine: The chords along the northwest corner were deemed background chords. Some CH_4 modulation following diurnal cycles was observed (likely boundary effect). Background spikes were encountered and were assumed to be indicative of contamination of the background chords. Background chord selection for the mine was more difficult than for the pond: "Winds from the S to E may push mine emissions towards the background chords; winds from the N to NW may also lead to contamination of the background chords due to the presence of basal wells on the north side of the mine; and winds from the W may be influenced by other onsite factors such as crusher activity." 2-D reconstruction of observed concentrations was performed using both a plume-based model and a newly developed box-based model. Both provide consistent results and depict and track similar macro-level features. The plume-based model however provides more detailed views and estimates of potential diffuse point source locations and associated concentration. The box-based model provides a sub-sector view of the distribution of concentrations values over the face of the mine. Reveal data was analyzed and wind fields generated but incorporation of these data into the 2-D mapping was beyond the scope of the project.
Comparison to Flux Measurements	Comparison to "installation overseen and operated under a collaboration between the UofA and RWDI" indicates the in situ measurements and the GREENLITE CO_2 data have a bias of approximately +2.1 ppm with a 1-sigma (1σ) value of ±3.9 ppm, and the CH_4 data have a bias of approximately -18 ppb with a 1-sigma (1σ) value of ±28 ppb.
Gaps/Limitations in Measurement or Analysis	Ability to differentiate between signal and noise is difficult, particularly for CO_2 considering interfering biogenic fluxes and the large variable atmospheric background. The GreenLITE method is generally designed for remote operations but reflectors eventually require cleaning due to dust buildup. This was problematic at the mine, particularly near the haul road, and could be an issue elsewhere if the site is impacted by off-site sources of aerosol (i.e., forest fire plumes). Regardless, the building up of dust on the mirrors would undoubtedly lead to loss of reflectivity and decline in instrument sensitivity. Longer term implementation of the technique would require that this decline be characterized and sensitivity-based cleaning thresholds or a regular cleaning schedule be established.
Compensation for Background Concentrations?	Background chords placed in the predominant upwind direction from the source are used for background correction.

Topic/Element	Comments/Critique
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	Instrumentation as required to establish additional background chords could help increase wind range where emission estimation is possible. Additional strategically located meteorological measurement stations would allow for more accurate dispersion modelling.
Is there a lower-cost alternative measurement approach?	A dual vertical chord approach might reduce expensive computational requirement and in the longer-term could lead to lower costs. However upfront instrumentation costs would be considerably increased. Alternative instrumentation options are potentially employable (e.g., OP-FTIR, LIDAR, etc.) but would lack some of the advantages offered by the eye-safe web connected solution offered by S3.
Recommendations for Improvement	Mentioned by the authors: • Additional strategically placed onsite met data or REVEAL integration could help ensure high quality emissions estimates. • More selective placement of background chords, or background chords in all directions would allow more accurate estimation from a wider range of wind directions. • An optimal dispersion model run time to establish stable meteorological conditions and release dispersion needs to be established. • Segmenting data into optimal sampling periods or time of day dependent analysis, particularly for CO_2, could help refine the ability to provide routine unbiased estimates of pond/mine emissions. • Dual vertically separated chords to explore flux gradients-based emissions. This could be compared to dispersion model-based emission and potentially eliminate the need for computationally expensive dispersion modelling. • Prior planning and stakeholder input to ensure chords are optimally placed and do not require location adjustments. • Hard-wired power, or generators with external fuel tanks, would increase system reliability and uptime. Additional recommendations: • Where REVEAL is not implemented, collocation of wind monitoring equipment with the transceiver on the edge of emissions source where background chords are measured is non-ideal. Winds measured over the source itself or downwind are more representative of met conditions during emissions. This is particularly important when dealing with the complex terrain of the mine or potential effects of the pond.

A.7 S3 Ice Breakup

Topic/Element	Comments/Critique
Report Title/ Authors/Date	GreenLITE CO_2 and CH_4 Concentration Measurement & Emissions Estimation of Tailings Pond Ice Breakup Spectral Sensor Solutions and Atmospheric and Environmental Research, Jeremy Dobler (Point of Contact), July 31, 2020
Theoretical/Conceptual Framework/General Approach	The approach relies on laser absorption spectroscopy combined with state-of-the-art radiative transfer retrieval methods alongside high-resolution modelled or on-site measured meteorological data to provide emission estimates. The spectroscopy measurement is achieved using two transceivers and multiple reflectors to measure CO_2 and CH_4 path integrated concentrations over path lengths up to 5 km. The GreenLITE method can be configured to provide two-dimensional (2-D) mapping of gas concentrations and estimated emissions over large open areas up to ~25 km^2. The solution provided allows for internet connected instrumentation and provides for a near real-time emission estimate to be monitored remotely. The solution provides an eye safe laser method.
Detailed Methodology (e.g., sampling plan, instrumentation utilized)	Two sophisticated internet connected (likely proprietary) transceivers were deployed alongside six reflectors to measure CO_2 and CH_4 concentrations and emissions during the annual breakup of the Horizon tailings pond surface ice. The instruments were deployed on March 15 and remain on site (due to the COVID-19 outbreak). The ice breakup covers the measurement period between March 18 and May 31. Instrumentation were deployed such that one edge of the pond had two collocated transceivers with the reflectors placed at various points across the area source. Each of the collocated transceivers measured a different gas. A total of six chords were established, with four crossing over some portion of the pond and two serving as background chords (assuming winds are predominantly from the west).  This report focused on attempting to measure emissions during the pond surface ice breakup. Previous field campaigns had captured an uptick in emissions but lacked the spatiotemporal resolution to examine the ice breakup with any depth. Two weather stations were collocated with the transceivers.
Additional Methodology Considerations	The locations of the reflectors were changed from the 2019 deployment – Authors noted this was done to provide more uniform coverage over the pond and to accommodate changes in site topography/operations. Transceivers were each installed on a set of four concrete blocks and powered by a single diesel-powered generator. 600 W draw of the two systems caused diesel generator underloading issues – later resolved by using a light stand to provide additional constant power draw. Air flow restrictors were put in place to allow them to operate in the cold weather. This caused issues when warmer temperatures arose but was remotely detected and resolved.

Topic/Element	Comments/Critique
	A 51-mm diameter reflector was used for R01 (the shortest chord, a background chord) while all other reflectors were 127 mm in diameter.
Analysis/Results	A large number of Chord samples were collected for both CH4 (163,295 samples) and CO2 (170,986 samples) during the measurement period. A chord sample is a 30-second average concentration measurement over one of the chords defined by the straight-line path between a transceiver and a retroreflector. Concentration measurements were combined with locally measured surface weather and publicly available NWP upper-air model fields and used as inputs to the Second Order Closure Integrated Puff Model with Chemistry (SCICHEM) dispersion model to estimate emissions of CH4 and CO2. R02-R05 measured concentrations were averaged per hour and background-corrected using R01 and R06 data that had been filtered by wind direction. SCICHEM was run using continuous area source release scenarios with the input being the integrated measurements that span the pond and east beach. SCICHEM has rectangular release areas so these were centred on the chord (did not specific width of the rectangle). The model was run with an initial emission rate with the difference between modelled and measured used to adjust the emission rate in an iterative process until the measured and modelled concentrations matched within 0.0005 ppm. This leads to an emission rate that can then be converted to a flux based on the area of the rectangle modelled. Error Analysis – Monte Carlo simulations were performed by Atmospheric and Environmental Research for three days during the campaign (March 22 and 27 and April 8) to attempt to estimate system precision. The error analysis established a chord concentration system precision of 0.05 ppm for CH4 and 0.1 ppm for CO2. Gaps in the results are a result of periods when wind direction was such that R01 and R06 could not provide an appropriate background or locally measured weather data was missing. CH4 and CO2 emission rates were periodically negative (Problem is more prevalent with CO2. As a sink is unlikely so interpreted to be a result of the natural variability of CH4 background at the site or due to wind-driven contamination effects from other nearby sources. Reran analysis without these negative values. CO2 concentration measurements at the pond likely also influenced by vegetation and respiration on the west bank. R01 (background chord) height relative to heights of the measurement chords might have contributed to additional issues at times when little vertical mixing was occurring. This effect occurred predominantly at night and later in the campaign consistent with the potential vegetation effect.
Comparison to Flux Measurements	
Gaps/Limitations in Measurement or Analysis	Straight line of sight paths/chords are required between the transceivers and the reflectors. Issue with CO2 and vegetation (strong diurnal pattern) – current approach for in situ tower (typically 50 m above ground) is to assume turbulent mixing and use the midday hours during the biogenic growth season. Turbulent assumption may not hold near the surface.
Compensation for Background Concentrations?	Surface chord used but requires more closer matching to pond chords in terms of height. Background chords were 5-10 m lower than the measuring chords and this likely compounded the issue with vegetation interference.
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	
Is there a lower-cost alternative measurement approach?	
Recommendations for Improvement	

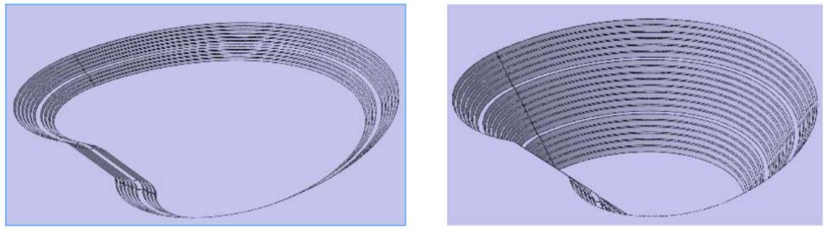
A.8. University of Guelph – Final Report

<table>
<tr><th>Topic/Element</th><th>Comments/Critique</th></tr>
<tr><td>Report Title/ Authors/Date</td><td>Addressing the Methane Challenge: Area Fugitive Emission Quantification from an Open-pit Mining Facility
Amir A. Aliabadi - University of Guelph, September 4, 2020</td></tr>
<tr><td>Theoretical/Conceptual Framework/General Approach</td><td>The work of the University of Guelph focused on understanding the Atmospheric Boundary Layer and accurately predicting and modelling the features of the surface boundary layer above a complex mine. The Authors used a Tethered Air Blimp (TAB) to observe the microclimate and determine boundary layer structure. The TAB system was also used to infer land surface temperatures from thermal camera observations. The authors employed Computational Fluid Dynamics (CFD) to understand atmospheric transport above complex terrain (similar to what is encountered at the Canadian Natural Mine). The authors also assisted by assessing the impact of changes to topography, land use and grid spacing on Weather Research and Forecasting (WRF- a numerical weather prediction model) output. This WRF output was then used by project collaborators to assess diurnal, seasonal and annual variations in area-fugitive methane emission fluxes from the Canadian Natural mine.

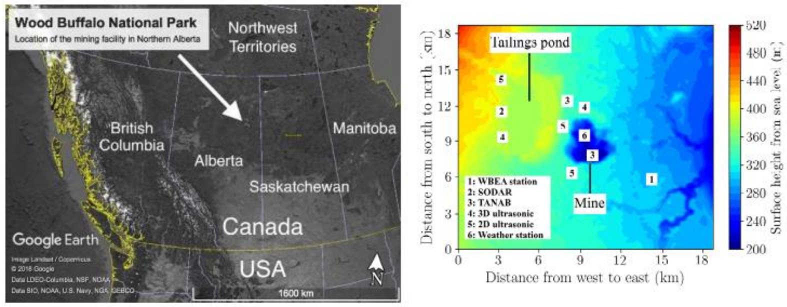
The team also used WRF 4.0 with a passive tracer dispersion option to model flux emissions from the pond. Near-surface boundary conditions were provided to the model alongside field measured methane mixing ratios. The model provided a methane emission flux at the model's inner domain boundary (not at the surface of the emission source). The modelled approach is associated with large uncertainties and is not appropriate for quantification (as it does not account for the dynamics of the surface atmosphere boundary) but is able to provide insight into diurnal and seasonal variability in emission fluxes.</td></tr>
<tr><td>Detailed Methodology (e.g., sampling plan, instrumentation utilized)</td><td>Tether Air Blimp (TAB)
The Tethered and Navigated Air Blimp (TANAB) or simply Tethered Air Blimp (TAB) developed by the authors consisted of a helium balloon (2.8 x 2.8 x 1.9 m, 8 m^3, 5 kg payload), up to 3 controlling tether, tether reels, and a gondola platform housing multiple sensors. Onboard sensors included a TriSonica Mini weather station, a thermal camera (DJI Zenmuse XT, 19-mm lens, uncooled) and a flight controller. The TriSonica Mini weather station employs an ultrasonic anemometer (manufactured by Anemoment™) that is capable of measuring the components of the wind velocity vector along with air temperature, relative humidity and barometric pressure at a sampling rate of up to 10 Hz. The TAB system was deployed to measure vertical profiles at the Canadian Natural mine and Horizon pond in May 2018.

Table 2: TANAB2 launch details; times are in Local Daylight Time (LDT).
<table>
<tr><th>Experiment</th><th>Location</th><th>Start date</th><th>Start time</th><th>End time</th><th>No. profiles</th><th>Duration</th></tr>
<tr><td>1</td><td>Tailings pond</td><td>7 May 2018</td><td>21:41:00</td><td>02:47:00</td><td>14</td><td>05:06:00</td></tr>
<tr><td>2</td><td>Tailings pond</td><td>9 May 2018</td><td>03:30:00</td><td>04:00:00</td><td>2</td><td>00:30:00</td></tr>
<tr><td>3</td><td>Tailings pond</td><td>10 May 2018</td><td>02:30:00</td><td>08:30:00</td><td>21</td><td>06:00:00</td></tr>
<tr><td>4</td><td>Tailings pond</td><td>15 May 2018</td><td>04:55:00</td><td>11:00:00</td><td>22</td><td>06:05:00</td></tr>
<tr><td>5</td><td>Mine</td><td>18 May 2018</td><td>04:12:00</td><td>11:12:00</td><td>20</td><td>07:00:00</td></tr>
<tr><td>6</td><td>Mine</td><td>19 May 2018</td><td>18:52:00</td><td>23:15:00</td><td>17</td><td>04:23:00</td></tr>
<tr><td>7</td><td>Mine</td><td>21 May 2018</td><td>11:00:00</td><td>12:17:00</td><td>4</td><td>01:17:00</td></tr>
<tr><td>8</td><td>Mine</td><td>23 May 2018</td><td>01:47:00</td><td>05:30:00</td><td>10</td><td>02:43:00</td></tr>
<tr><td>9</td><td>Mine</td><td>24 May 2018</td><td>11:19:00</td><td>14:25:00</td><td>12</td><td>03:06:00</td></tr>
<tr><td>10</td><td>Mine</td><td>27 May 2018</td><td>14:38:00</td><td>17:50:00</td><td>18</td><td>03:12:00</td></tr>
<tr><td>11</td><td>Tailings pond</td><td>30 May 2018</td><td>10:55:00</td><td>18:57:00</td><td>24</td><td>08:02:00</td></tr>
<tr><td>12</td><td>Tailings pond</td><td>31 May 2018</td><td>11:07:00</td><td>14:43:00</td><td>8</td><td>03:36:00</td></tr>
</table>

Computational Fluid Dynamics (CFD)
CFD modelling employed was a Very Large Eddy Simulation (VLES) model developed by UofG. For the CFD modelling study kidney shaped mines were modelled. The shallow mine with a depth of 100 m approximates an oil sands mine while the deep mine is more akin to ore mining operations. CFD modelling was performed under various thermal stability conditions (i.e., unstable, near stable and stable). Modelling was also performed using the simpler Monin-Obukhov Similarity Theory (MOST) (the theory that underpins the modelling framework used by UofA's WindTrax IDM method).</td></tr>
</table>

Topic/Element	Comments/Critique
	 (a) (b) Figure 26: a) Shallow and b) deep mine wall geometries. To calculate flux from an area source the model works by enclosing the area source in the box and calculating the flux based on accounting for wind velocity components and the mixing ratio of the pollutant of concern at each box boundary. Field data was collected at the Canadian Natural site in May 2018 and July 2019. Wind Speed and direction were measured from 30 – 200 m altitude (10 m vertical resolution) using a 4000 series mini Sonic Detection and Ranging (mini SODAR) instrument (atmospheric Systems Corporation). During Summer 2019 the mini SODAR was deployed on the west side of the tailings pond (which itself lies to the west of the west mine pit). TAB, which contains a microclimate sensor as described above, was also launched to an altitude of 200 m from the surface on the west side of the pond. A CSAT 3B ultrasonic anemometer (Campbell Scientific Inc.) was also deployed to the southwest edge of the pond. The CSAT 3B measured 3D wind components alongside temperature. Data from all sensors were filtered to include only data collected during westerly winds. By filtering the data, the atmospheric conditions upstream of the mine would be considered. 3D-wind data from the ultrasonic anemometer were used to generate modelled CFD and MOST wind fields and these models were compared to TAB and Mini SODAR profile data. **Weather Research and Forecasting (WRF)** To assess the impact of topography, land use and grid spacing modifications on WRF and its applicability to be used over the complex terrain of the mine data collected on three days in May 2018 were used (May 18, 24 and 30). These were clear sky days with no synoptic events. A PA-5 Sonic Detection and Ranging (SODAR) (Remtech Inc.) was used to measure wind speed and direction from 100 m to 2700 m (1-hour frequency). TAB was launched to 200 m from the surface of the mine on May 18 and 24 and from the east side of the pond on May 30 (1-hour long launches). Two CSAT 3B ultrasonic anemometers (Campbell Scientific Inc.) measuring 10 m 3D wind and temperature were located at the north side of the mine and the southwest of the pond. Three YOUNG Model 86004 2D ultrasonic anemometers (R.M. Young Company) measuring 10 m wind speed and wind direction were placed at the southwest edge of the mine, the east edge of the pond and the northwest edge of the pond. Data from two nearby weather stations which were operational during the field campaign were also used. A weather station located atop a 2 m high trailer on the north side of the mine was equipped with a Gill 3-cup anemometer and model 41382 relative humidity and Temperature Probe (R.M. Young Company). The second weather station, which reported data to the Wood Buffalo Environmental Association Website (WBEA), was located at the southeast corner of the Canadian Natural site

Topic/Element	Comments/Critique



(a) Wood Buffalo National Park (b) Mining site

Figure 34: (a) Map of the regional area where the mining facility is located; (b) Location of the meteorological instruments deployed at the site for model comparison; Figure color coded with surface height above sea level.

Light Detection and Ranging (LIDAR) operated by Clean Harbours Company and mounted on a fixed-wing drone was used to determine the actual topography of the Canadian Natural site. LIDAR observations were accurate to ±0.3 m in the horizontal direction and ±0.1 m in the vertical direction. This LIDAR dataset was used to correct the SRTM 1s and the land use datasets employed during WRF simulations.

The WRF Unified Environmental Modelling System (UEMS) version 18.1.1 distribution was used. Different domain sizes were selected ranging from one covering most of Canada (D1) to a domain restricted to the facility itself (D5). Simulation times varied from 6 hours to 14 days depending on the horizontal and vertical grid spacing (simulations were run on 25 CPUs). Vertical Grid spacing was increased from the default 45 vertical levels to 90 and then to 120 vertical levels. Topography was obtained from the courser GTOPO dataset as well as the finer SRTM dataset (which was also further refined with LIDAR data). Land Use data was also varied with refined land use based on collected LIDAR data and incorporating the pond as a lake being implemented. Finally, different planetary boundary layer schemes were used: a Yonsei University (YSU) scheme (when grid spacing was >500 m) and a Large-Eddy Simulation (LES) Scheme (when grid spacing was <500 m). WRF simulations for the three campaign days were executed for 36 hours including 12 hours of spin-up time.

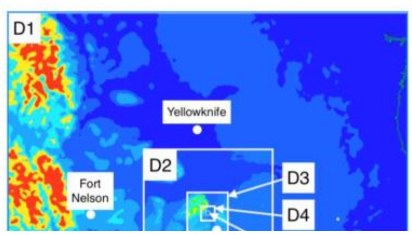
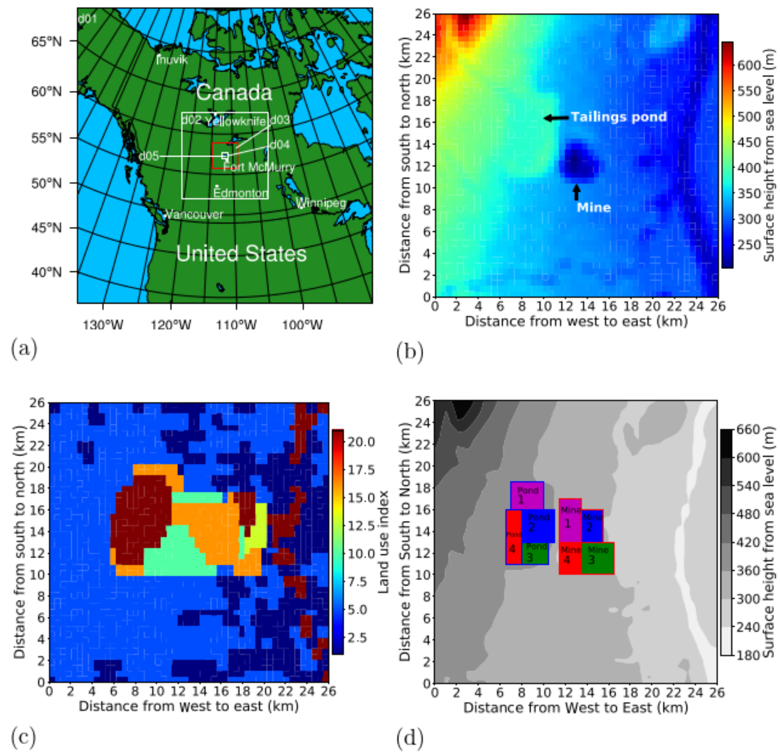


Table 12: Domain configurations and associated parameters.

Parameter	Domain 1	Domain 2	Domain 3	Domain 4	Domain 5
Domain size (km × km)	2000	632.7	197.6	61.4	18.5
Coarse horizontal grid spacing (km)	15	5	1.67	0.56	0.18
Mid horizontal grid spacing (km)	10	3.33	1.11	0.37	0.12
Fine horizontal grid spacing (km)	7	2.33	0.77	0.26	0.09
Elements for coarse horizontal grid spacing	133	127	119	110	100
Elements for mid horizontal grid spacing	200	190	178	166	154
Elements for fine horizontal grid spacing	285	271	256	244	232
Top of the domain (km)	25	25	25	25	25
Vertical levels for coarse vertical grid spacing	45	45	45	45	45
Vertical levels for mid vertical grid spacing	90	90	90	90	90
Vertical levels for fine vertical grid spacing	120	120	120	120	120
Output frequency (min)	60	60	60	60	60
GTOPO 30s topographical resolution (m)	900	900	900	900	900
SRTM 1s topographical resolution (m)	-	-	-	30	30

Data from the WRF simulation were compared to measured data. Above 200 m SODAR data was used for the comparison while surface data was used for comparison below 200 m.

Simulated Area-fugitive Methane Emission Flux

Topic/Element	Comments/Critique
	The WRF 4.0 model with the Advanced Research WRF (ARW) dynamical core and the passive tracer dispersion option was used to model fluxes from the mine. A 5-tier nested modelling domain setup was used with time step and horizontal grid spacing in successive nesting grids jumping by a factor of a third. D01, the largest domain, spatial coverage spanned much of north America with grid spacing of 41,000 m and 60 s time steps. D05, the smallest domain encompassed the Canadian Natural site itself, had horizontal grid spacing of 5066.17 m and 1 s time steps. In the vertical direction all domains were setup with 90 levels up to an altitude of 20 km with the lowest level at 25 m above the ground. The first 12 levels were below 2 km – the approximate height of the daytime planetary boundary layer. Domains were populated with increasingly refined topography with the D05 topography supplied by SRTM 1s and both topography and land use further refined by incorporation of updates from recent LIDAR imaging of the mine site. Methane mixing ratio measurements were provided by four Los Gatos Research Ultra-Portable Greenhouse Gas Analyzers (LGRs) placed at four locations surrounding the mine and four locations surrounding the pond. The Pond and Mine were divided up into four rectangle source areas each which remained constant throughout the study.  Figure 46: a) WRF simulation domains centered at the mining facility; b) surface topography in WRF domain 05; c) land-use configuration in WRF domain 05; d) areas for applying methane tracer boundary condition in WRF domain 05; measurement sites are approximately at the centre of each rectangle. Mixing ratio data, collected at a frequency of 15 minutes was averaged every four hours and used to update the WRF model boundary condition at the specific locations of the pond and mine (this required modification of the model source code). The WRF model needed to be recompiled every four hours with the updated near-surface boundary conditions for methane. Meteorological data was obtained from the National Centre for Environmental Prediction's Global Data Assimilation System (GDAS) dataset with a spatial resolution of 0.25˚ and a temporal resolution of 6 hours. (on-site meteorological data was NOT used.) The passive tracer mixing option was enabled during simulations with passive tracers having no chemical properties and treated by the model as scalar variable. Model simulations were spun-up for

<table>
<tr><th>Topic/Element</th><th>Comments/Critique</th></tr>
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12 hours before releasing the passive tracers from the specified surface grid points. Tracer output after 3 hours of release was used the initial and lateral boundary conditions with observed mixing ratios being used as the near-surface boundary condition. To examine diurnal trends model output was broken up into 4-hour time intervals (i.e., 0-4, 4-8, 8-12, 12-16, 16-20, 20-24).

Simulations were made for observations made during a late spring measurement campaign in 2018 and a winter and early spring measurement campaign in 2019. Mine simulations were performed for two time periods: 18-27 May 2018 (M18) and 16-25 March 2019 (M19). Similarly, Pond simulations were performed for two periods: 1-10 May 2018 (P18) and 14-23 February 2019 (P19).
</td></tr>
<tr><td>Additional Methodology Considerations</td><td>
Methane flux was calculated by a calculation of the advective flux. Other fluxes (i.e., turbulent, surface, mass and chemical fluxes) were ignored based on previous studies of the same facility that indicate they would make up ~3-5% of the advective flux combined.
</td></tr>
<tr><td>Analysis/Results</td><td>
Data collected by TAB was compiled and used to calculate relevant meteorological parameters. Analysis of vertical profile data collected by TAB at the mine and pond showed some differences with mean wind speed, turbulence kinetic energy and friction velocity being lower within the mine. These data suggests that the mine boundary layer may be isolated from the boundary layer above grade (the mine itself is ~100 m deep).

Comparison of TAB and mini SODAR temperature data to MOST and CFD model results indicate decent agreement between both models and measurement. CFD did appear to over predict wind speeds in the lower portion of the surface layer during stable conditions. Of note, the MOST model is only valid for the first 50 m under stable conditions. MOST also underpredicted wind speeds during neutral atmospheric conditions. Results did indicate that observed patterns were distinct from flows over flat and homogeneous terrains.

WRF model refinements including refined topography, land use and lake modelling led to bias reductions in model output. A grid configuration with a horizontal grid size of 0.12 or 0.09 km in the smallest domain and a vertical coarseness employing 90 vertical levels (the medium vertical coarseness case) for all domains was found to be sufficient to accurately.

Simulated Area-fugitive Methane Emission Flux
Mixing ratio data collected during spring 2018 and winter/spring 2019 showed strong diurnal variation and diurnal trends in methane measured near the mine.

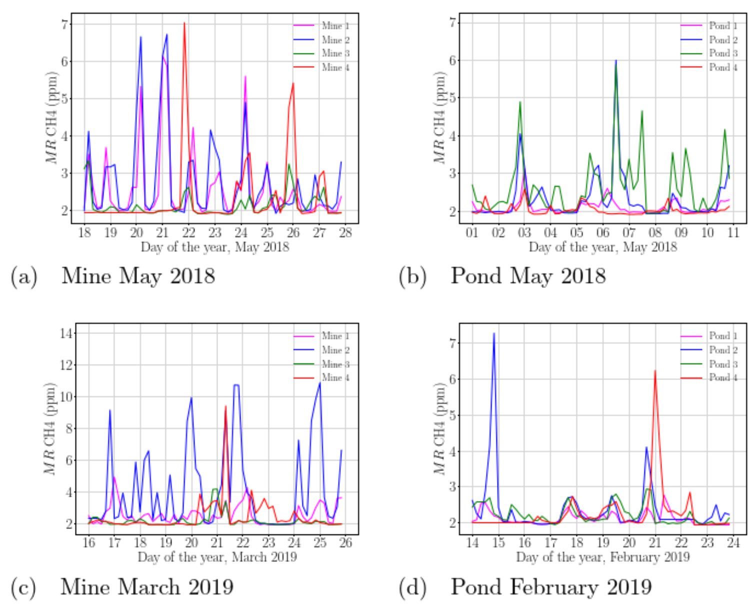
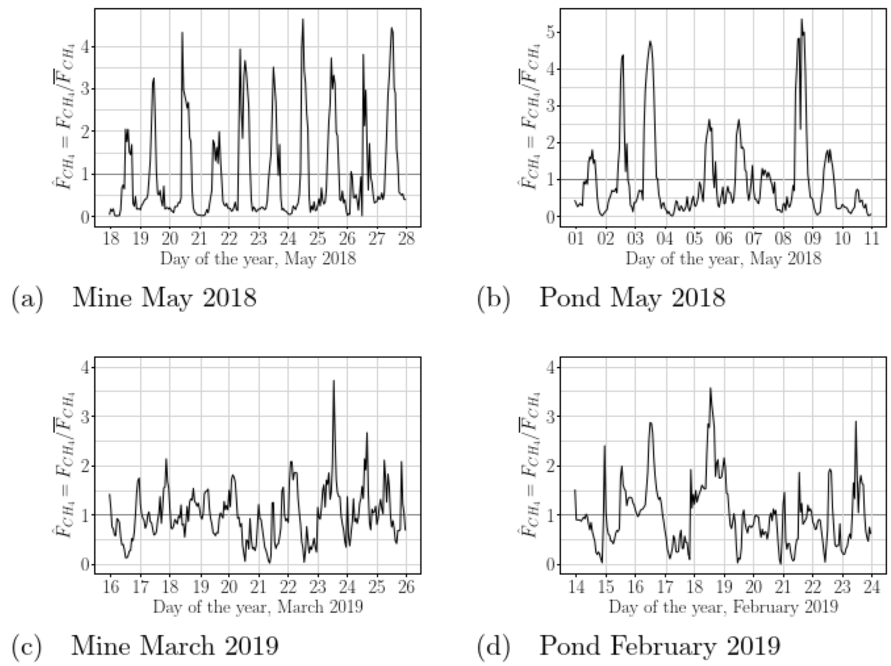
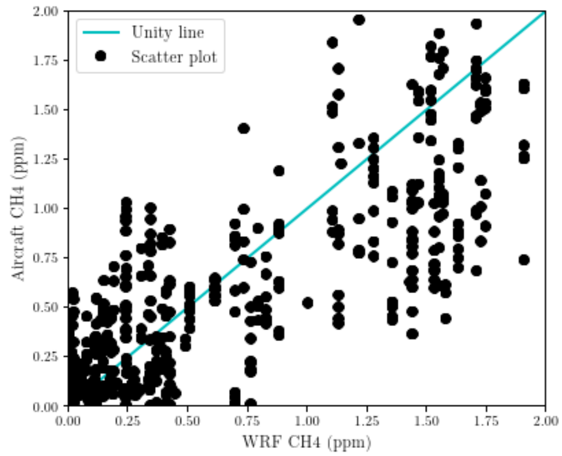
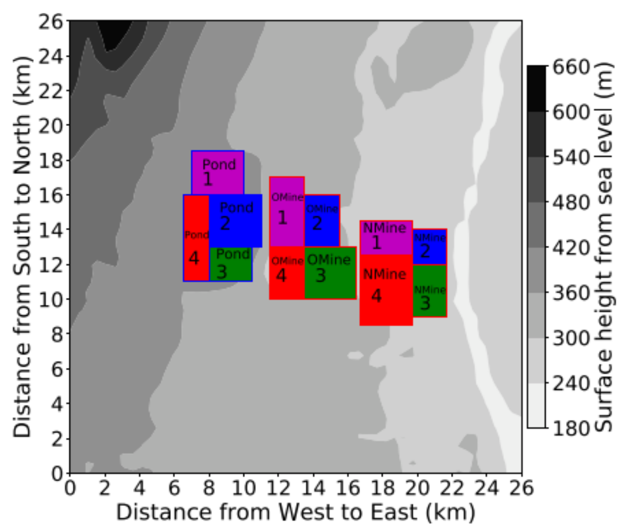
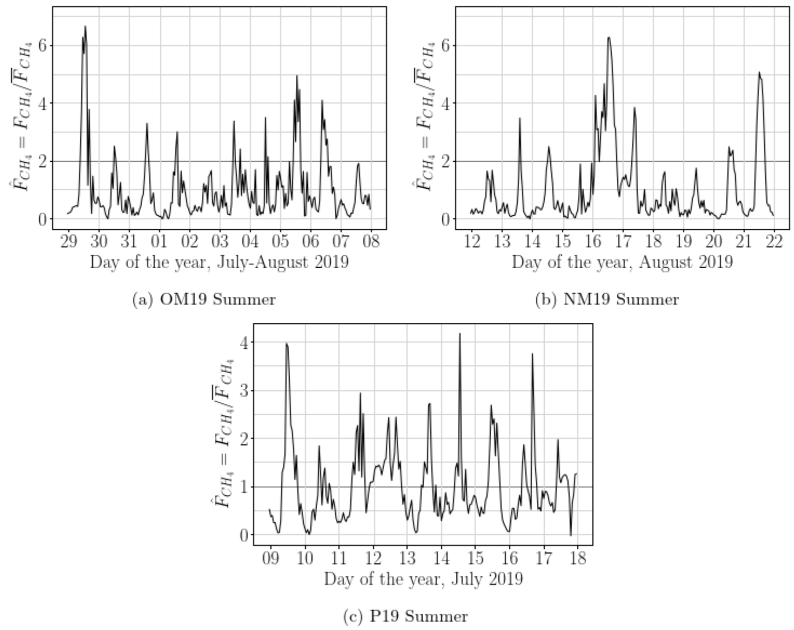
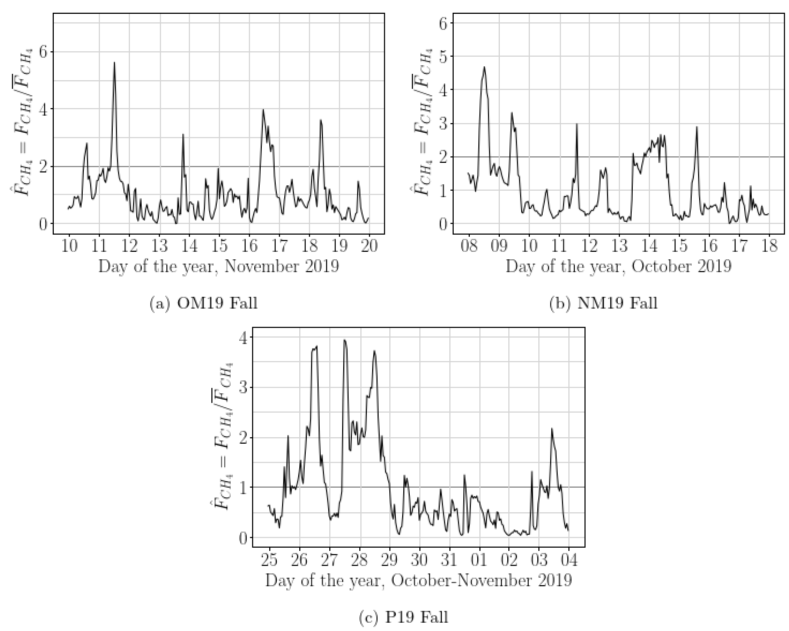


Figure 47: Time series of LGR-measured four-hour-averaged near-surface level mixing ratios MR of methane at four observation locations during the M18, P18, M19 and P19 field campaigns indicated in Fig. 46d; numbers on the horizontal axis indicate the start of day using local standard time (LST=UTC-7).
</td></tr>
</table>

Topic/Element	Comments/Critique
	Hourly-simulated methane emission fluxes from the inner domain boundaries surrounding the open-pit mining facility were calculated. However, due the fact that the method requires rigorous measurement of methane mixing ratios near the surface and only four measurements were available absolute values are inaccurate. The data was instead represented normalized by the average hourly emission flux (i.e., 1 in the figure below is representative of the average hourly emission flux). Spring 2018 mine simulations indicated fluxes as low as 20% of the average were associated with early morning and nighttime, both of which are typically thermally stable. Thermally unstable midafternoon hours were associated with fluxes as high as 400%. The Pond (P18) diurnal trend is not as consistent.  Figure 48: Time series of WRF-simulated normalized emission flux of methane ($\hat{F}_{CH_4}$) from the inner domain (05) boundaries, surrounding the open-pit mining facility; numbers on the horizontal axis indicate the start of day using local standard time (LST=UTC-7). Diurnal trends were not as consistent for both M19 and P19 which could be result of the meteorological conditions and the increased likelihood of synoptic events. In all cases emissions were most highly correlated with wind speed. Normalized average differences were calculated after data were grouped in four-hourly time intervals. This allowed normalized averages to be compared and indicated that M18 were slightly higher than P18 fluxes, but the difference was not statistically significant. M19 was however significantly higher than P19 data. Late spring data (M18 and P18) was significantly higher than winter/spring data (M19 and P19). Methane total column mixing ratios were calculated based on the sum of the methane mixing ratio in each grid cell in a vertical column. A comparison was made between WRF output and aircraft observations made by the Convair-580 belonging to the National Research Council (NRC) of Canada. The aircraft flew a box flight pattern around the facility on around 11 local time on May 31, 2018 and measured methane using a Picarro model G2401-m instrument. The aircraft flew between 550 and 1850 m above ground level. For comparison the WRF simulations were run using four-hourly=average methane mixing ratios over both the mine and the pond in May 2018 as boundary conditions. This was done as was done previously but the two 2018 datasets were combined for comparison to flight data (which could see

Topic/Element	Comments/Critique
	emissions from both the pond and the mine). The WRF output could be compared to the flight data in grid cells closest to the aircraft latitude, longitude, and altitude. The comparison revealed a coefficient of determination R^2 to be 0.68 with a bias of 0.0543 ppm and a root mean square error of 0.0530 ppm. This provided confidence in the ability of the WRF model to simulate plume transport adequately.  Figure 57: Comparison of aircraft observations and WRF predictions of methane mixing ratio at 1100 LST on 31 May 2018 ($R^2 = 0.68$); the background mixing ratio of methane is subtracted from the aircraft observations. Summer and Fall 2019 data were also modelled with the new mine (NM) pit east of the old mine (OM) also being addressed by WRF.  Figure 58: Area sources for the methane boundary condition associated with the pond (left), old mine (middle), and new mine (right). Summer and Fall data were consistent in that flux data presented daytime highs and nighttime lows, but the diurnal pattern was not as well defined as it was for the late spring measurements.

Topic/Element	Comments/Critique
	 Figure 59: Time series of WRF-simulated normalized emission flux of methane ($\hat{F}_{CH_4}$) from the inner domain (05) boundaries, surrounding the open-pit mining facility; (a) Old mine 2019; (b) New mine 2019; (c) Pond 2019; numbers on the horizontal axis indicate the start of day using local standard time (LST=UTC-7).  Figure 65: Time series of WRF-simulated normalized emission flux of methane ($\hat{F}_{CH_4}$) from the inner domain (05) boundaries, surrounding the open-pit mining facility; (a) Old mine 2019; (b) New mine 2019; (c) Pond 2019; numbers on the horizontal axis indicate the start of day using local standard time (LST=UTC-7).
Comparison to Flux Measurements	Flux Chamber • Absolute flux measurement • Inability to monitor temporal trends WRF Modelled Methane Emission Flux • Normalized flux measurement (without rigorous ground measurements) • Ability to monitor temporal trends (via normalized fluxes)

Topic/Element	Comments/Critique
Gaps/Limitations in Measurement or Analysis	A lot of work was done to refine WRF to simulate the complex terrain above the mine with input from the network of meteorological sensors at the site. Although lessons learned from this model are applied moving forward the more refined complex terrain model is not used in the final attempt at modelling flux measurements. WRF modelled methane emission fluxes are highly uncertain to the extent that they were not even reported by the authors. The modelling scheme assumes the measured methane mixing ratio is generated by the area source and not influenced by the background methane levels.
Compensation for Background Concentrations?	The modelling scheme assumes the measured methane mixing ratio is generated by the area source and not influenced by the background methane levels.
Additional Instrumentation Needed to Provide Sufficiently Representative Measurements?	Atmospheric variables need to be measured at least up to 100 m. TAB, SODAR, LIDAR, or microwave profilers are needed for WRF to accurately predict the emission profile above Accurate absolute emission fluxes are only possible using the method if the mixing ratio of methane near the surface is rigorously measured. This would require tens of methane measuring instruments to be deployed near the surface.
Is there a lower-cost alternative measurement approach?	Other modelling approaches do not require the extensive ground observation network nor he computational demands that the WRF model requires.
Recommendations for Improvement	Author's Recommendations: • More extensive observations as achieved ideally by up to 50 or more surface stations to get absolute flux measurements from WRF directly. • WRF to be used to provide high Spatio-temporal resolution for IDM models such as CALPUFF and WindTrax. • Alternatively, use air mass balance. This is the Environment and Climate Change Canada approach which is currently limited to daytime hours and larger aircraft. Smaller drones "could" potentially do this. • Alternatively, use satellite technology - no satellite data providing column-integrated mixing ratio of greenhouse gases over the mining facility were found.