Full Scale Implementation of Methane Oxidation Bed Technology at Four Landfills in the Thompson-Nicola Regional District

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EXECUTIVE SUMMARY

This report evaluates the performance of methane oxidation technology applied to four small rural landfills in the Thompson Nicola Regional District (TNRD) of British Columbia, Canada.

The objective of this study is to assess the full implementation of Methane Oxidation Technology in four TNRD landfills at Barriere, Clearwater, Chase and Logan Lake. This is the first full implementation of this technology as an integrated and complimentary add on to the Evapotranspirative cover technology used for the landfill closure. This is also part of the TNRD longer term strategy in dealing with its smaller, older and/or closed landfills in the area. Methane oxidation technology represents a GHG mitigation technology which will improve air quality in the surroundings of the two landfill sites.

In particular the following sub-objectives were addressed:

- Initial LFG assessment done by conducting real time surface emission monitoring events on the TNRD site(s).
- Design and construction of methane oxidizing biofilter beds on TNRD site(s) at the Barriere (two beds), Clearwater (four beds), Chase (3 beds) and Logan Lake (4 beds) landfills.
- Installation of monitoring equipment to monitor LFG composition, temperature and surface emission at the biofilter bed sites.
- Monitoring field test performance by measuring LFG composition, temperature and surface emission at the biofilter beds at regular intervals.
- Evaluating monitoring results and presenting the results in a final report submitted to TNRD.

The initial study results showed that methane scanning is a useful technique for locating ‘hot spots’ methane emissions on the landfill surface. These ‘hot spots’ can be possible locations for methane oxidation biofilter beds, but need to be confirmed by flux measurements.

Field monitoring of temperatures and regular monitoring of gas composition and surface flux was found to be a robust method of assessing the biofilter performance. Monitoring the biofilter temperature proved to be an excellent tool to assess biological activity and thus potential methane oxidation. Temperatures inside the biofilter were always higher than air temperatures indicating the presence of biological activity generating heat from the oxidation of methane. Temperature changes also allowed us to assess heterogeneity in the biofilter material and the presence of pronounced site effects.

We found that methane levels decreased from the bottom of the biofilter to the top layers showing methane oxidation activity corroborating the temperature data. Oxygen levels were close to zero in most of the biofilter layers except at 20 cm depths (and only occasionally where they were above zero but still very low). The absence of oxygen limits methane oxidation and thus the ability of the biofilter to treat methane emissions. Carbon dioxide levels decreased from the bottom of the biofilter to the top layers showing the likely effect of gas dilution with atmospheric air. Nitrogen levels increased from the bottom of the biofilter to the top layers showing the likely effect of nitrogen enhancement due to gas dilution with atmospheric air (large nitrogen concentration). Flux measurements and calculations showed significant methane oxidation at the biofilters with Clearwater showing higher amounts while Barriere showed higher % rates of methane removal.

Methane oxidation can lead to significant removal of landfill methane, and thus has the potential to earn GHG credits.

1 INTRODUCTION

This study presents the results of a project undertaken by Abboud Research Consulting Inc. (ARC) and the Thompson-Nicola Regional District (TNRD) with shared funding from the Greater Vancouver Regional District (GVRD).

The TNRD is in the process of implementing a new regional solid waste management plan. Along the way five of the smaller sites will be successively closed and one fully engineered regional waste management facility will be developed to serve the District. The single facility may be a landfill or an alternative innovative disposal method such as waste to energy or conversion technology.

The TNRD pioneered the use of Methane Oxidation Technology by funding pilot studies to assess the use of the technology at two landfill sites (Barriere and Lower Nicola). The results showed that this technology was successful at treating methane emissions from these landfills (Abboud and Chen, 2010 and Abboud, 2011)

Rather than traditional capping and leave behind strategies the TNRD is actively managing the remaining landfill gas emissions from these smaller sites. Traditional capping activities will delay the issue of landfill gas emissions from these sites on to future generations. Also, not dealing with landfill gas at this time will increase the risk of uncontrolled emissions, through cracks or subsurface, now or in the future, which can potentially lead to fires and explosions. By including Methane Oxidation Technology as part of the capping and closure of the smaller landfill sites, the TNRD is looking to actively deal and treat remaining LFG emissions now and during the closure and post-closure period of these landfill sites. It is anticipated that the implementation of Methane Oxidation Technology will significantly shorten the length and simplify the post closure operation of the TNRD landfill sites. The eventual capital project will be a series of facilities distributed over the five TNRD landfill sites and will improve air quality and mitigate greenhouse gas emissions in the area.

1.1 OBJECTIVE

The objective of this study is to field test Methane Oxidation Technology in four TNRD landfills. This will help the TNRD in dealing with its smaller, older and/or closed landfills in the area. It is based on internal and external project experiences at the TNRD pilot projects at Barriere and Lower Nicola landfills and the Leduc and District Regional Landfill in Alberta.

This study will significantly benefit the TNRD in their plan to close and responsibly manage their older smaller sites, while concentrating on a more regional waste management approach. Methane oxidation technology represents a GHG mitigation technology which will improve air quality in the surroundings of the two landfill sites.

In particular the following sub-objectives will be addressed:

- Design and construction of methane oxidizing biofilter beds on TNRD sites at the Barriere, Clearwater, Chase and Logan Lake landfills.
- Installation of monitoring equipment to monitor LFG composition, temperature and surface emission at the biofilter bed sites.
- Monitoring field test performance by measuring LFG composition, temperature and surface emission at the biofilter beds at regular intervals.
- Evaluating monitoring results with regards to the field performance of the methane oxidation beds.
- Presenting the results in a final report submitted to TNRD.

2 MATERIALS AND METHODS

2.1 Methane Emission Surface Scanning

Scans of surface methane concentrations were conducted at the Chase (May 17, 2011), Barriere (May 18, 2011), Clearwater (May 19, 2011), and Logan Lake (June 9, 2011) landfill sites. ARC personnel conducted the scans using an SEM 500 portable Flame-Ionization detector device (LandTec Corp, Colton, California). The instrument was calibrated beforehand and was set to measure and record the readings on the surface CH_4 concentration for every 5 seconds (CEC-LandTec, 1999). A Trimble (LandTec Corp, Colton, California) GPS device was utilized to generate a tracklog (Trimble, 2005) as the landfill surface was scanned with the SEM with a receiver wand 5-10 cm above the ground surface. The time on the GPS devise and SEM was synchronized prior to use and the tracklog was set to record the positions every 3 seconds.

The SEM 500 surface methane high level alarm was set for 500 ppm, and for the spots where the alarm was triggered, flux measurements were undertaken. The flux samples were taken with a custom made flux chamber over a 30 minutes interval. The flux samples were brought back to the ARC lab to be analyzed with the Varian CP 3800 GC, equipped with a TCD and FID detectors, and the concentrations of the CH_4, CO_2, O_2 and N_2 were produced and used to calculate the gas emissions.

Once the readings of the CH_4 concentrations from the SEM and the tracklog data from the Trimble were downloaded to the computer, the software program ArcMap (ESRI, 2006) was used to generate a map with the distribution of surface CH_4 concentrations. Methane surface concentration maps of the landfills were generated using ArcGIS software (ESRI, 2006) and geo-referenced air photos.

2.2 Biofilter Material

The biofilter material was stockpiled on site and was a mixture of GVRD biosolids and wood chips. The material was analyzed for moisture, particle and bulk densities, organic matter, pH, and carbon, nitrogen and sulphur contents. The moisture content was done using a modified TMECC method 03.09-A, where the drying temperature was 105 ^{o}C instead of the recommended 75 ^{o}C (TMECC, 2002). The particle densities were measured by the immersion method developed for soils and adapted for composts. (Weindorf and Wittie, 2003). Wet Bulk Density was calculated from sample weight and volume determinations according to TMECC method 03.0-C (TMECC, 2002). Dry Bulk Density was calculated from Wet Bulk Density values and Moisture contents. Organic matter was analyzed using TMECC method 05.07-A (loss on ignition) (TMECC, 2002). pH(H_2O) was analyzed in a compost sample made into a paste with distilled water, and the pH is measured by insertion of an electrode into the paste. (Doughty, 1941). pH($CaCl_2$) was analyzed in a compost sample mixed in 0.01M $CaCl_2$ at a 1:2 soil:solution ratio (w:v), and the pH is measured with a glass electrode dipped into the solution. (Peach, 1965). Total carbon, nitrogen and sulphur contents were analyzed using a LECO TruSpec CN Carbon/Nitrogen Analyzer (LECO, 2006). Table 1 shows the analytical parameters for the biofilter material used in this study.

Table 1. Chemical and Physical Properties of the MOB mix and its constituents.

Sample Description	**Moisture**			**Vol Solids**	**Ash**	**Wet Bulk Density**
	wet wt (%)	**wet wt (g H20/g wet wt)**	**(g H20/g solids)**	**(% g/g)**		**(g wet/cm3 wet)**
Iona Biosolids	55.4	0.554	**1.24**	29.2	70.8	0.88
Heffley Tolko Chip	43.9	0.439	0.78	99.8	0.20	0.30
MOB Mix	55.0	0.550	1.22	53.5	46.5	0.58
	Dry Bulk Density	**Particle Density**	**Porosity**	**Air Filled**	**Air Por/Por**	**Void Ratio**
	(g dry/cm3)	**(g/cm3)**		**Porosity**		
Iona Biosolids	0.39	2.15	0.82	0.33	0.40	4.45
Heffley Tolko Chip	0.17	1.78	0.91	0.77	0.85	9.54
MOB Mix	0.26	1.85	0.86	0.54	0.63	6.13
	pH	**pH**	**pH**	**Carbon**	**Nitrogen**	**Sulfur**
	(H2O)	**(CaCl2)**	**Change**	**dry (%)**	**dry (%)**	**(%)**
Iona Biosolids	5.9	5.8	0.1	15.4	1.17	0.479
Heffley Tolko Chip	4.2	3.9	0.3	48.1	0.16	0.016
MOB Mix	5.6	5.4	0.2	18.4	1.29	0.474
	C:N	**C:S**	**N:S**	**Org Mat:C**	**Carbon**	**Nitrogen**
	Ratio	**Ratio**	**Ratio**	**Ratio**	**wet (%)**	**wet (%)**
Iona Biosolids	13	32	2	1.89	6.87	0.522
Heffley Tolko Chip	301	3008	10	2.07	26.98	0.090
MOB Mix	14	39	3	2.90	8.30	0.582

2.3 Biofilter Construction

The construction of the Clearwater biofilters was started in July 2012 and completed in August 2012, Barriere biofilters were started in September 2012 and completed in October 2012, Chase biofilters were started in early May 2013 and completed in late June 2013, and the Logan Lake biofilters were started in late July 2013 and completed in early September 2013. The site selection was based on the emissions surveys conducted in May (17, 18 and 19) and June 8, 2011. Hot spots were identified and potential candidate biofilter sites were suggested. The biofilters were designed with a surface area of 20 x 20 m (except for one Chase biofilter at 10 x 40 m) and a depth of 2 m (0.5 m dug into the MSW material and filled with gravel and a 1.5 m layer filled with biofilter material). Figure 1 shows the general design of the biofilters at the four landfill sites.

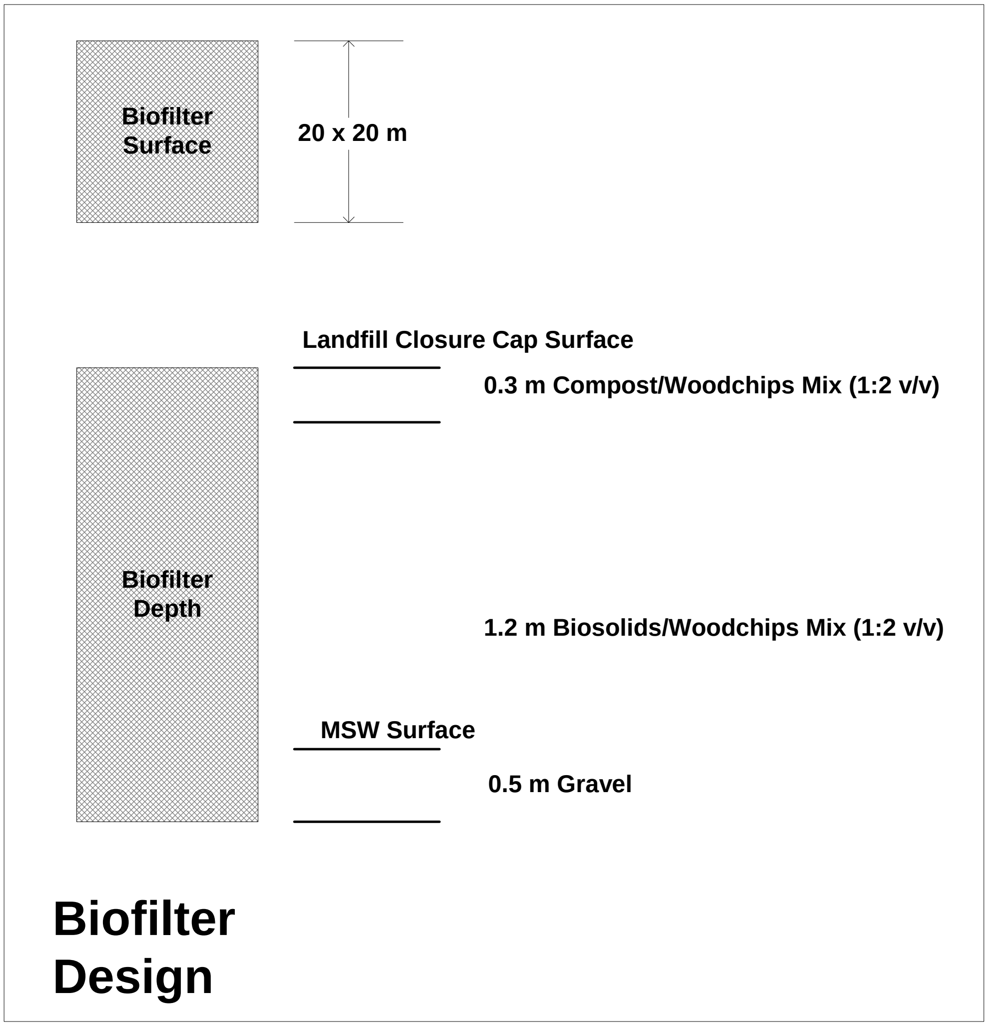

Figure 1. General Design of the Biofilters at the four landfill sites.

Once the biofilters were built, a data logger CR1000 (Campbell Sci. Inc.) was set at the centre of one biofilter at each landfill (biofilter 1), fixed into a metal pole. A 2.5 meter long metal pole was sunk into the biofilter with the force from the hoe (1.0 meter into the ground) to support the logger enclosure. Four locations were selected to install the monitoring equipment. They were 10 meters from the centre station aligned to the corners. The assembled monitoring equipment (4 units in each biofilter) was installed in the biofilter. The monitoring equipment consisted of a one inch PVC pipe, 5 temperature sensors and 5 gas probes, which measure the temperature and gases in the biofilter at the depths of 160, 125, 90, 55, and 20 cm below the surface. The PVC pipe stands 90 cm above the ground, with an open/close valve attached to its end. The thermocouple wires were connected to a data logger, and the data logger started to record the temperature and store on an hourly basis. In each landfill, the only monitoring equipment installed at the other biofilters (other than biofilter 1) consisted of similar gas composition monitoring equipment except that only the 20 cm and 160 cm depth monitoring probes were installed.

2.3.1 Barriere

Two Barriere biofilters were built on flat surface and were constructed by TNRD personnel. A backhoe was used to dig into the biofilter, to the gravel layer, and the monitoring equipment was buried 10 cm into the gravel. Biofilter material was then filled in to cover the monitoring equipment. All wiring was connected and the data logger started so that temperatures can be recorded hourly.

2.3.2 Clearwater

Four Clearwater biofilters were built on flat surface and were constructed by TNRD personnel. The cover material and waste were excavated to 0.5 m below the waste level then filled with 0.5 m of gravel and then 1.5 m of biofilter material. Monitoring equipment was installed during the construction phase. The final biofilter surface was aligned with the newly constructed landfill closure cover surface. All wiring was connected and the data logger started so that temperatures can be recorded hourly.

Figures 1, 2 and 3 show one biofilter surface before, during and after the installation of the monitoring equipment.

2.3.3 Chase

Three Chase biofilters were built on flat surface and were constructed by TNRD personnel. The cover material and waste were excavated to 0.5 m below the waste level then filled with 0.5 m of gravel and then 1.5 m of biofilter material. Monitoring equipment was installed during the construction phase. The final biofilter surface was aligned with the newly constructed landfill closure cover surface. All wiring was connected and the data logger started so that temperatures can be recorded hourly.

2.3.4 Logan Lake

Four Logan Lake biofilters were built on flat surface and were constructed by TNRD personnel. The cover material and waste were excavated to 0.5 m below the waste level then filled with 0.5 m of gravel and then 1.5 m of biofilter material. Monitoring equipment was installed during the construction phase. The final biofilter surface was aligned with the existing landfill closure cover surface. All wiring was connected and the data logger started so that temperatures can be recorded hourly.

2.4 Biofilter Monitoring

The monitoring started right after the installation of the monitoring equipment, and was conducted several times after the biofilters' establishment in 2012. The regular monitoring events included: assessing the weather condition at the time of sampling, downloading temperature data from the data loggers, taking LFG gas composition measurements and conducting flux measurements using the flux chamber and preparing the gas samples for transport to ARC Edmonton laboratories.

2.4.1 Temperature

At each monitoring event, the temperature data were downloaded to the laptop computer. The daily temperature was compiled from the original downloads to generate the charts on the locations and depths. The data loggers CR1000 (Campbell Sci. Inc.) were used to record temperatures continuously and store an hourly average of each temperature thermocouple.


Figure 2. Clearwater biofilter surface before installation of the monitoring equipment.


Figure 3. Installation of the monitoring equipment at the Clearwater biofilter.

Figure 4. Clearwater biofilter surface after installation of the monitoring equipment.

2.4.2 Gas Composition

Landfill gas composition was measured with the GEM 2000 Gas Analyzer by (LandTec, Colton, California). The concentrations (vol %) of CH_4, CO_2, O_2 and calculates N_2 as (100 – sum of the CH_4, CO_2 and O_2 concentrations) (CES- LandTec, 2005) at 5 depths (20, 55, 90, 125 and 160 cm below the biofilter surface) and 4 locations were analyzed and recorded. The average of the four readings of CH_4 concentrations at 160 cm (drainage layer just above the landfill waste) were used as the LFG influx from waste into the biofilter and these values were used in the calculation for removal rates.

2.4.3 Flux Measurements

Landfill gas (CH_4 and CO_2) flux measurements_were taken using a stainless steel custom built flux chamber (60 x 60 x20 cm). The gas samples were collected from the flux chamber every 5 minute for a period of 30 minutes. The gas samples were collected through running a syringe needle into the septum (installed on the top of the chamber), drawing 20 ml of the gas samples. The sample in the syringe was transferred to a pre-evacuated sample container (Exetainer 12 ml, Labco Limited, UK). A small battery powered fan was installed to mix the gas and a thermometer also installed for reading the temperature inside the chamber at the time of sampling. The samples were brought back to ARC lab and analyzed for CH_4, CO_2, O_2 and N_2 using a Varian Gas Chromatograph CP-3800 model (Varian, 1999, 2002a and 2002b). The gas samples were injected through an auto-sampler to a Varian Molsieve 5A/Porabond Tandem Column, where all the permanent gases were separated and analyzed by a Thermal Conductivity Detector. A calibration curve was established for CO_2, O_2, N_2 and CH_4 with RSD of 1.7, 2.3, 2.7, and 1.0 % respectively.

The CH_4 and CO_2 flux were calculated using the following equation:

$\mathrm{Jout}_{CH4} = \Delta C.p.V/(\Delta t.A) = (\Delta C/\Delta t).p(V/A)$

Where $\Delta C/\Delta t$ is the slope of gas concentration versus time curve, p is the density of the gas determined from the ideal gas law($g.m^{-3}$), V is the volume of the chamber and A is the surface area covered by the chamber.

The influx of CH_4 was assumed to equal the effluent LFG flux, since theoretically every unit of volume of CH_4 that is oxidized produced an equal volume of CO_2. The equation from (Zeiss, 2002) was used for calculate CH_4 influx.

$\mathrm{J\ in}_{CH4} = \mathrm{Cin}_{CH4}(\mathrm{Jout}_{CH4} + \mathrm{Jout}_{CO2})$

Where $\mathrm{J\ in}_{CH4}$ is the concentration of methane (L/L) in the landfill.

The methane removal rate (%) is calculated using the equation:

CH_4 removal = $((\mathrm{Jin}_{CH4} - \mathrm{Jout}_{CH4})/\mathrm{Jin}_{CH4}) \times 100$.

3 RESULTS AND DISCUSSIONS

This section will report on the results of the study and any relevant discussions of these results. It will address the methane emissions from the landfill and biofilter surfaces and the monitoring results for temperature and gas composition.

3.1 Methane Emission Surface Scans

Methane surface emissions are an important tool in identifying "hot spots" of methane emission from the landfill surface. Once located, the hot spots can then be assessed for emissions using flux measurements. The location of these "hot spots" allowed us to site the biofilters at the appropriate landfill surfaces, where methane is already moving through the landfill surface and thus maximizing our ability to treat these emissions.

3.1.1 Barriere

The attached table (Table 2) and map (Figure 5) show the results of the methane surface scanning conducted over the complete Barriere landfill area. A total of 1118 surface gas samples were analysed. Methane surface concentration values ranged from 0 (background) to 564 ppm (0.06 Vol %) methane, with a mean of 7.40 ppm (0.0007 Vol %) and a standard deviation of 42 ppm (0.0042 Vol %). Hot spots were identified (red circles) and methane emission was measured at these locations using a flux chamber and the results are shown in Figure 5. The methane scan showed the presence of two methane "hot spots" near the southern edge of the landfill.

3.1.2 Clearwater

The attached table (Table 2) and map (Figure 6) show the result of the methane surface scanning conducted over the complete Clearwater landfill area. A total of 2227 surface gas samples were analysed. Methane surface concentration values ranged from 0 (background) to 2674 ppm (0.27 Vol %) methane, with a mean of 15.7 ppm (0.0016 Vol %) and a standard deviation of 105 ppm (0.01 Vol %). Hot spots were identified (red circles) and methane emission was measured at these locations using a flux chamber and the results are shown in Figure 6. The methane scan showed the presence of four methane "hot spots" at the landfill, one each at the northern and north eastern edges and two at the south west edge of the landfill.

3.1.3 Chase

The attached table (Table 2) and map (Figure 7) show the result of the methane surface scanning conducted over the complete Chase landfill area. A total of 1504 surface gas samples were analysed. Methane surface concentration values ranged from 0 (background) to 2003 ppm (0.20 Vol.%) methane, with a mean of 31.8 ppm (0.0032 Vol.-%) and a standard deviation of 163 ppm (0.0163 Vol.-%). Figure 7 shows the presence of four methane "hot spots" at the landfill, one each at the northern and north eastern edges and two at the south west edge of the landfill.

3.1.4 Logan Lake

The attached table (Table 2) and map (Figure 8) show the result of the methane surface scanning conducted over the complete Logan Lake landfill area. A total of 1926 surface gas samples were analysed. Methane surface concentration values ranged from 0 (background) to 1301 ppm (0.13 Vol.%) methane, with a mean of 11.5 ppm (0.0012 Vol.-%) and a standard deviation of 66.7 ppm (0.0067 Vol.-%). Figure 8 shows the presence of five methane "hot spots" at the landfill, two each at the eastern and southern edges and one at the centre of the landfill.

Table 2. Statistical Analysis of the landfills' methane scan data (ppm)				
Statistical Parameter	Barriere	Clearwater	Chase	Logan Lake
Mean	7.40	15.7	31.8	11.5
Standard Error	1.26	2.22	4.20	1.52
Median	0.56	0.37	0.46	0.49
Mode	0	0	0	0
Standard Dev.	42.0	105	163	66.7
Sample Variance	1762	11004	26544	4442
Kurtosis	85.3	360	76.0	196
Skewness	8.86	17.5	8.32	12.3
Range	564	2674	2003	1301
Minimum	0	0	0	0
Maximum	564	2674	2003	1301
Sum	8271	34930	47891	22232
Count	1118	2227	1504	1926

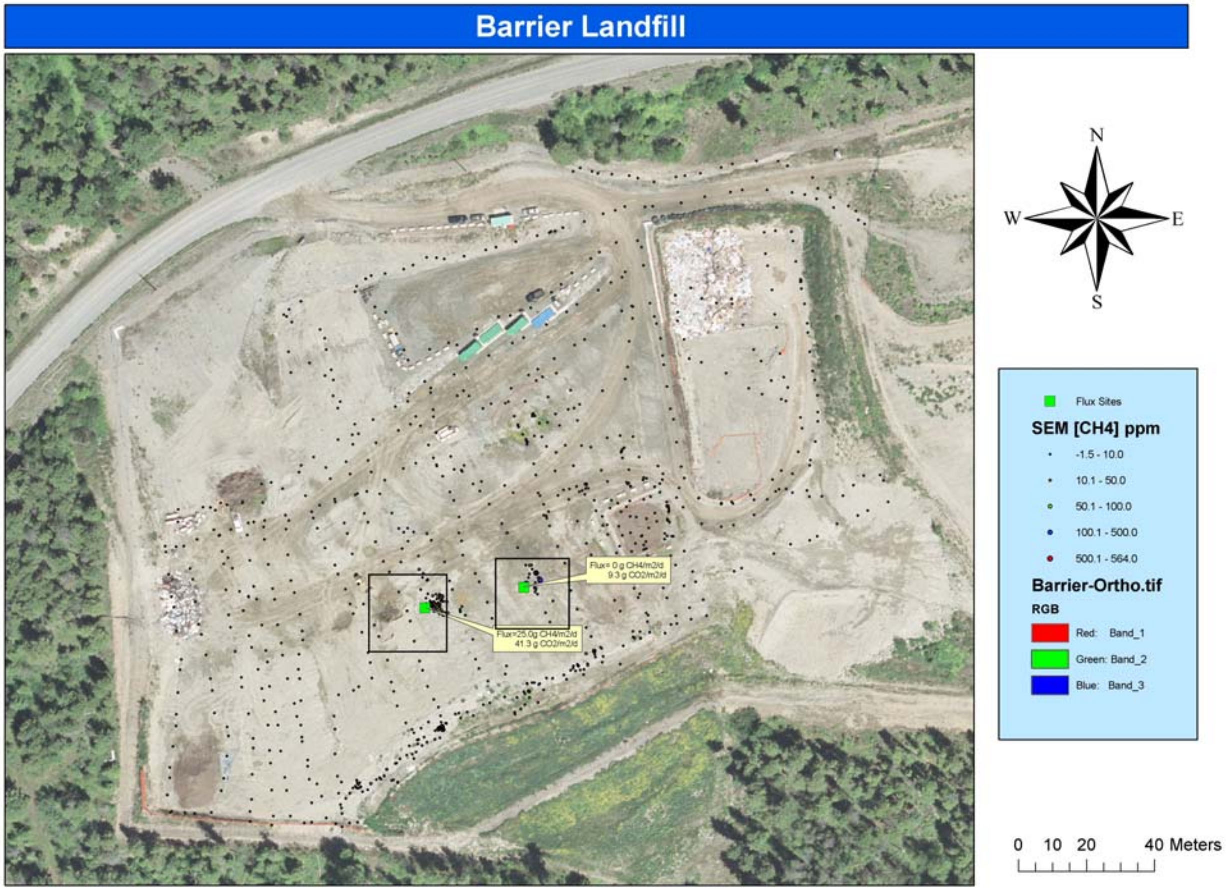

Figure 5. Surface methane scan of the Barriere landfill showing the proposed location of the Methane Oxidation beds.

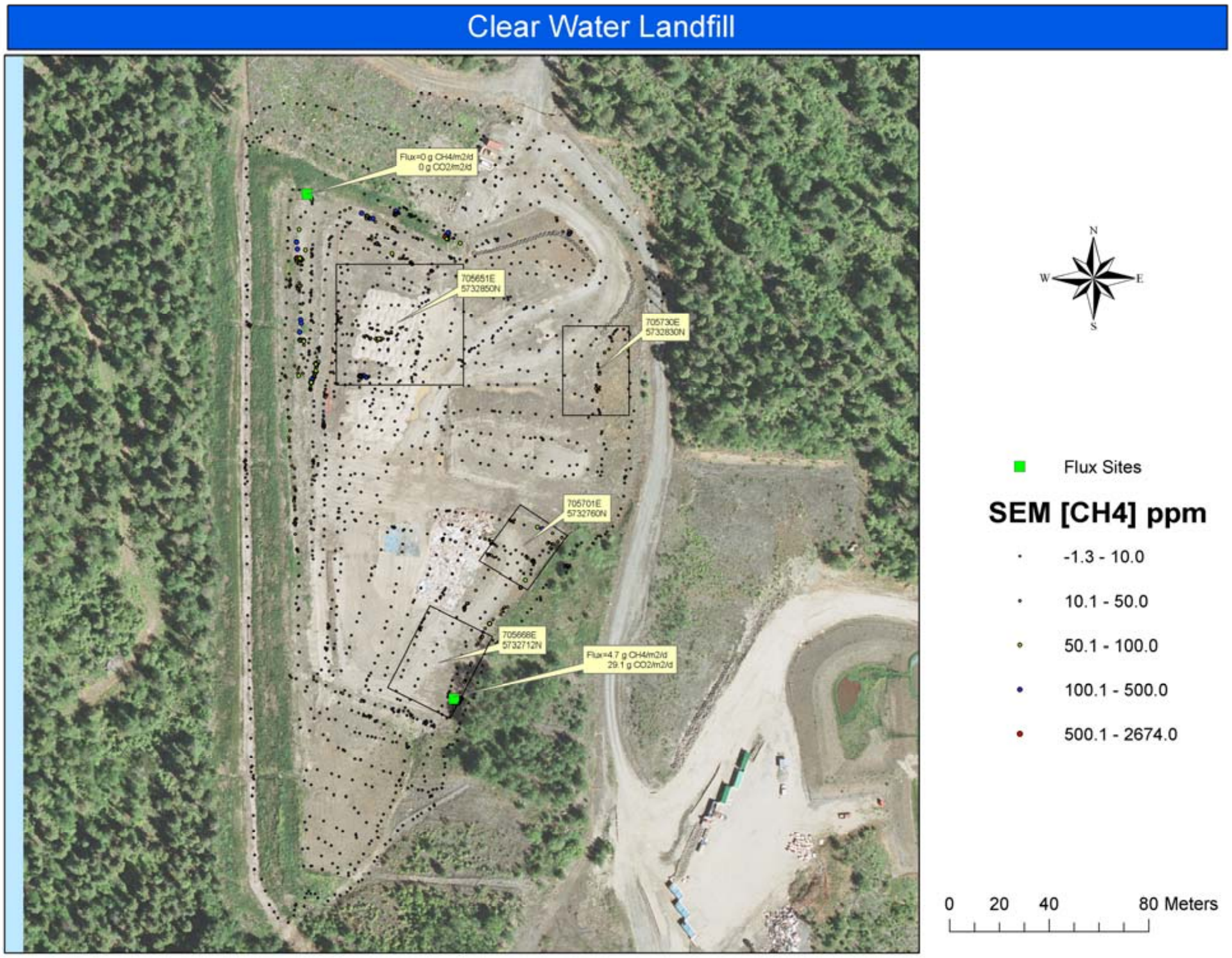

Figure 6. Surface methane scan of the Clearwater landfill showing the proposed location of the Methane Oxidation beds.

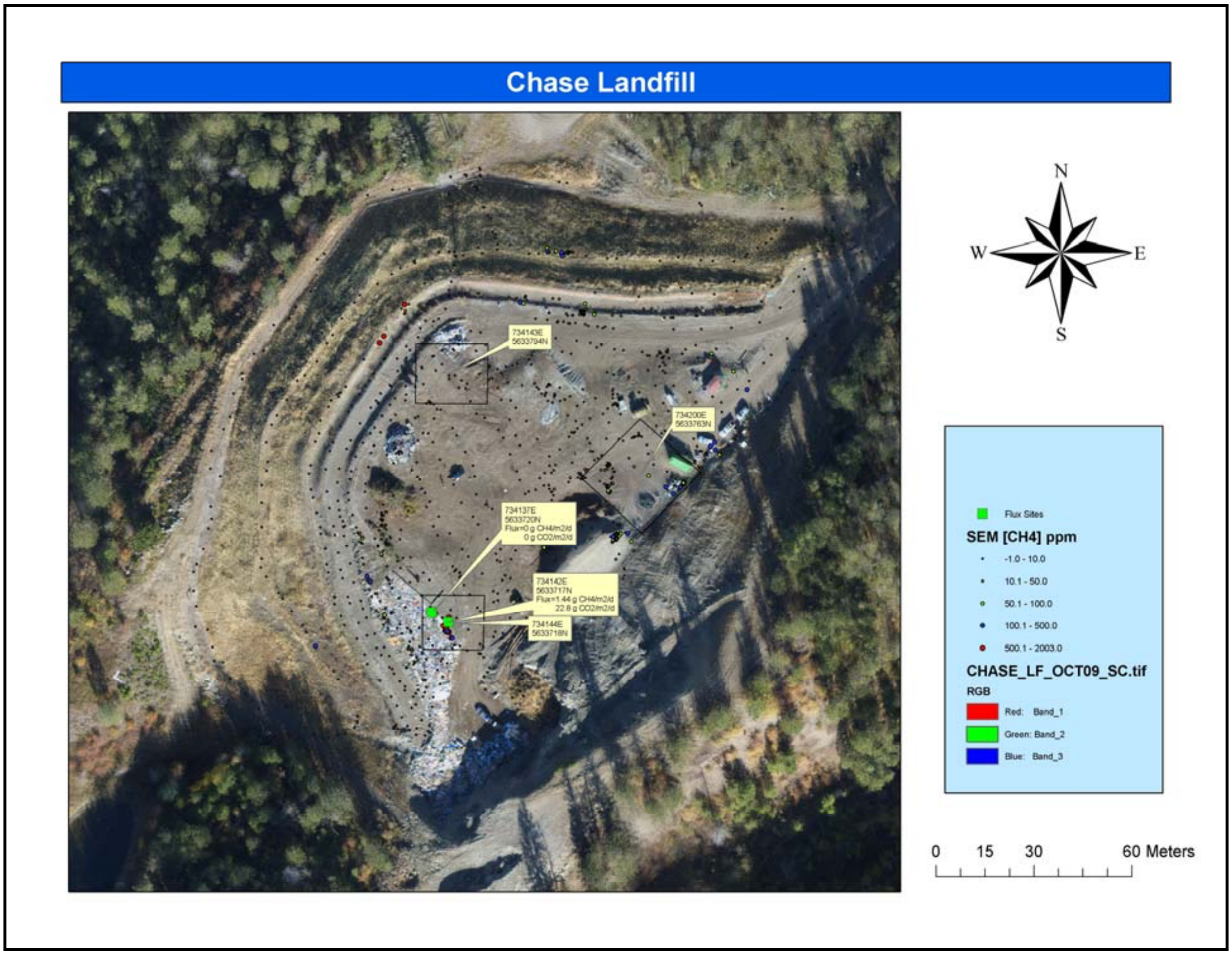

Figure 7. Surface methane scan of the Chase landfill showing the proposed location of the Methane Oxidation beds.

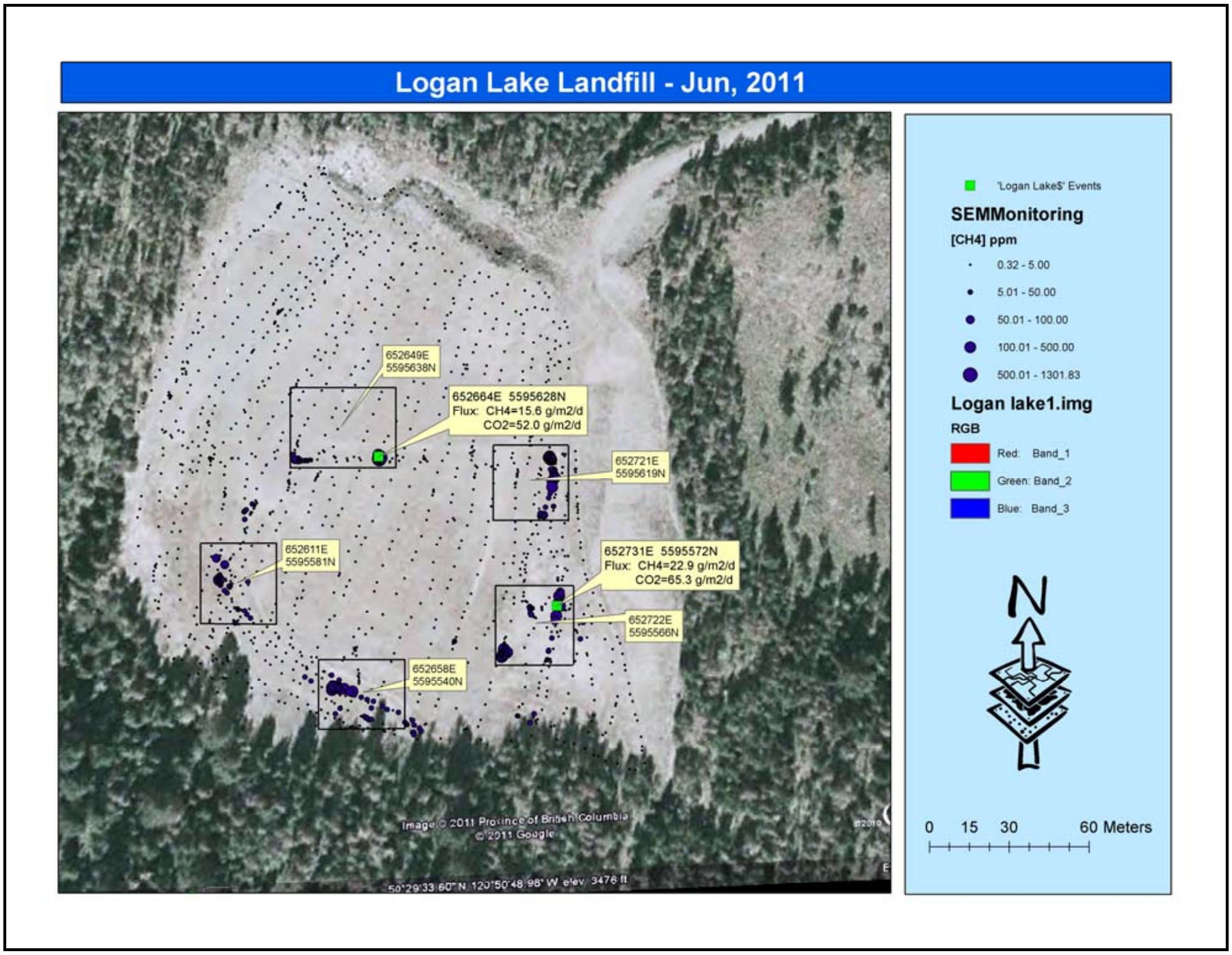

Figure 8. Surface methane scan of the Logan Lake landfill showing the proposed location of the Methane Oxidation beds.

3.2 Temperature Profiles

Temperature is an important parameter in assessing the functioning of any biofilter, as it is used as a surrogate for biological activity. The oxidation of methane by microorganisms into CO_2 and biomass is a heat producing reaction and this heat is reflected in increased temperatures. Monitoring the changes in biofilter temperature affords us the chance to monitor the microbiological activity in the biofilter and thus its ability to oxidize methane.

3.2.1 Barriere

The temperature changes in the Barriere biofilter was recorded hourly and the daily averages are plotted in Figures 9 and 10.

Figure 9 presents the temperature changes over time as the averages at each of the 4 monitoring locations. The data clearly shows that the biofilter temperature is always higher than the air temperature, that the temperatures are highest in the summer and lowest in the winter. Furthermore, the data from the 4 locations show remarkable similarities, which indicate good replication due to the homogeneity of the biofilter.

Figure 10 presents the temperature changes over time as the averages at each of the 5 monitoring depths. Again, the data clearly shows that the biofilter temperature is always higher than the air temperature, that the temperatures are highest in the summer and lowest in the winter. Furthermore, the data from the 5 depths show different values for the summer months but less different for the winter months. The data from the 5 depths show that the highest variability is in the 20 cm depth as it is closest to the surface while the lowest variability is in the 120 and 160 cm depths as they are close to the almost constant internal landfill temperature.

The temperature data seem to indicate that biological activity is occurring in the biofilter and is highest in the summer and lowest in the winter months. We can thus expect to see that the methane removal rates to behave similarly to the temperatures and show highest values in the summer months.

3.2.2 Clearwater

The temperature changes in the Clearwater biofilter was recorded hourly and the daily averages are plotted in Figures 11 and 12.

Figure 11 presents the temperature changes over time as the averages at each of the 4 monitoring locations. The data clearly shows that the biofilter temperature is always higher than the air temperature, that the temperatures are highest in the summer and lowest in the winter. The data from the 4 locations show two distinct groupings as similarities exist between locations 1 and 2 (1st group) and 3 and 4 (2nd group), which indicate that the biofilter has 2 areas, each showing good replication due to the homogeneity of the particular area of the biofilter. This anomaly is likely due to the construction of the biofilter where a rock sling was used to fill the biofilter with the MOB material leading to a segregation of the heavier biosolids (higher bulk density) from the wood chips (lower bulk density).

Figure 12 presents the temperature changes over time as the averages at each of the 5 monitoring depths. Again, the data clearly shows that the biofilter temperature is always higher than the air temperature, that the temperatures are highest in the summer and lowest in the winter. Furthermore, the data from the 5 depths show different values for the summer months but less different for the winter months. Also, the data from the 5 depths show that the highest variability is in the 20 cm depth as it is closest to the surface while the lowest variability is in the 120 and 160 cm depths as they are close to the almost constant internal landfill temperature.

The temperature data seem to indicate that biological activity is occurring in the biofilter and is highest in the summer and lowest in the winter months. We can thus expect to see that the methane removal rates to behave similarly to the temperatures and show highest values in the summer months.

3.2.3 Chase

The temperature changes in the Chase biofilter was recorded hourly and the daily averages are plotted in Figures 13 and 14.
Figure 13 presents the temperature changes over time as the averages at each of the 4 monitoring locations. The data clearly shows that the biofilter temperature is always higher than the air temperature, that the temperatures are highest in the summer and lowest in the winter. The data from the 4 locations show two groupings as similarities exist between locations 1 and 2 (1st group) and 3 and 4 (2nd group), which indicate that the biofilter has 2 areas, each showing good replication due to the homogeneity of the particular area of the biofilter. The difference between the two groupings, although not large, seems to have arisen after the start of the biofilter and is likely due to the addition of new MOB materials to the biofilter after construction was completed or to differential settling of the MOB material.

Figure 14 presents the temperature changes over time as the averages at each of the 5 monitoring depths. Again, the data clearly shows that the biofilter temperature is always higher than the air temperature. Furthermore, the data from the 5 depths show that the highest variability is in the 20 cm depth as it is closest to the surface while the lowest variability is in the 120 and 160 cm depths as they are close to the almost constant internal landfill temperature.

The temperature data seem to indicate that biological activity is occurring in the biofilter and is highest in the summer and lowest in the winter months. We can thus expect to see that the methane removal rates to behave similarly to the temperatures and show highest values in the summer months.

3.2.4 Logan Lake

The temperature changes in the Logan Lake biofilter was recorded hourly and the daily averages are plotted in Figures 15 and 16.

Figure 15 presents the temperature changes over time as the averages at each of the 4 monitoring locations. The data clearly shows that the biofilter temperature is always higher than the air temperature, that the temperatures are highest in the summer and lowest in the winter. Furthermore, the data from the 4 locations show remarkable similarities, which indicate good replication due to the homogeneity of the biofilter materials.

Figure 16 presents the temperature changes over time as the averages at each of the 5 monitoring depths. Again, the data clearly shows that the biofilter temperature is always higher than the air temperature. Furthermore, the data from the 5 depths show that the highest variability is in the 20 cm depth as it is closest to the surface while the lowest variability is in the 120 and 160 cm depths as they are close to the almost constant internal landfill temperature.

The temperature data seem to indicate that biological activity is occurring in the biofilter and is highest in the summer and lowest in the winter months. We can thus expect to see that the methane removal rates to behave similarly to the temperatures and show highest values in the summer months.

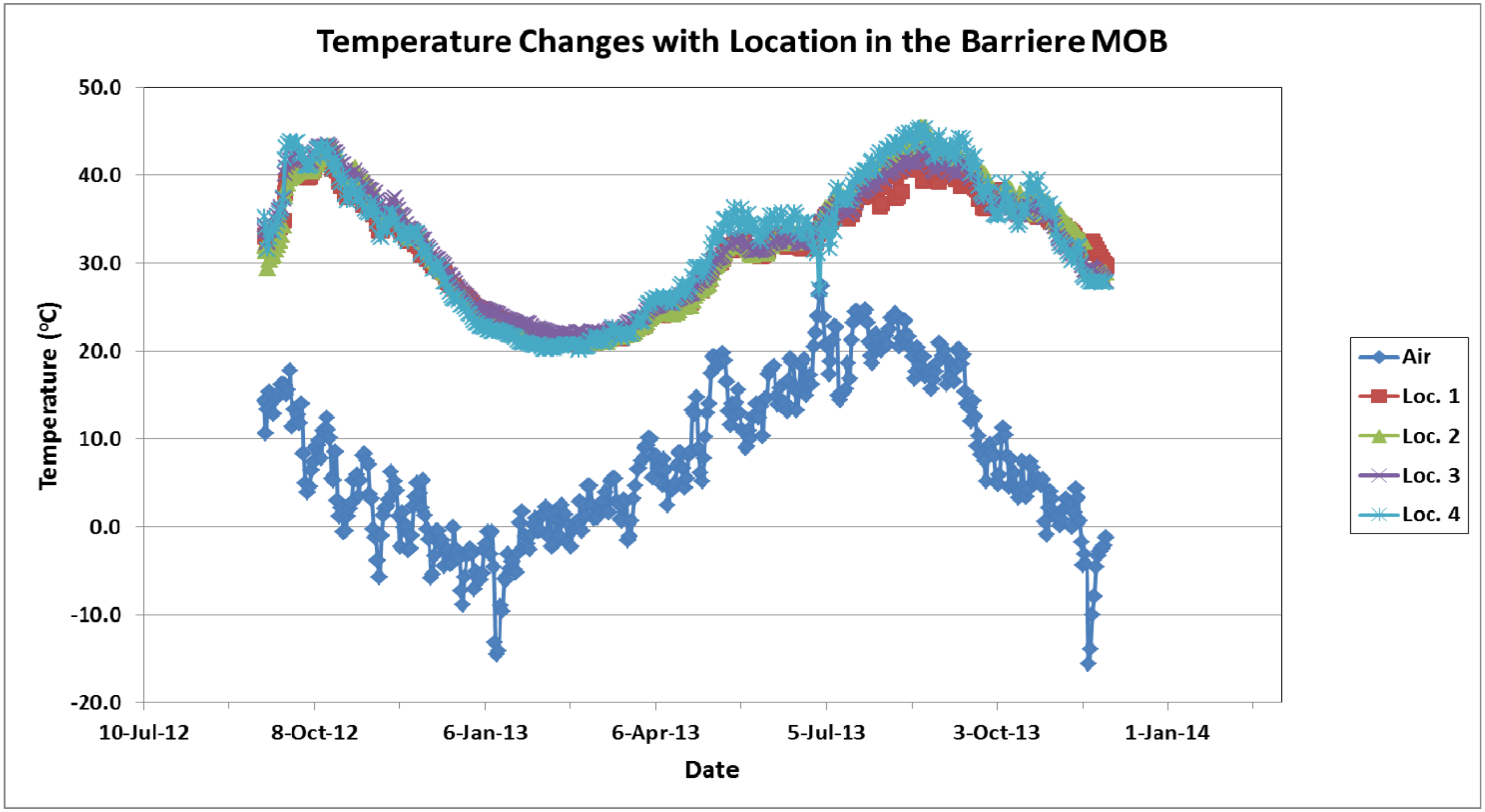

Figure 9. Barriere landfill temperature profile for each measurement location (averaged over 4 biofilter depths).

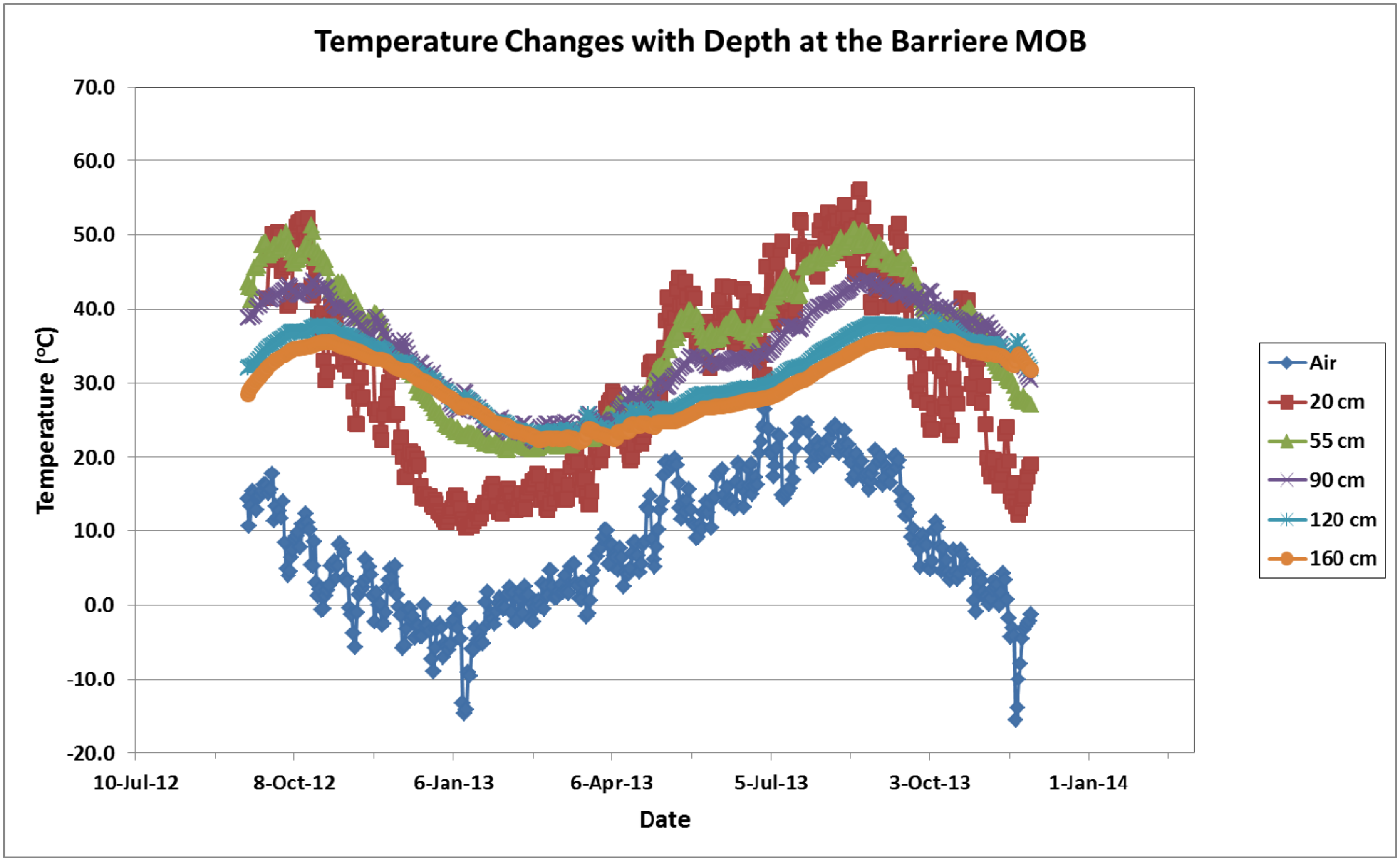

Figure 10. Barriere landfill temperature profile for each measurement depth (averaged over 4 measurement locations).

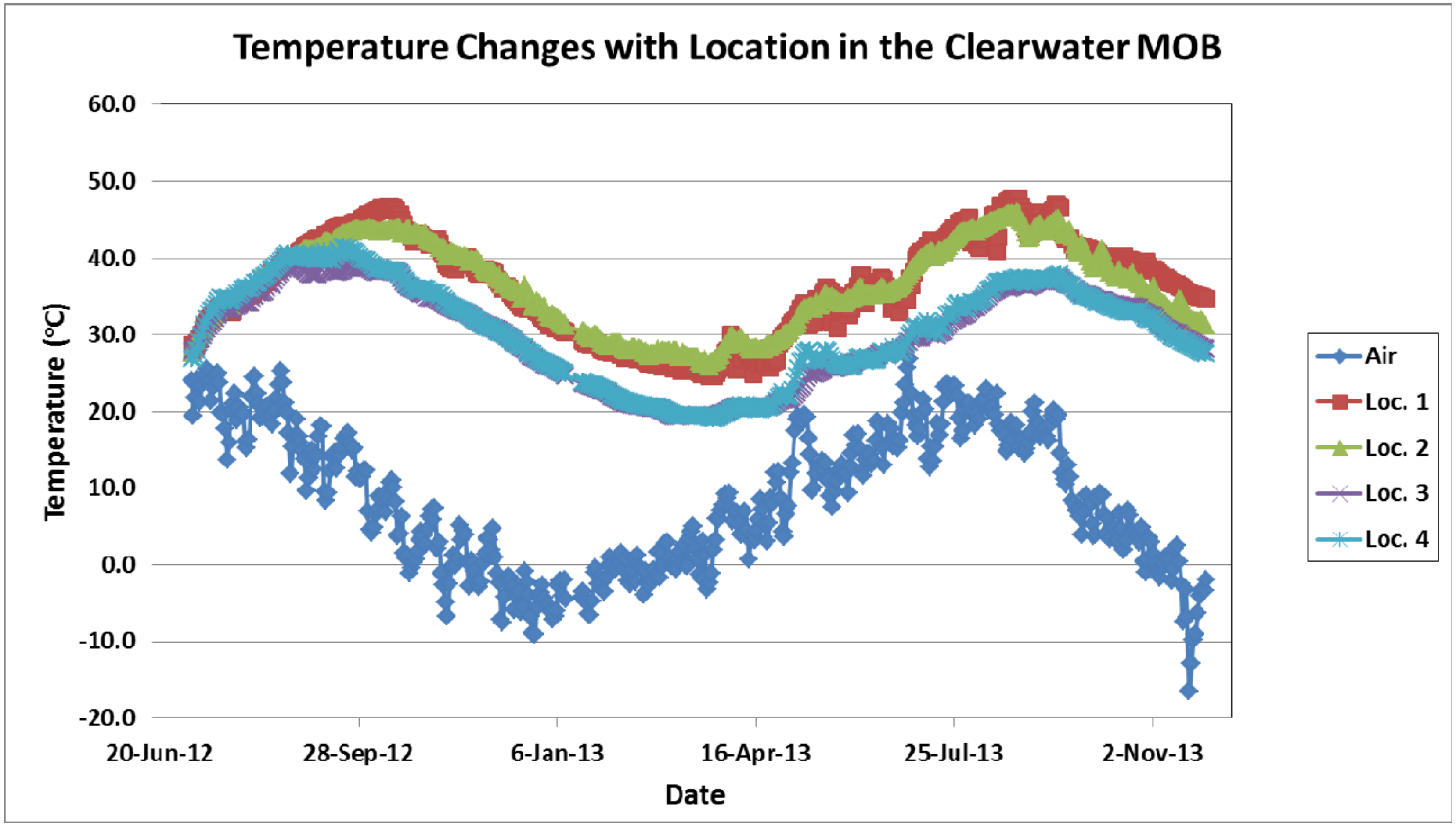

Figure 11. Clearwater landfill temperature profile for each measurement location (averaged over 4 biofilter depths).

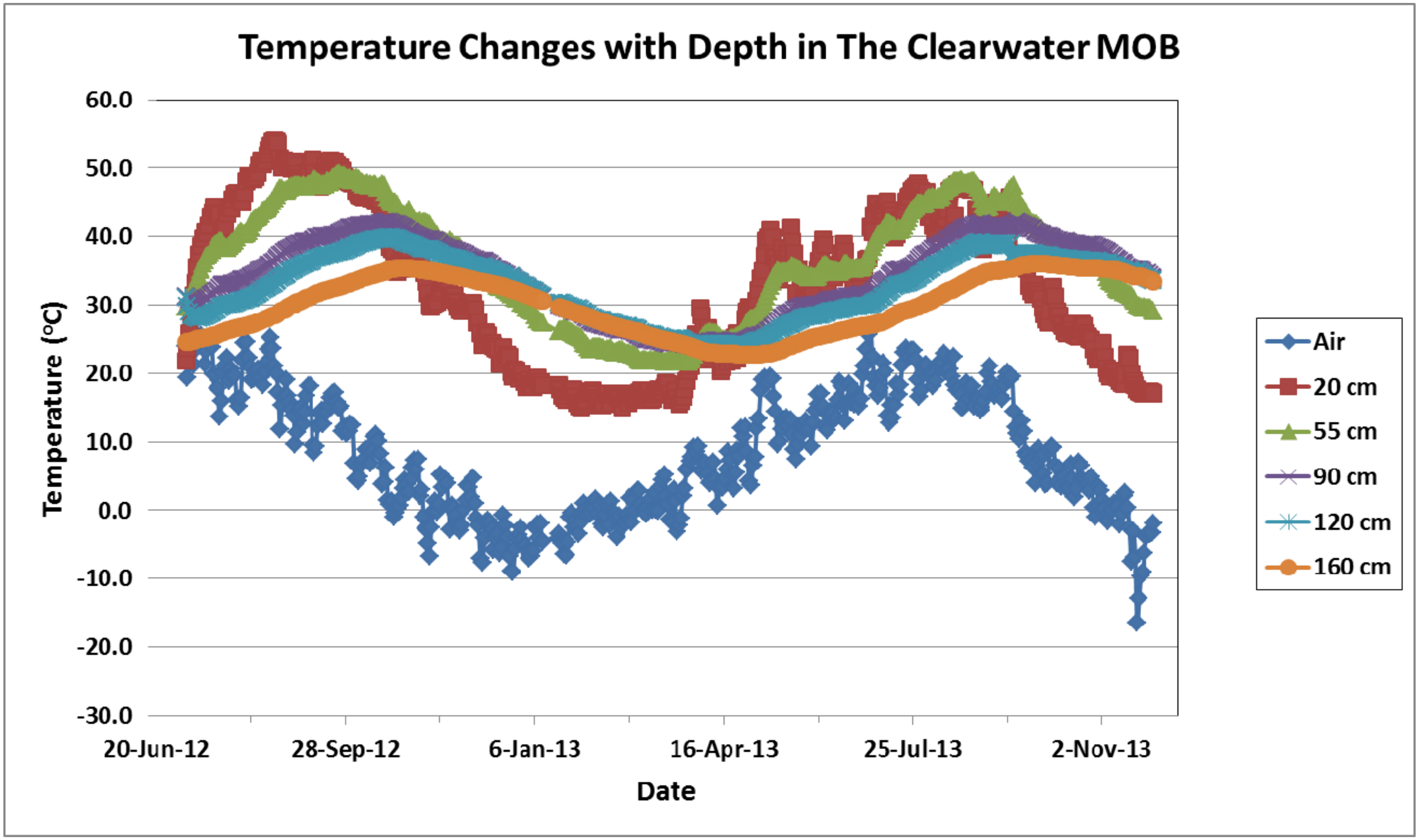

Figure 12. Clearwater landfill temperature profile for each measurement depth (averaged over 4 measurement locations).

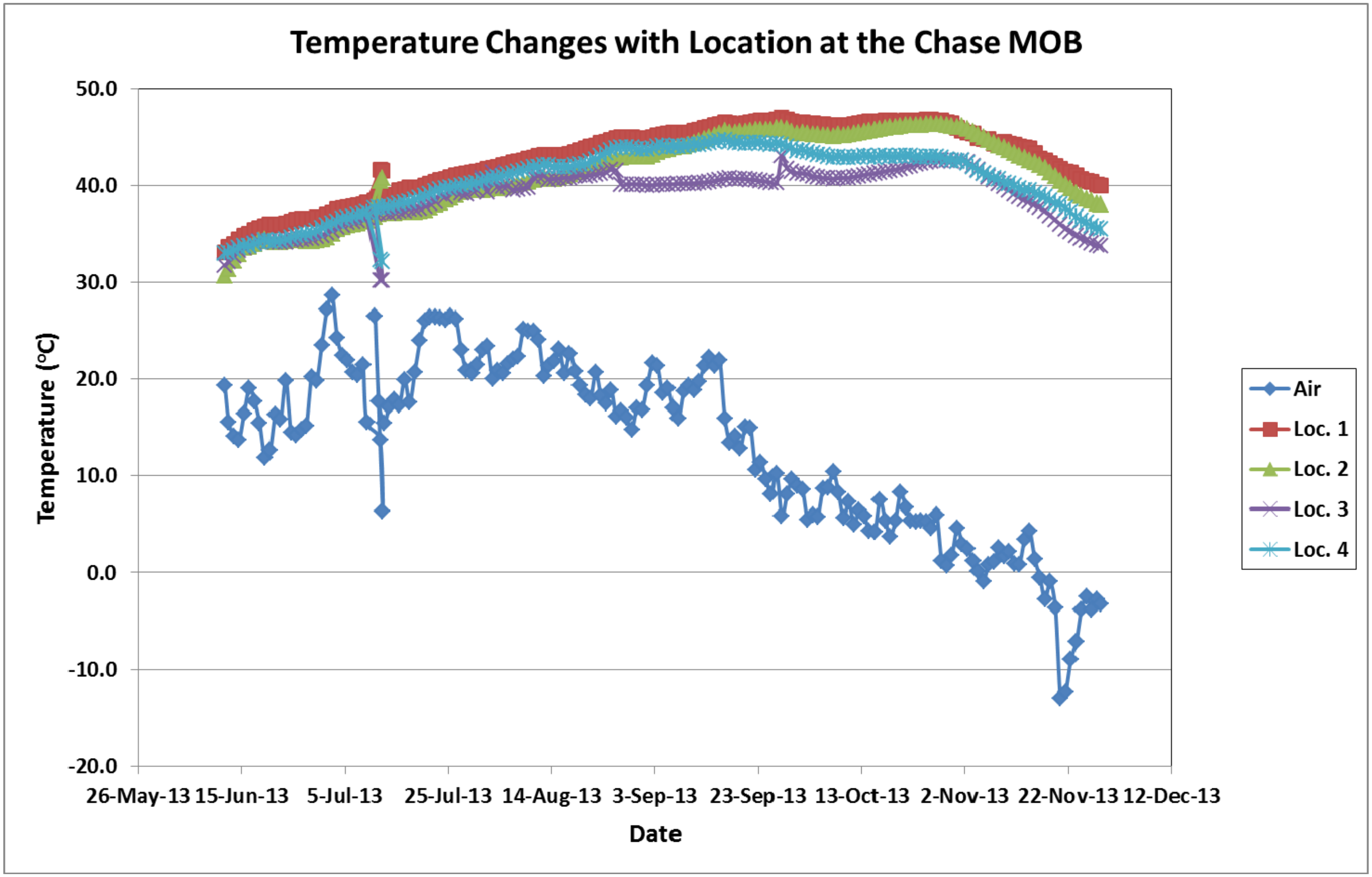

Figure 13. Chase landfill temperature profile for each measurement location (averaged over 4 biofilter depths).

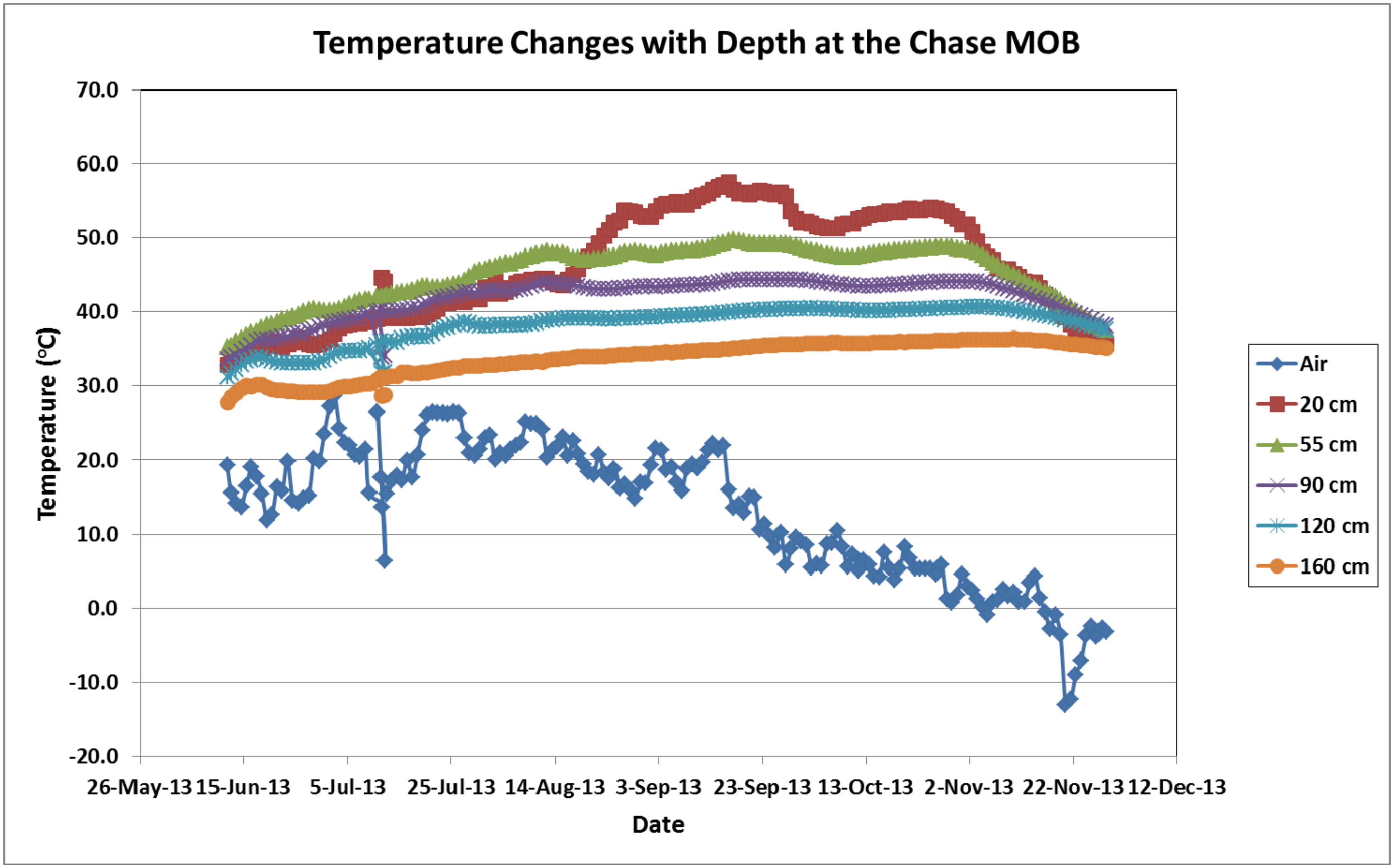

Figure 14. Chase landfill temperature profile for each measurement depth (averaged over 4 measurement locations).

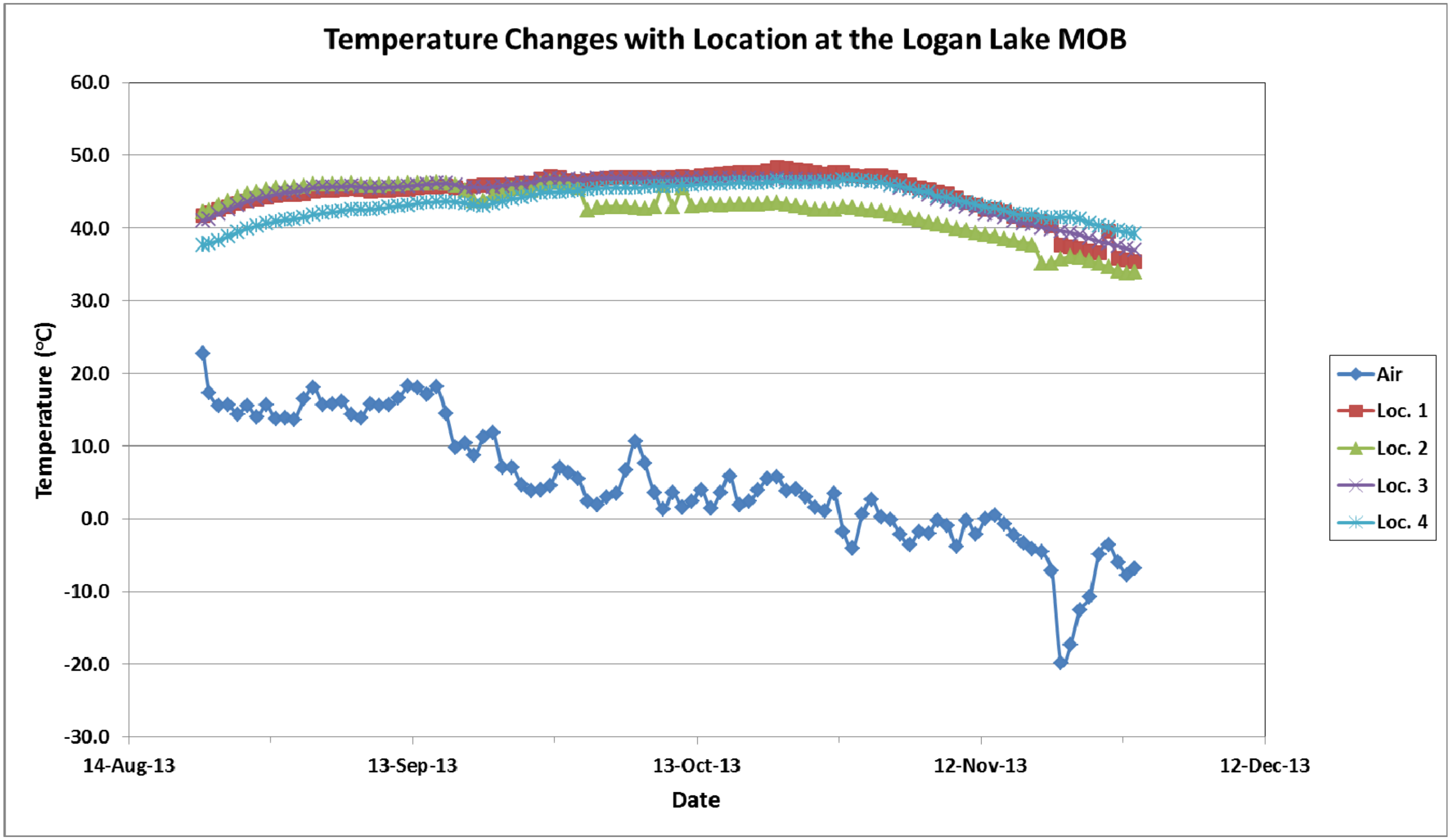

Figure 15. Logan Lake landfill temperature profile for each measurement location (averaged over 4 biofilter depths).

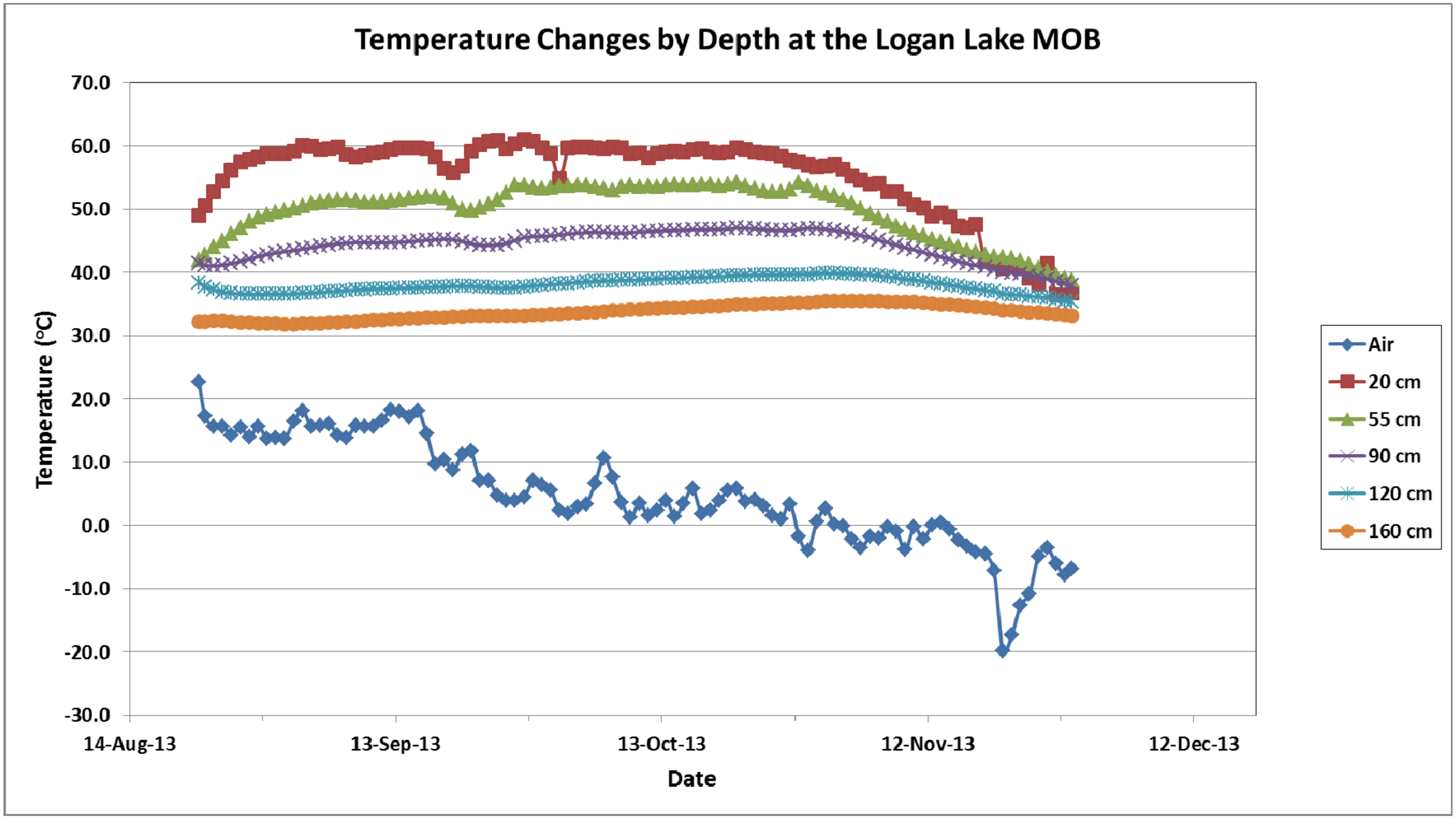

Figure 16. Logan Lake landfill temperature profile for each measurement depth (averaged over 4 measurement locations).

3.3 Gas Composition

Landfill gas consists primarily of CH_4 and CO_2 with traces of other gases. Monitoring the changes in gas composition at different biofilter depths allows us to observe changes due to biological activity in the biofilter. One expects to have the highest CH_4 concentrations at the drainage layer (160 cm) as it is the same as the landfill CH_4 concentrations (no treatment yet). As the gas moves up it is treated by microbial aerobic degradation, which requires O_2 to move into the biofilter from the atmosphere. Thus the monitoring of gas composition with depths allows us to observe the oxidation of CH_4 as it travels up the biofilter medium.

Figures 17, 18, 19 and 20 show the changes in gas composition by depth, for the Barriere, Clearwater, Chase and Logan Lake biofilters. The data indicates that the concentration of methane at the landfill surface (160 cm) varies with time which could be due to variations in weather conditions (temperature and pressure).

3.3.1 Barriere

The gas composition in the Barriere biofilter is presented in Figure 17 for the 2013 monitoring events showing the changes by depth for each monitoring period and the changes between monitoring events (seasonal).

Figure 17 shows that the CH_4 and CO_2 concentrations are highest in the lowest depths and decrease as one progresses up through the biofilter. The decrease in CH_4 concentrations as it travels up the biofilter is due to biological oxidation which reduces the CH_4 concentrations and generates heat (as shown in Figure 10). The decrease in CO_2 concentrations is likely due to the dilution by air as evidenced by the increased N_2 concentrations. O_2 concentration decrease rapidly down the biofilter depth and are often near zero, indicating the complete use of O_2 in CH_4 oxidation. We can enhance CH_4 removal by oxidation if we can introduce more O_2 into the biofilter, especially to the layers lower than 20 cm.

It is evident from the data that the biofilter is capable of removing CH_4 from the landfill gas stream by microbial oxidation, but that ability is limited by the amount of O_2 introduced into the biofilter. Thus increasing the O_2 concentrations down the biofilter depths will allow for increased CH_4 removal.

3.3.2 Clearwater

The gas composition in the Clearwater biofilter is presented in Figure 18 for the 2013 monitoring events showing the changes by depth for each monitoring period and the changes between monitoring events (seasonal).

Figure 18 shows that the CH_4 and CO_2 concentrations are highest in the lowest depths and decrease as one progresses up through the biofilter. The decrease in CH_4 concentrations as it travels up the biofilter is due to biological oxidation which reduces the CH_4 concentrations and generates heat (as shown in Figure 12). The decrease in CO_2 concentrations is likely due to the dilution by air as evidenced by the increased N_2 concentrations. O_2 concentration decrease rapidly down the biofilter depth and are often near zero, indicating the complete use of O_2 in CH_4 oxidation. We can enhance CH_4 removal by oxidation if we can introduce more O_2 into the biofilter, especially to the layers lower than 20 cm.

It is evident from the data that the biofilter is capable of removing CH_4 from the landfill gas stream by microbial oxidation, but that ability is limited by the amount of O_2 introduced into the biofilter. Thus increasing the O_2 concentrations down the biofilter depths will allow for increased CH_4 removal.

3.3.3 Chase

The gas composition in the Chase biofilter is presented in Figure 19 for the 2013 monitoring events showing the changes by depth for each monitoring period and the changes between monitoring events (seasonal).

Figure 19 shows that the CH_4 and CO_2 concentrations are highest in the lowest depths and decrease as one progresses up through the biofilter. The decrease in CH_4 concentrations as it travels up the biofilter is due to biological oxidation which reduces the CH_4 concentrations and generates heat (as shown in Figure 14). The decrease in CO_2 concentrations is likely due to the dilution by air as evidenced by the increased N_2 concentrations. O_2 concentration decrease rapidly down the biofilter depth and are often near zero, indicating the complete use of O_2 in CH_4 oxidation. We can enhance CH_4

removal by oxidation if we can introduce more O_2 into the biofilter, especially to the layers lower than 20 cm.

It is evident from the data that the biofilter is capable of removing CH_4 from the landfill gas stream by microbial oxidation, but that ability is limited by the amount of O_2 introduced into the biofilter. Thus increasing the O_2 concentrations down the biofilter depths will allow for increased CH_4 removal.

3.3.4 Logan Lake

The gas composition in the Logan Lake biofilter is presented in Figure 20 for the 2013 monitoring events showing the changes by depth for each monitoring period and the changes between monitoring events (seasonal).

Figure 20 shows that the CH_4 and CO_2 concentrations are highest in the lowest depths and decrease as one progresses up through the biofilter. The decrease in CH_4 concentrations as it travels up the biofilter is due to biological oxidation which reduces the CH_4 concentrations and generates heat (as shown in Figure 16). The decrease in CO_2 concentrations is likely due to the dilution by air as evidenced by the increased N_2 concentrations. O_2 concentration decrease rapidly down the biofilter depth and are often near zero, indicating the complete use of O_2 in CH_4 oxidation. We can enhance CH_4 removal by oxidation if we can introduce more O_2 into the biofilter, especially to the layers lower than 20 cm.

It is evident from the data that the biofilter is capable of removing CH_4 from the landfill gas stream by microbial oxidation, but that ability is limited by the amount of O_2 introduced into the biofilter. Thus increasing the O_2 concentrations down the biofilter depths will allow for increased CH_4 removal.

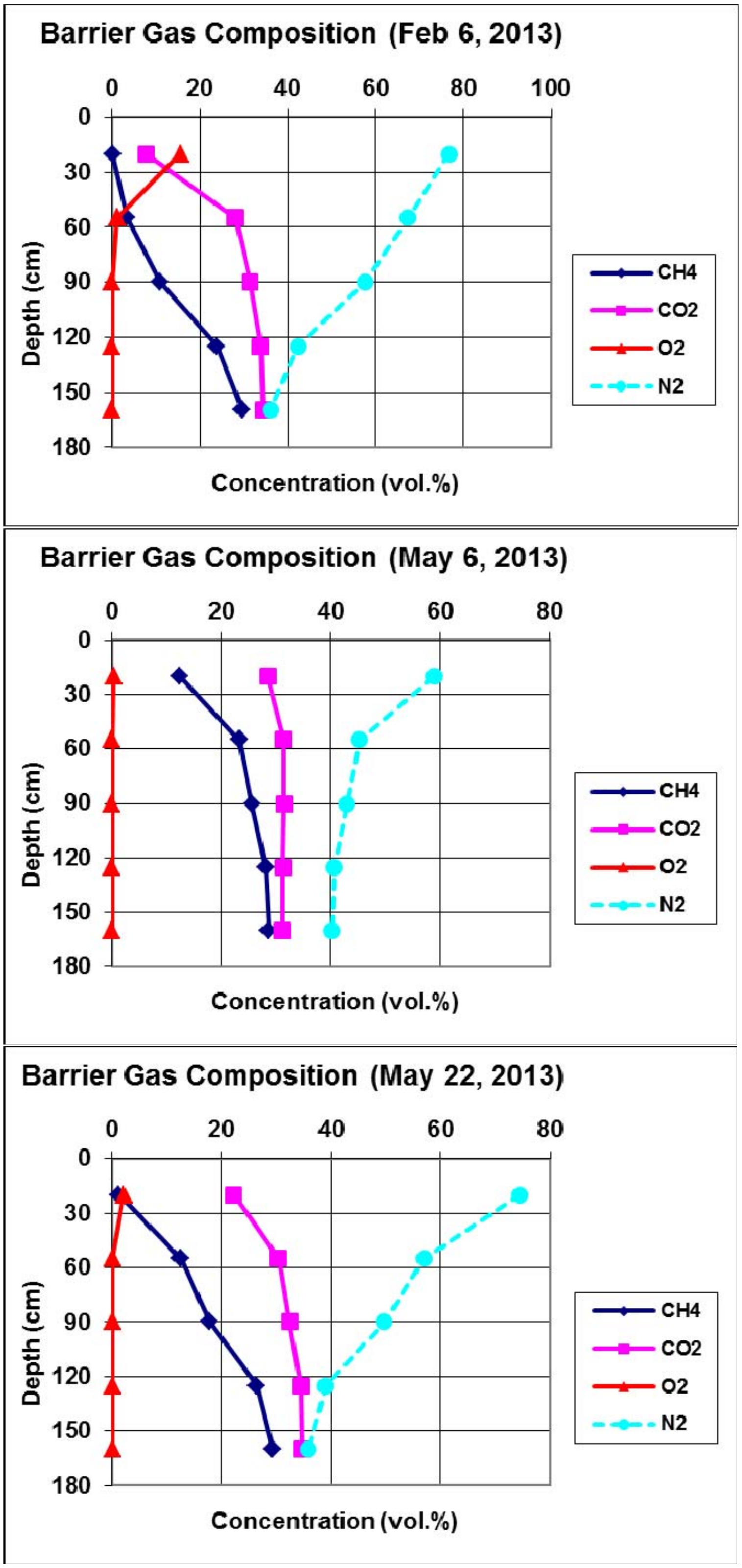

Figure 17. Barriere gas composition at several depths and sampling dates.

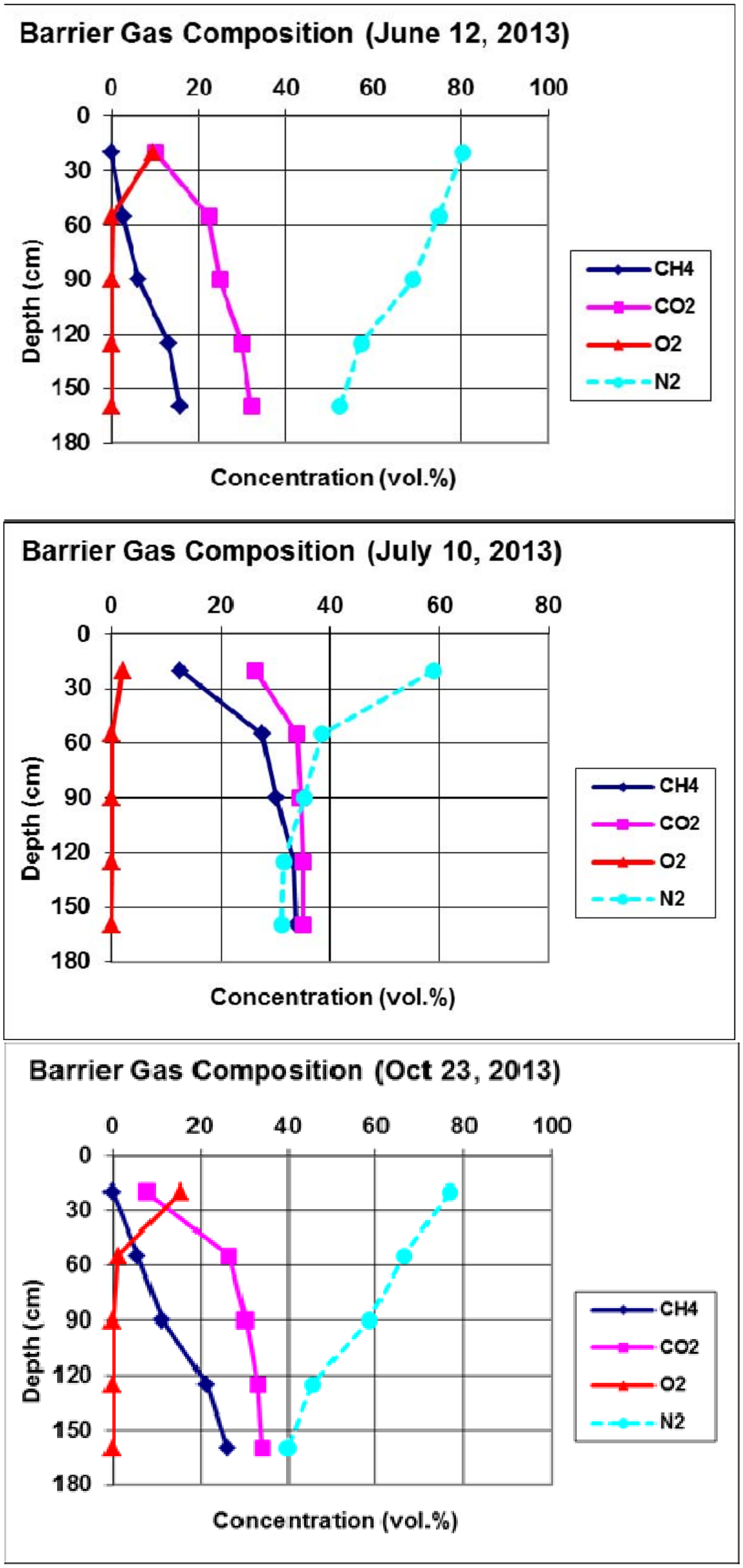

Figure 17 (Continued). Barriere gas composition at several depths and sampling dates.

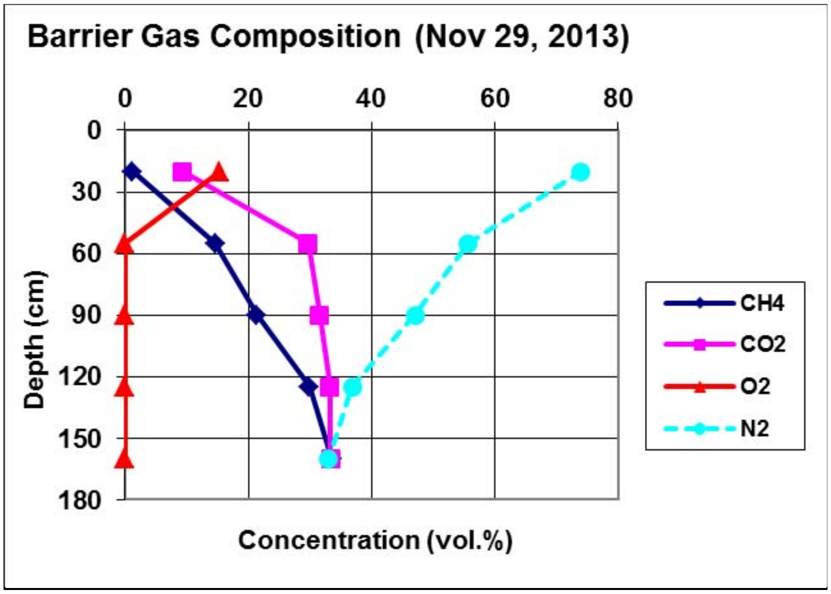

Figure 17 (Continued). Barriere gas composition at several depths and sampling dates.

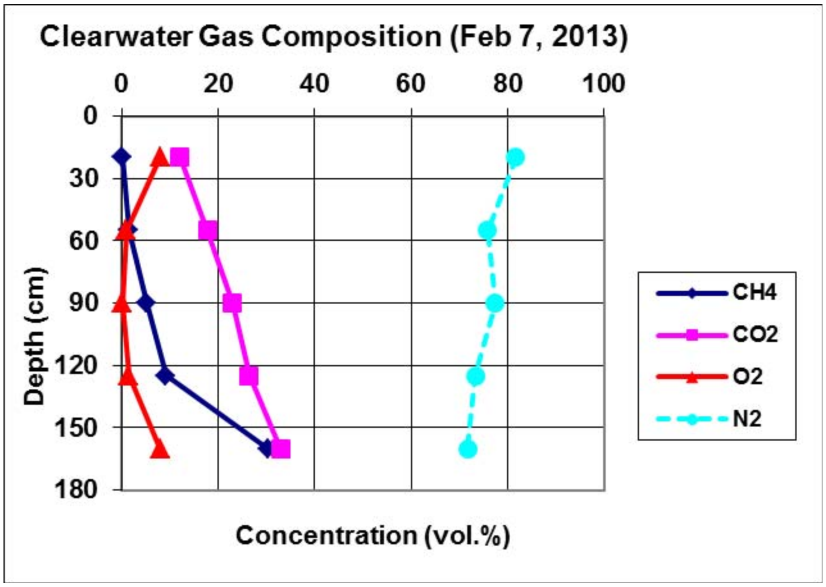

Figure 18. Clearwater gas composition at several depths and sampling dates.

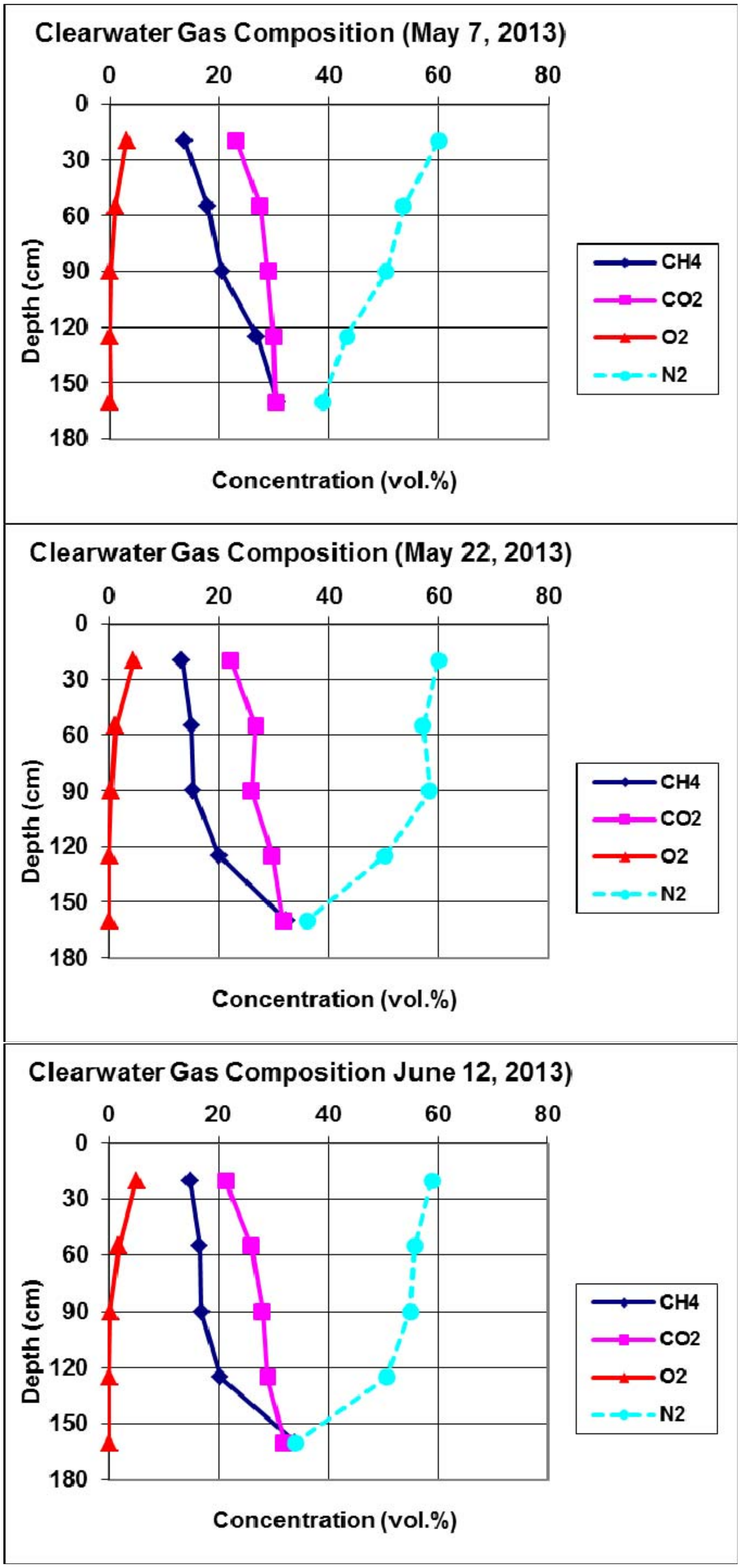

Figure 18 (Continued). Clearwater gas composition at several depths and sampling dates.

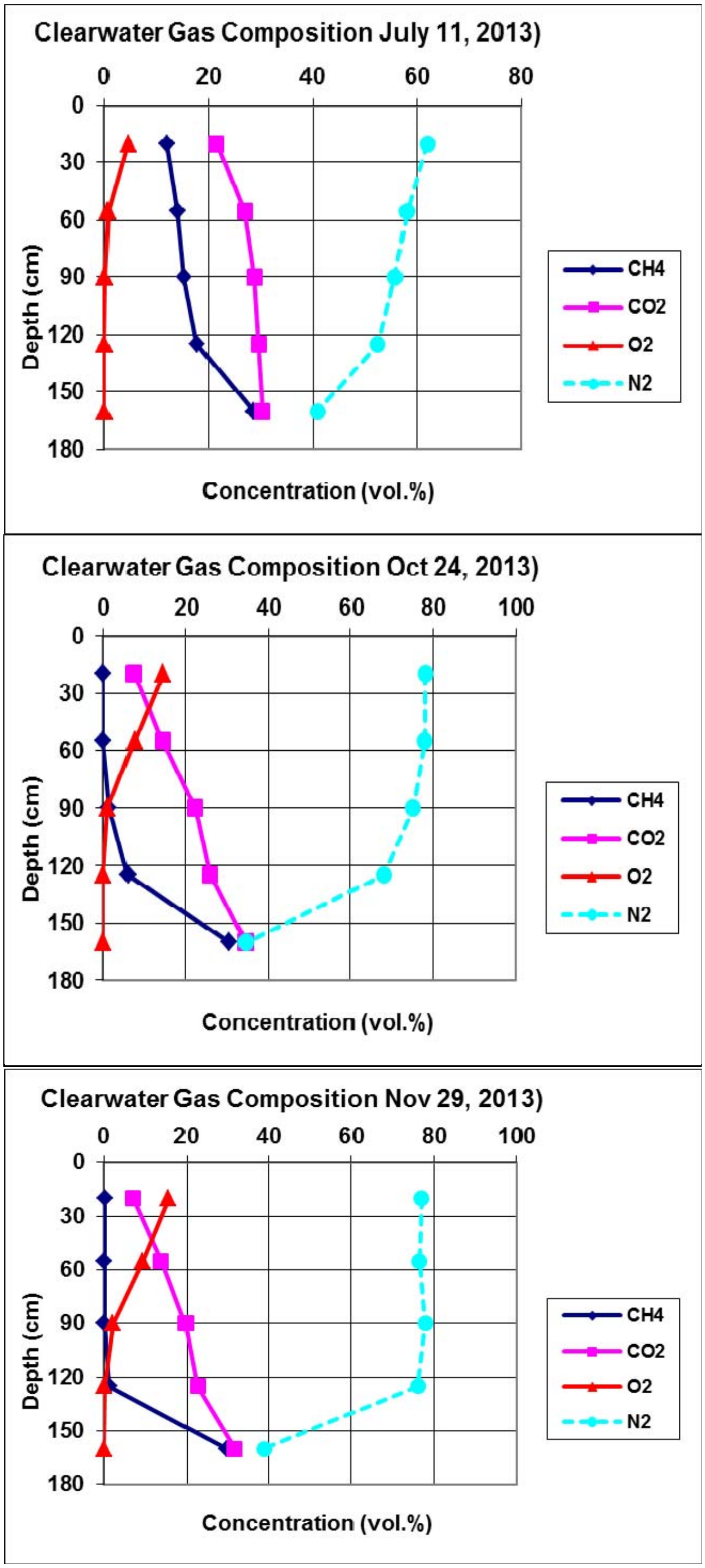

Figure 18 (Continued). Clearwater gas composition at several depths and sampling dates.

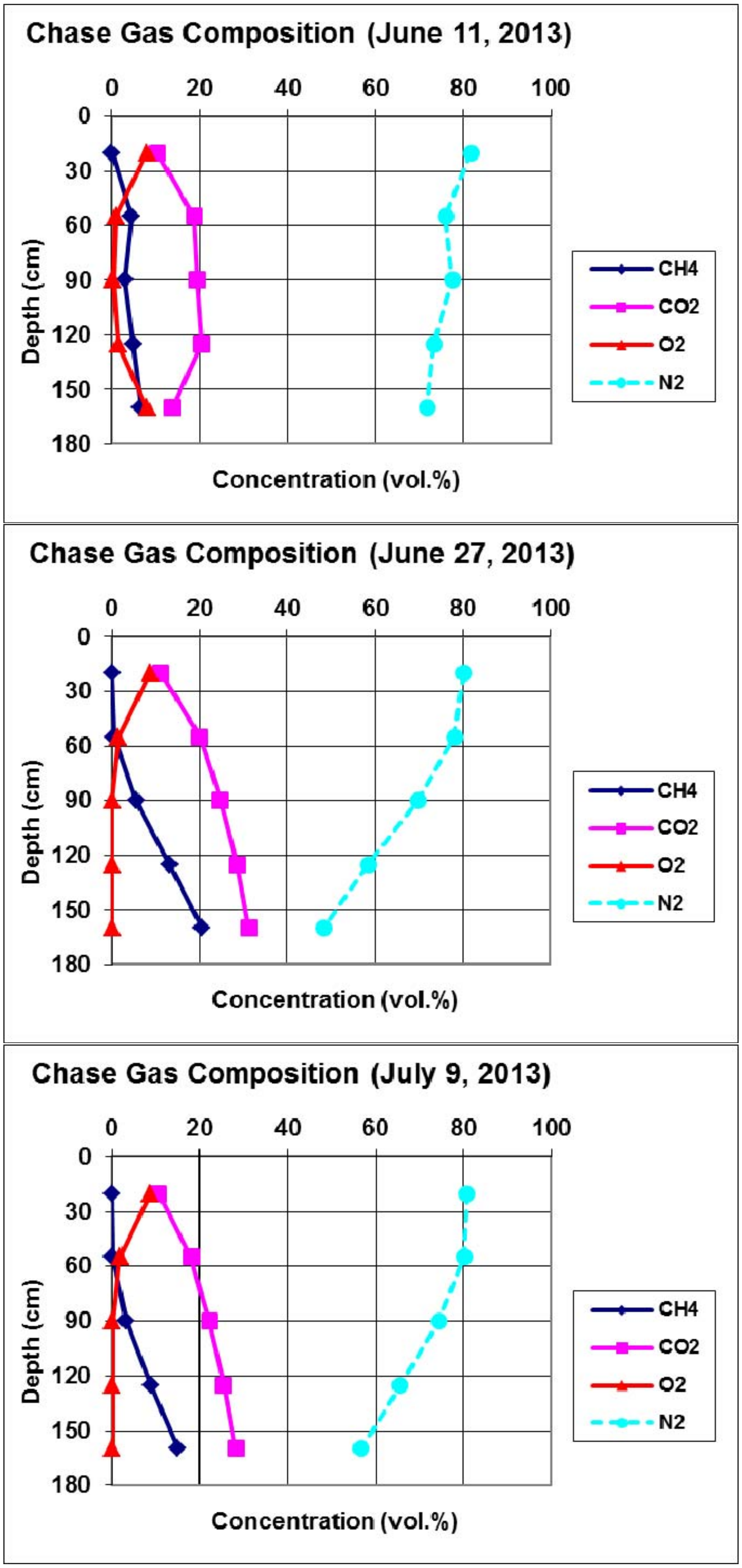

Figure 19. Chase gas composition at several depths and sampling dates.

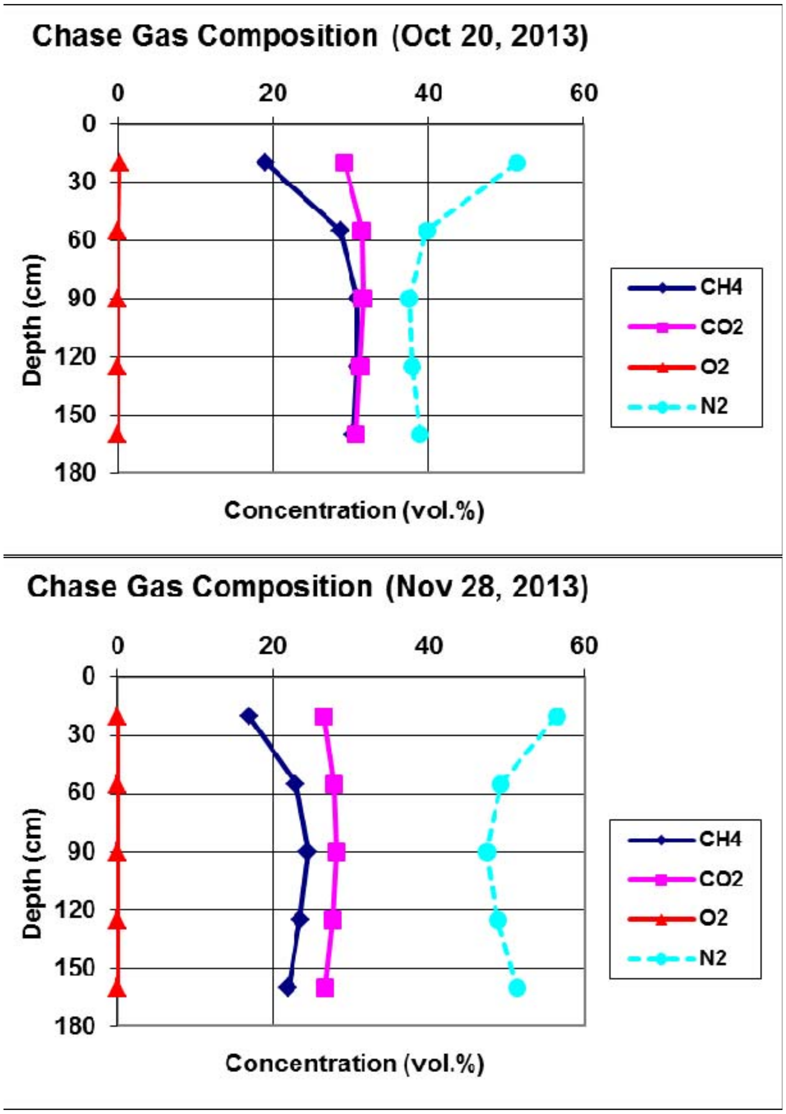

Figure 19 (Continued). Chase gas composition at several depths and sampling dates.

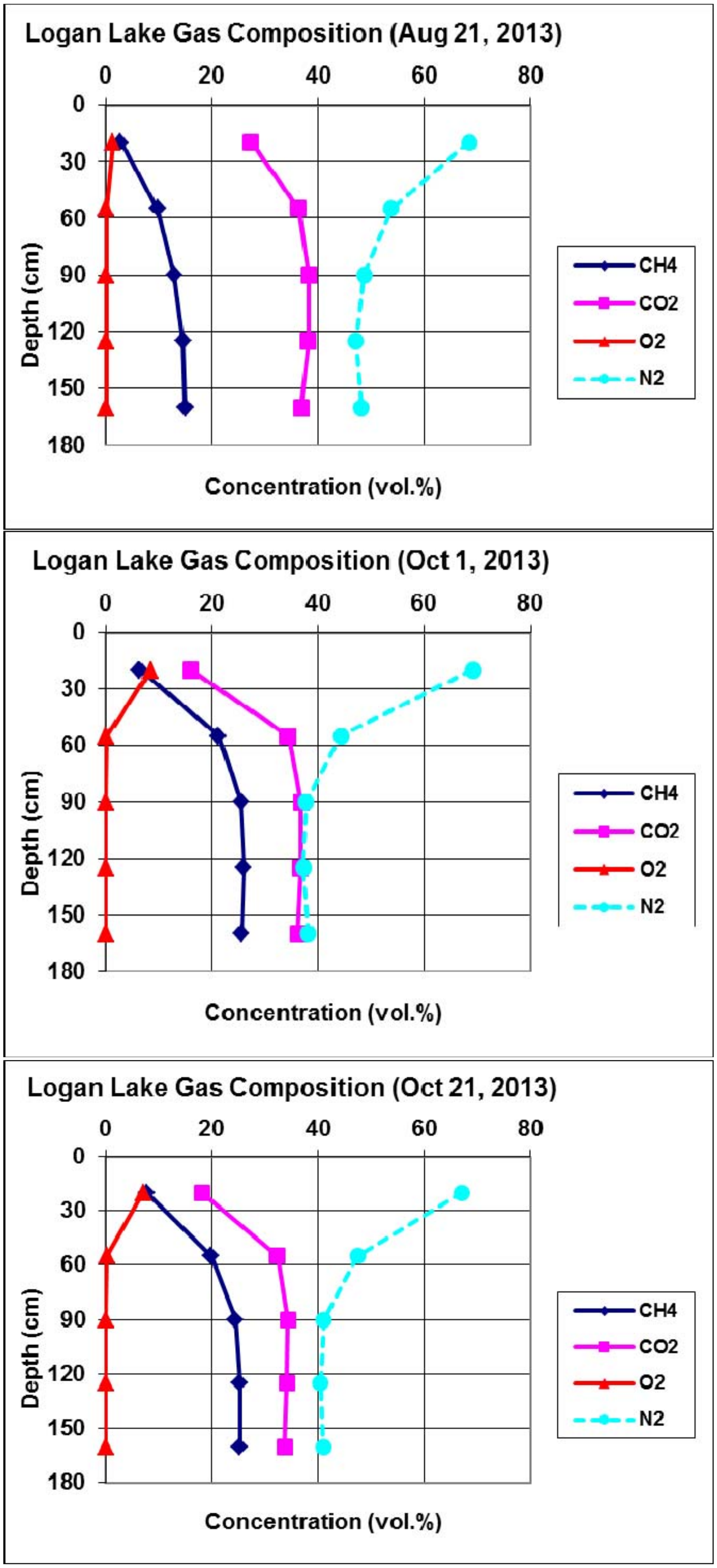

Figure 20. Logan Lake gas composition at several depths and sampling dates.

3.4 Flux Measurements

Gas flux measurements are considered as one of the more definitive methods for ascertaining the true gas emissions from landfill and other surfaces. We used our CH_4 and CO_2 surface flux measurements to locate “hot spots” on the landfill surface and thus potential biofilter sites, as discussed previously.

Another use of the CH_4 flux measurements is to assess the efficiency of biofiltration technology by calculating the amount of CH_4 removed from the landfill gas stream as it travels through the biofilter and into the atmosphere. These measurements can also be used to calculate the amounts of CH_4 oxidized to CO_2 and biomass and thus prevented from entering the atmosphere. This quantity can be used as GHG credit as it is representative of the CH_4 diverted from emission to the atmosphere.

3.4.1 Barriere

The amounts of methane removed by the biofilter from the Barriere landfill are shown in Figures 21, 22 and 23 and Table 3 and 4. The data shows highest values in the summer and lowest values in the early spring and late fall, confirming the same trend observed with the temperature data. The values ranged from a low of 5.36 g $CH_4/d/m^2$ in early May for the 2nd Barriere MOB to a high of 108 g $CH_4/d/m^2$ in the middle of July. The CH_4 removal rates (%) show high efficiencies (100%) for the sampling period (May to October 2013), thus indicating that the biofilter was still active during the cold times of the year.

The mean and maximum methane removal rates correspond to reductions in greenhouse gas emissions of 228 and 662 t CO_2 eq./yr respectively; equivalent to 505,047 to 1,465,575 L of gasoline, 593,469 to 1,722,165 L of diesel, 531 to 1,540 barrels of oil or 48 to 138 passenger cars.

3.4.2 Clearwater

The amounts of methane removed by the biofilter from the Clearwater landfill are shown in Figures 24, 25 and 26 and Table 3 and 4. The data shows highest values in the summer and lowest values in the early spring and late fall, confirming the same trend observed with the temperature data. The values ranged from a low of 0 g CH_4/d/m^2 to a high of 214 g CH_4/d/m^2. Methane Oxidation bed number 1 experienced problems in the north corner as the methane oxidation was reduced to near 0 in that region for early and middle summer. The problem was traced to low water contents (dry) inhibiting the microbial action. Low moisture was traced to the particle size distribution that was dominated with fine materials rather than a mixture of fine and coarse materials as found in the rest of the bed. In the fall, the moisture contents of the bed increased due to rain and the activity of the microbial community and the methane oxidation returned to previous values. The CH_4 removal rates (%) show high efficiencies (88-100%) for the sampling period.

The mean and maximum methane removal rates correspond to reductions in greenhouse gas emissions of 516 and 2,622 t CO_2 eq./yr respectively; equivalent to 1,141,024 to 5,802,221 L of gasoline, 1,340,792 to 6,818,061 L of diesel, 1,199 to 6,097 barrels of oil or 107 to 546 passenger cars.

3.4.3 Chase

The amounts of methane removed by the biofilter from the Chase landfill are shown in Figures 27, 28 and 29 and Table 3 and 4. The data shows highest values in the fall months and lowest values in the spring and summer, this is likely due to the fact that this biofilter was started in late spring and early summer and the microbial community needed time to acclimatize to degrading methane efficiently. The values ranged from a low of 0 g CH_4/d/m^2 to a high of 168 g CH_4/d/m^2 at the end of October, 2013. The low methane oxidation values reported for June and July are likely due to the initial establishment of the beds (started in middle of May to June). The CH_4 removal rates (%) show high efficiencies (87-100%) for the sampling period.

The mean and maximum methane removal rates correspond to reductions in greenhouse gas emissions of 240 and 1,542 t CO_2 eq./yr respectively; equivalent to 531,602 to 3,412,720 L of gasoline, 624,674 to 4,010,212 L of diesel, 559 to 3,586 barrels of oil or 50 to 321 passenger cars.

3.4.4 Logan Lake

The amounts of methane removed by the biofilter from the Logan Lake landfill are shown in Figures 30, 31 and 32 and Table 3 and 4. The data shows highest values in the fall months and lowest values in the summer, this is likely due to the fact that this biofilter was started in late summer and the microbial community needed time to acclimatize to degrading methane efficiently. The values ranged from a low of 0 g $CH_4/d/m^2$ to a high of 117 g $CH_4/d/m^2$ at the end of October, 2013. The low methane oxidation value reported for August is likely due to the initial establishment of the beds (started in August to September). The CH_4 removal rates (%) show high efficiencies (80-90%) for the sampling period.

The mean and maximum methane removal rates correspond to reductions in greenhouse gas emissions of 560 and 1,433 t CO_2 eq./yr respectively; equivalent to 1,238,605 to 3,170,596 L of gasoline, 1,455,458 to 3,725,697 L of diesel, 1,301 to 3,331 barrels of oil or 117 to 298 passenger cars.

The methane oxidation calculated for all 4 landfill sites (Barriere, Clearwater, Chase and Logan Lake) corresponds to the following mean and maximum reductions in greenhouse gas emissions of 1,544 and 6,258 t CO_2 eq./yr respectively; equivalent to 3,416,276 to 13,851,111 L of gasoline, 4,014,393 to 16,276,135 L of diesel, 3,590 to 14,554 barrels of oil or 322 to 1,304 passenger cars.

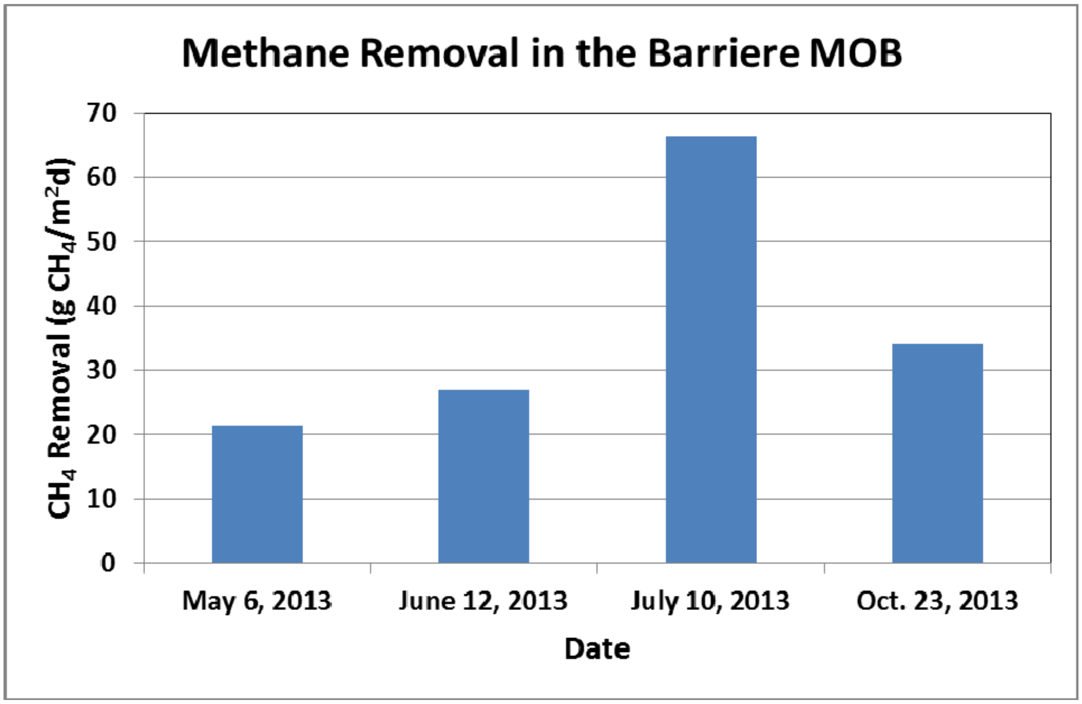

Figure 21. Methane removal rates (g/m^{2}d) by the Barriere biofilter.

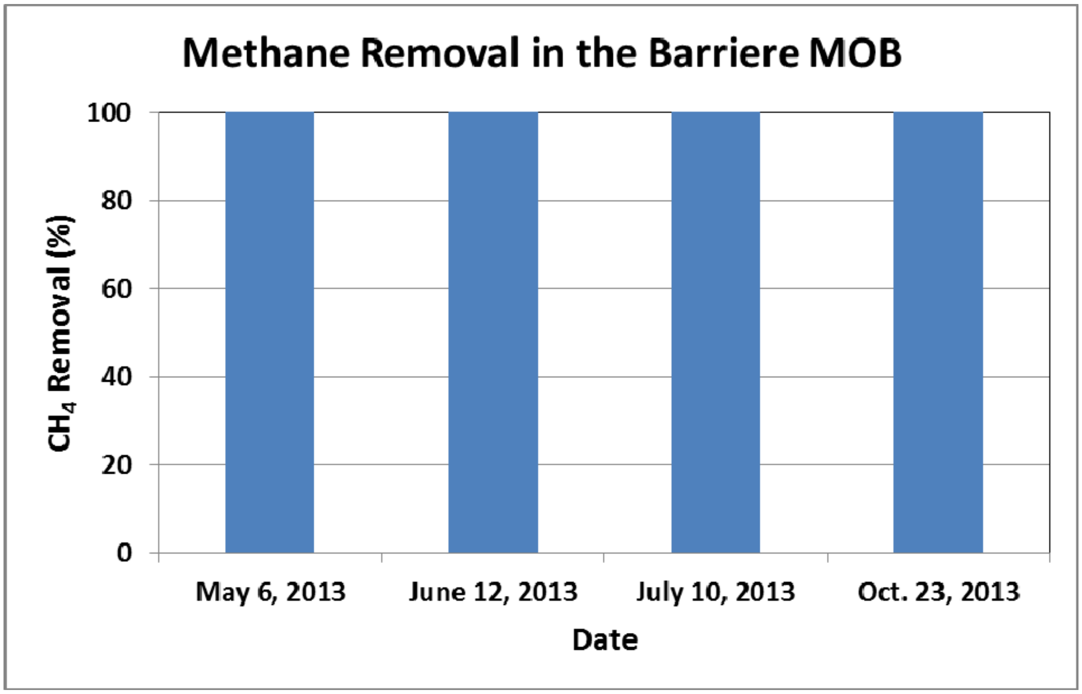

Figure 22. Methane removal rates (%) by the Barriere biofilter.

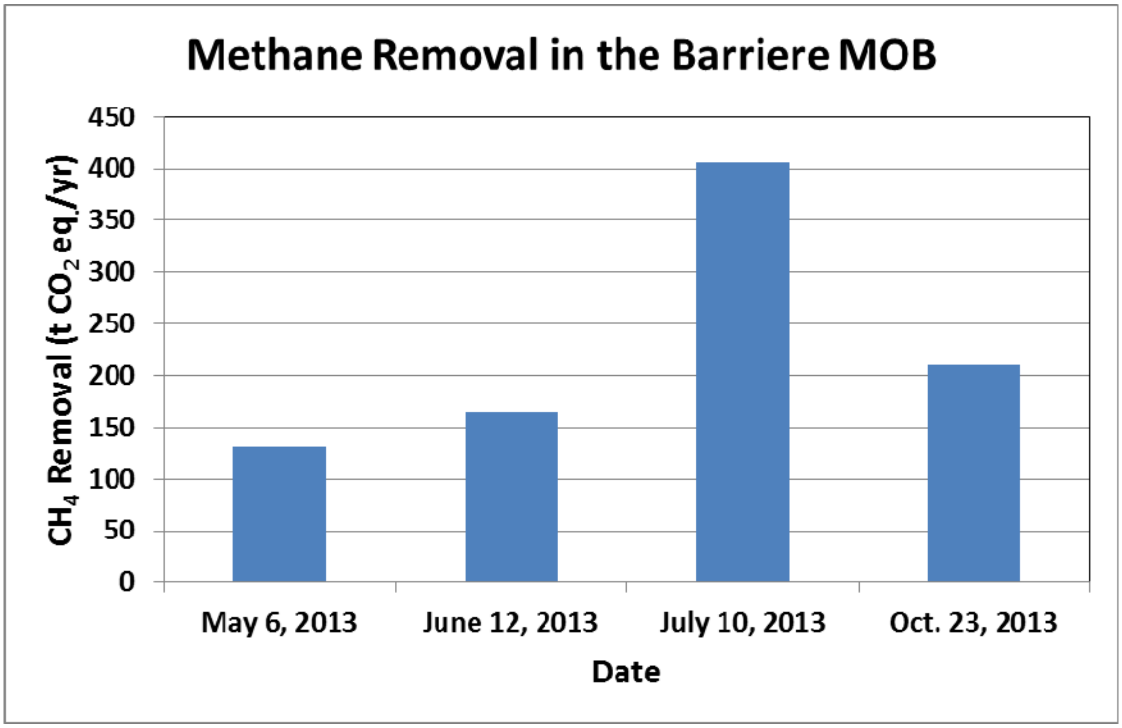

Figure 23. Methane removal rates (t CO_2 eq./yr) by the Barriere biofilter.

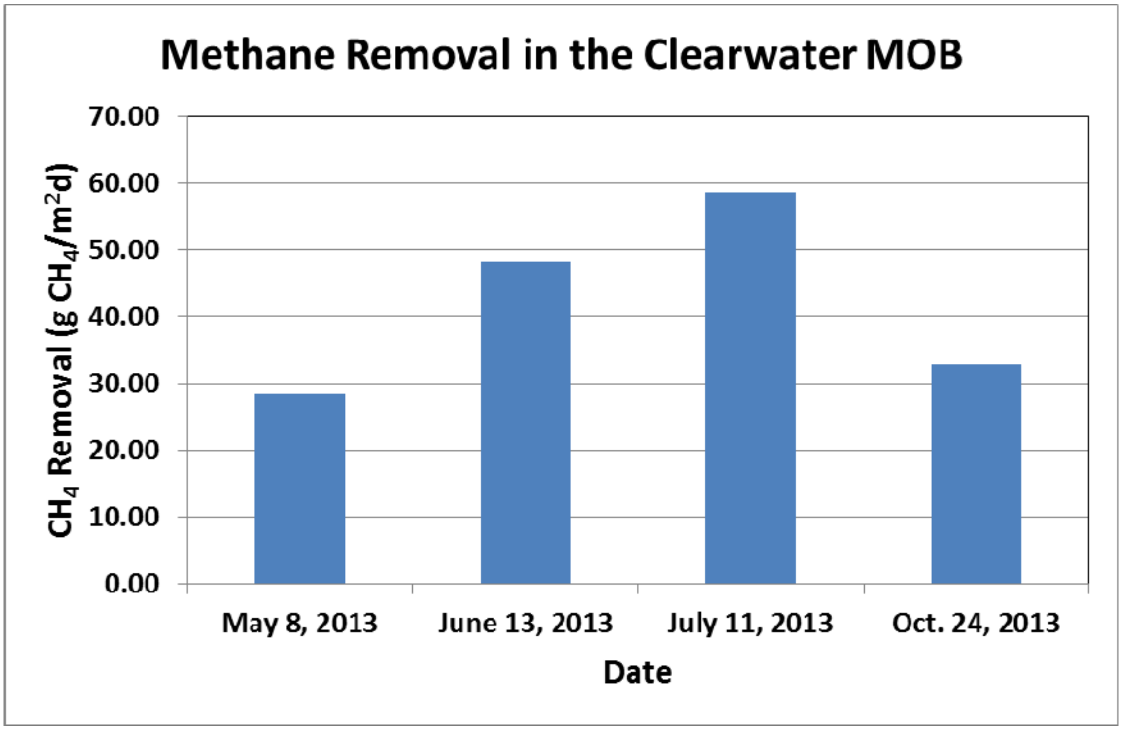

Figure 24. Methane removal rates (g/m^2d) by the Clearwater biofilter.

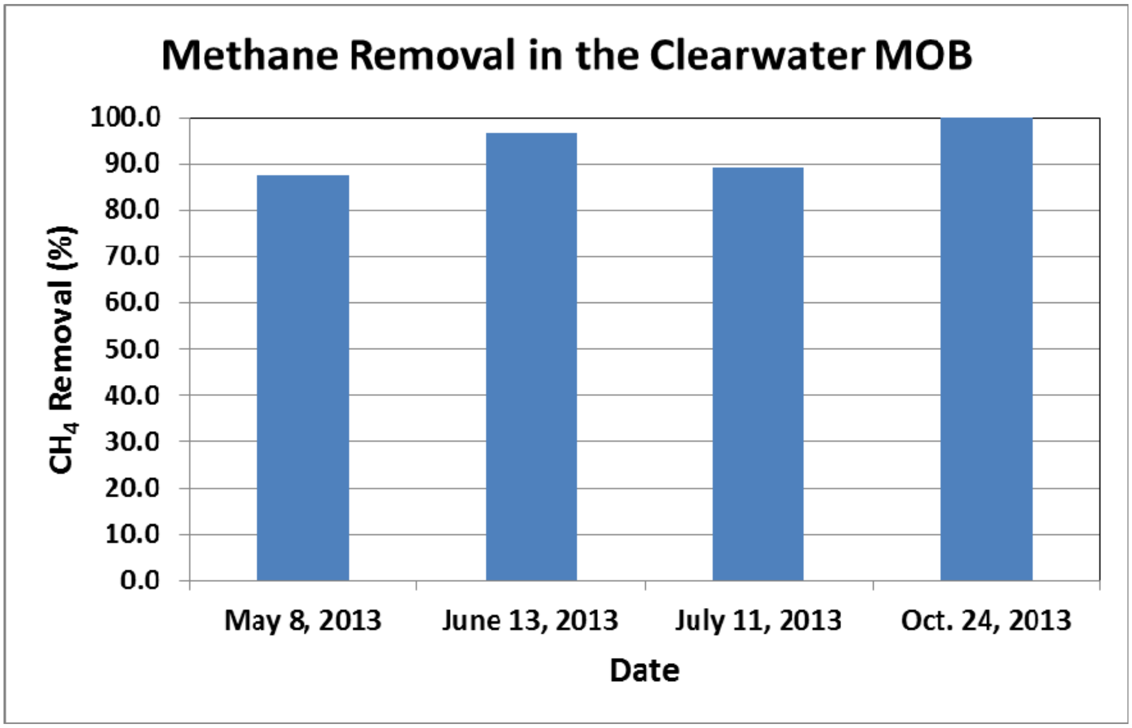

Figure 25. Methane removal rates (%) by the Clearwater biofilter.

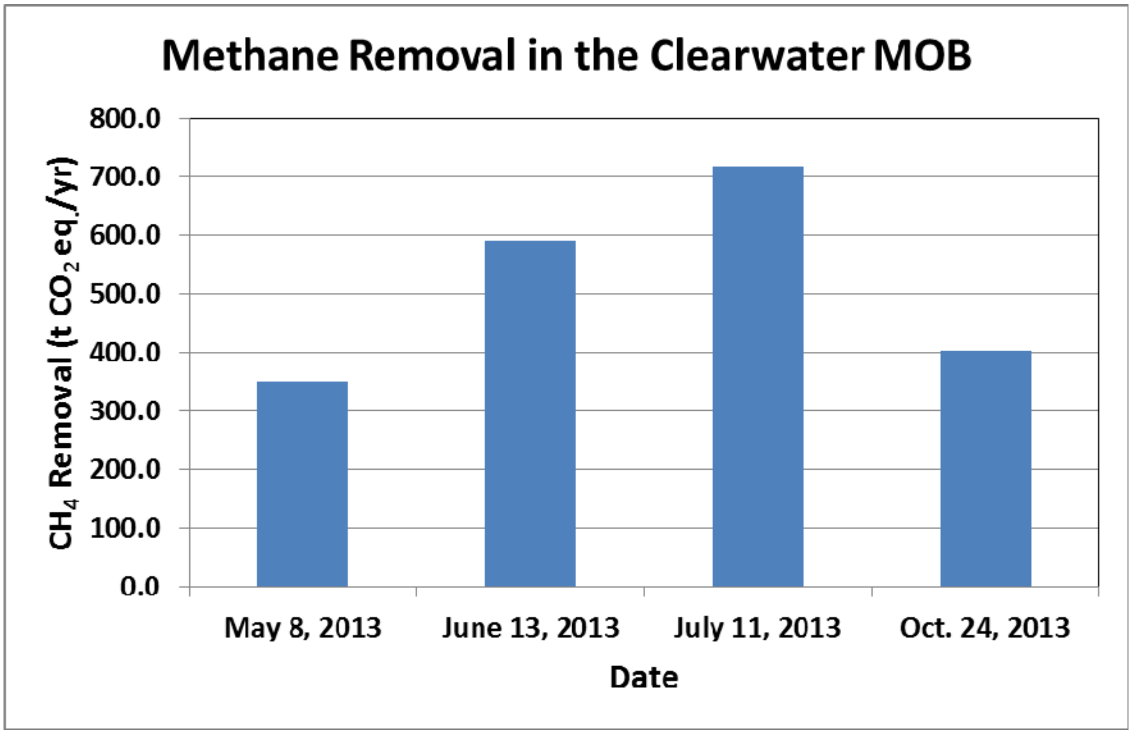

Figure 26. Methane removal rates (t CO_2 eq./yr) by the Clearwater biofilter.

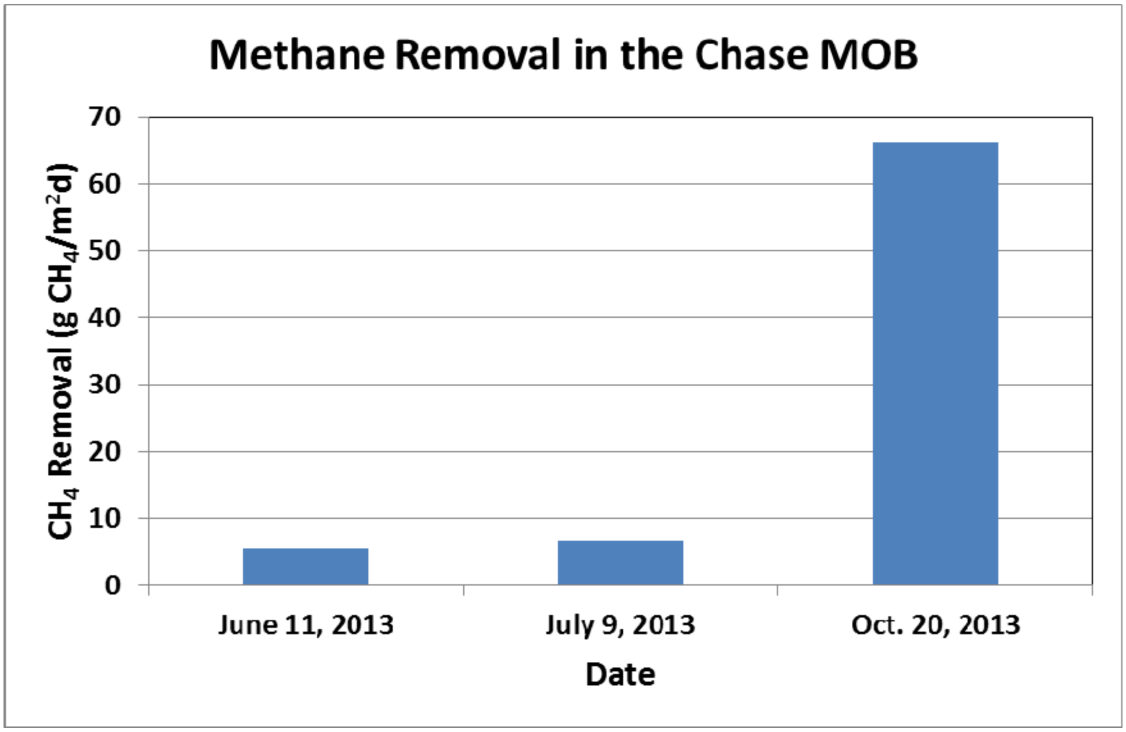

Figure 27. Methane removal rates (g/m^{2}d) by the Chase biofilter.

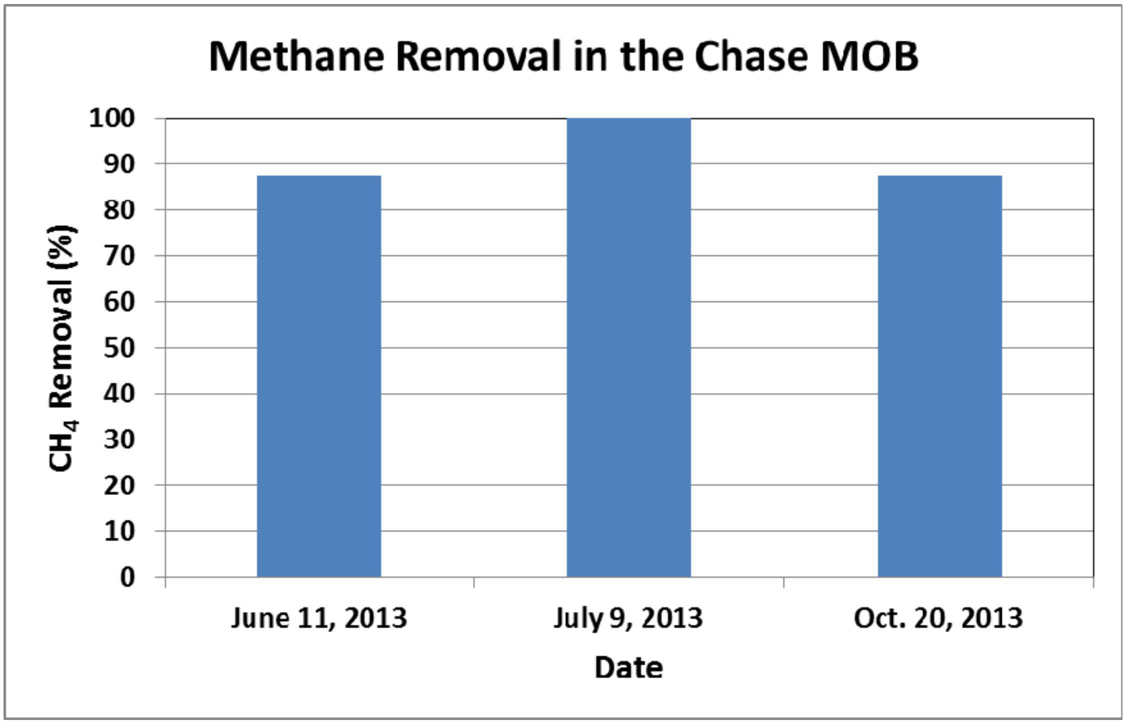

Figure 28. Methane removal rates (%) by the Chase biofilter.

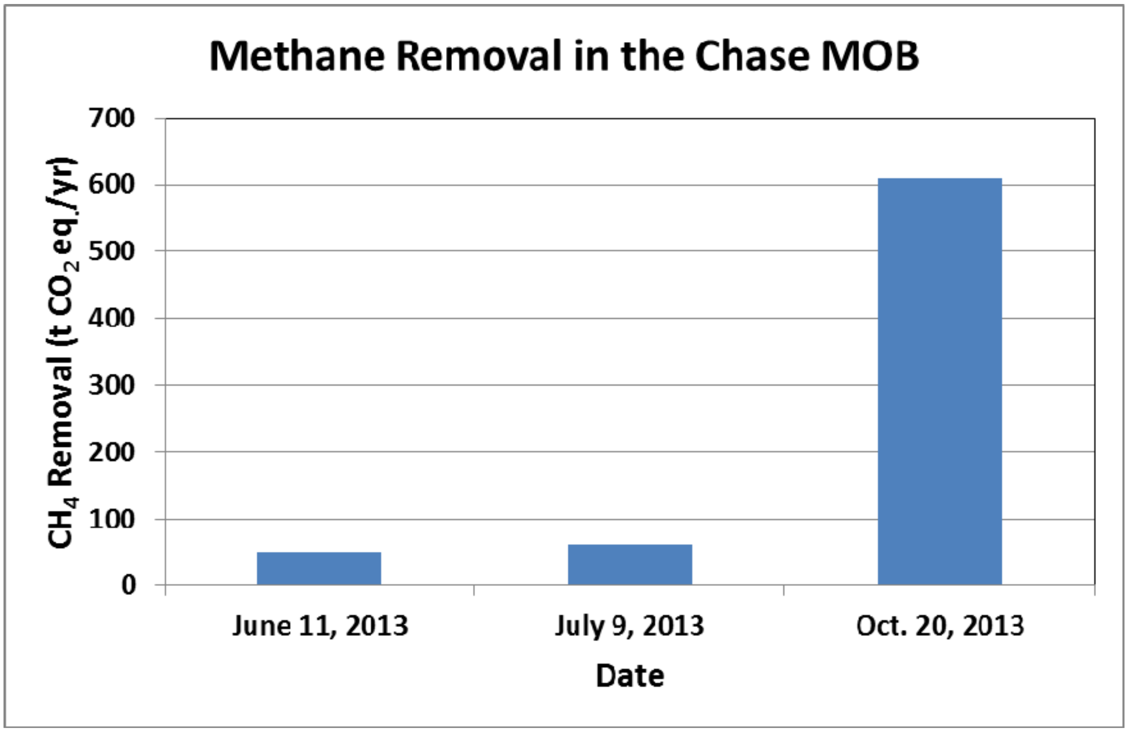

Figure 29. Methane removal rates (t CO_2 eq./yr) by the Chase biofilter.

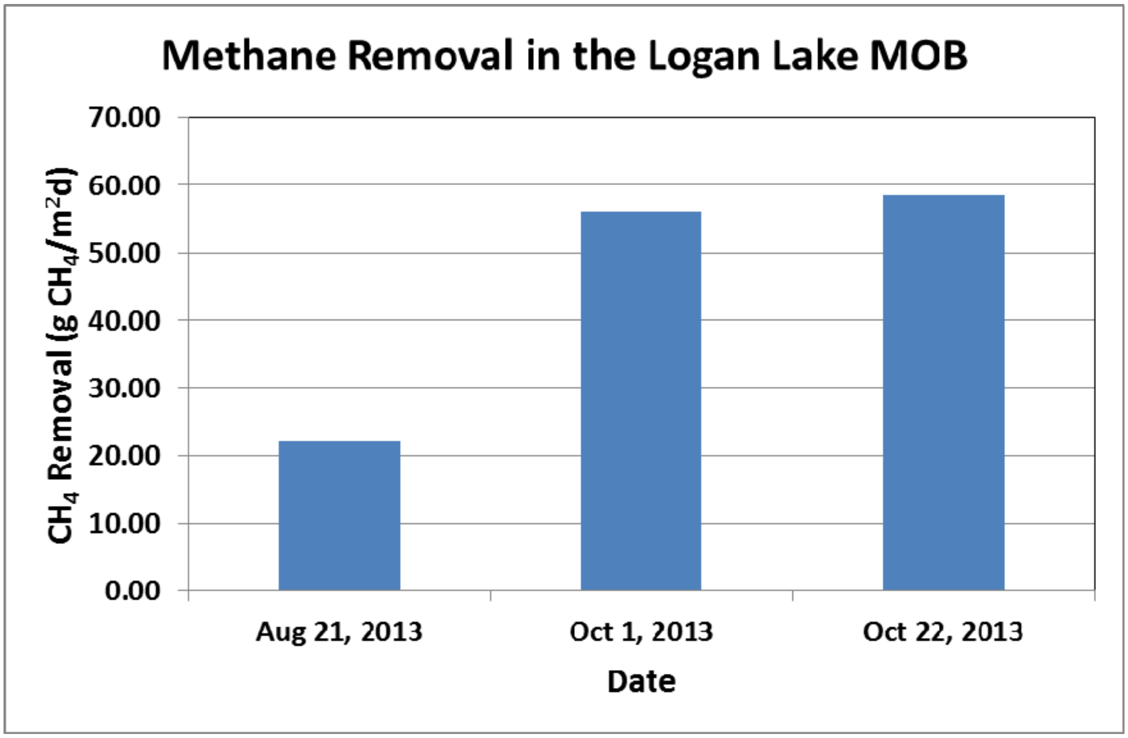

Figure 30. Methane removal rates (g/m^2d) by the Logan Lake biofilter.

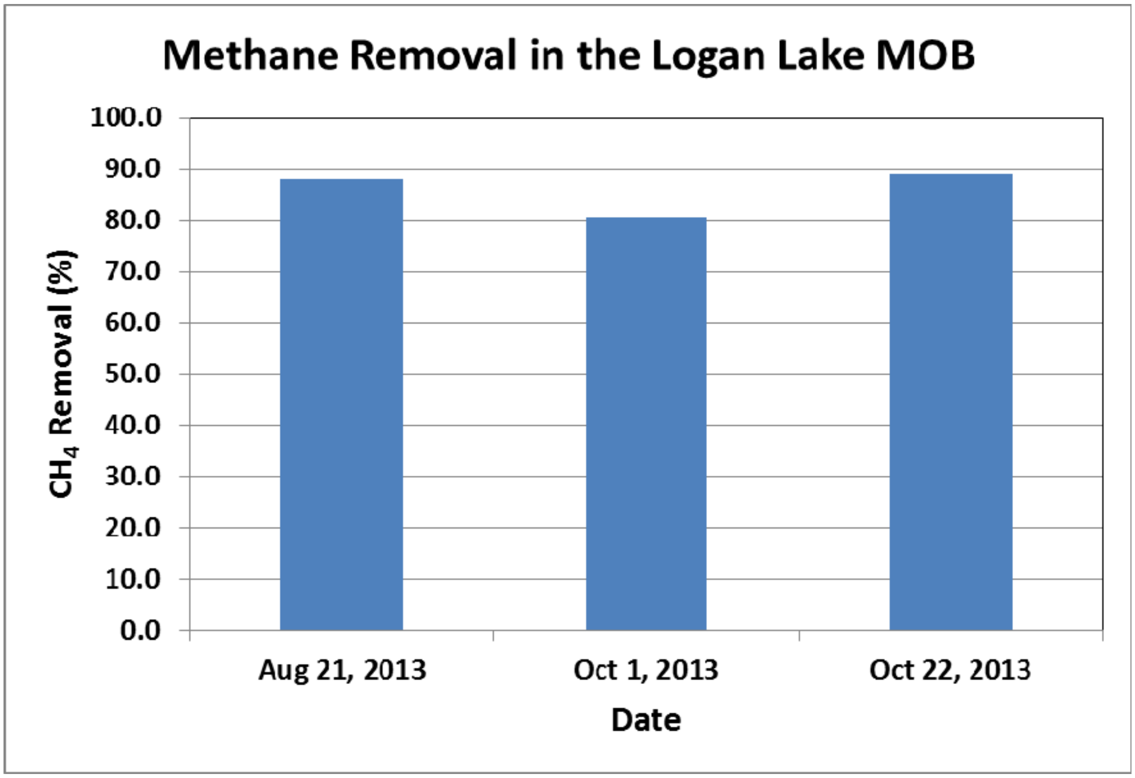

Figure 31. Methane removal rates (%) by the Logan Lake biofilter.

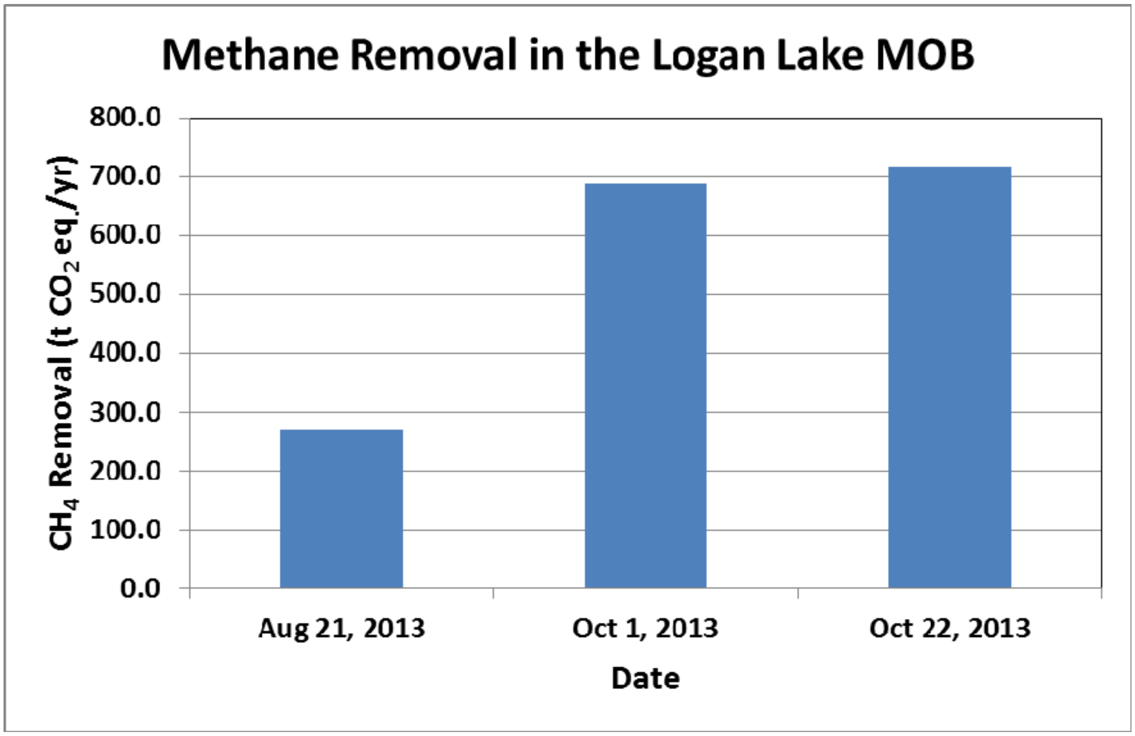

Figure 32. Methane removal rates (t CO_2 eq./yr) by the Logan Lake biofilter.

Table 3. Annual GHG Equivalents of Mean Methane Reduced by Oxidation at the TNRD Landfills

Landfill	Mean CH_4 Removal			Gasoline[a]	Diesel[b]	Oil[c]	Pasenger
	(%)	(g CH_4/m2d)	(t CO_2 eq./yr)	(L)		(Barrels)	Cars[d]
Barriere	100	37.2	228	505,047	593,469	531	48
Clearwater	89.0	42.0	516	1,141,024	1,340,792	1,199	107
Chase	91.6	26.1	240	531,602	624,674	559	50
Logan Lake	85.7	45.6	560	1,238,605	1,455,458	1,301	117
Total			**1,544**	**3,416,278**	**4,014,393**	**3,590**	**322**

a. 2.2144 kg CO_2 eq./L gasoline (Carbon Trust (2013))

b. 2.6008 kg CO_2 eq./L diesel (Carbon Trust (2013))

c. 0.43 t CO_2 eq./barrel of oil (USEPA (2013))

d. 4.8 t CO_2 eq./vehicle/yr (USEPA (2013))

Table 4. Annual GHG Equivalents of Max. Methane Reduced by Oxidation at the TNRD Landfills

Landfill	Maximum CH_4 Removal			Gasoline[a]	Diesel[b]	Oil[c]	Pasenger
	(%)	(g CH_4/m2d)	(t CO_2 eq./yr)	(L)		(Barrels)	Cars[d]
Barriere	100	108	662	1,465,575	1,722,165	1,540	138
Clearwater	100	214	2,622	5,802,221	6,818,061	6,097	546
Chase	100	168	1,542	3,412,720	4,010,212	3,586	321
Logan Lake	100	117	1,433	3,170,596	3,725,697	3,331	298
Total			**6,258**	**13,851,111**	**16,276,135**	**14,554**	**1,304**

a. 2.2144 kg CO_2 eq./L gasoline (Carbon Trust (2013))

b. 2.6008 kg CO_2 eq./L diesel (Carbon Trust (2013))

c. 0.43 t CO_2 eq./barrel of oil (USEPA (2013))

d. 4.8 t CO_2 eq./vehicle/yr (USEPA (2013))

4 CONCLUSIONS

The results of this study allow us to make the following conclusions:

- Methane scanning proved a useful technique for locating ‘hot spots’ methane emissions. This indicates possible locations for methane oxidation biofilter beds, but only if confirmed by flux measurements.
- Monitoring the biofilter temperature proved to be an excellent tool to assess biological activity and thus potential methane oxidation. Temperature also exposed heterogeneity in the biofilter material and pronounced slope effects.
- Temperatures inside the biofilter were always higher than air temperatures indicating the presence of biological activity generating heat from the oxidation of methane.
- Methane levels decreased from the bottom of the biofilter to the top layers showing methane oxidation activity corroborating the temperature data.
- Oxygen levels were close to zero in most of the biofilter layers except at 20 cm depths (and only occasionally where they were above zero but still very low). The absence of oxygen limits methane oxidation and thus the ability of the biofilter to treat methane emissions.
- Carbon dioxide levels decreased from the bottom of the biofilter to the top layers showing the likely effect of gas dilution with atmospheric air.
- Nitrogen levels increased from the bottom of the biofilter to the top layers showing the likely effect of nitrogen enhancement due to gas dilution with atmospheric air (large nitrogen concentration).
- Flux measurements and calculations showed significant methane oxidation at all biofilters.
- Methane oxidation can lead to significant removal of landfill methane, and thus has the potential to earn GHG credits.

5 RECOMMENDATIONS

The results of this study and our experience in conducting it lead us to the following recommendations:

- Add methane surface scanning and flux measurements at the methane “hot spots” as the first step in any methane oxidation project.
- Maintain a clean biofilter surface by regular clearing of the surface vegetation.
- Regular maintenance (e.g. tilling) of the top biofilter layer in order to maximize oxygen levels entering the biofilter.
- Continue monitoring of the beds to explore the long term viability and robustness of the technology and to collect a historic body of data that is beneficial in making the case for carbon credits.
- TNRD should consider extending the implementation of this technology to other landfills (existing or closed).

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