Quantification of the methane emission from Masons landfill - Part II

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The relative atmospheric concentration of methane and tracer gas approximate 1700 metres downwind from Masons landfill on August 12th 2014. Triangles mark the tracer gas release points on the landfill. The atmospheric background methane and tracer concentration is subtracted.

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1. Introduction and purpose

Methane is a greenhouse gas and the anthropogenic emission of methane to the atmosphere contributes to global warming. Worldwide emissions from the waste sector have been estimated to account for 18% of the global anthropogenic methane emitted in 2004 (Bogner et al., 2008), with landfills accounting for a large proportion of this (IPCC, 2007). Several initiatives have been taken to minimize the methane emission from landfills, e.g. by methane recovery followed by flaring or utilization, or by constructing mitigation installations such as a cover material with enhanced methane oxidizing capability. Due to a series of factors, methane emissions from landfills are very heterogeneous in both time and space. These temporal and spatial emission variations, combined with the large size and an often difficult working environment on a landfill, make methane emission quantification a challenging task. Several methods have been developed to quantify methane emissions from landfills, but none of these have been accepted internationally as the best way to perform emission measurements.

The Technical University of Denmark (DTU) has implemented a novel analytical setup enabling the mobile measurement of small changes (ppb level) in atmospheric methane concentrations. This enables detection and quantification of methane sources by performing measurements downwind from the source in combination with release and measurement of a tracer gas. The mobile analytical setup and the dynamic tracer dispersion method have been tested at approximately 20 Danish landfills since November 2011 (Mønster et al., 2014a; Mønster et al., 2014b), building up a sound knowledge on quantification of the total fugitive methane emission from landfills. However, Danish landfills are, on an average, relatively small compared to UK landfills, and the possibility for testing the methodology on larger emission areas with potentially higher emissions, led to a collaboration between the DTU and University of Southampton (UoS) performing a two day trial measurement campaign in June 2014 at the Masons landfill near Ipswich, UK (Mønster et al., 2014c). This trial campaign was successful, and it was therefore agreed that DTU & UoS would join in a larger methane quantification and method comparison study at Masons landfill in August 2014 as part of research co-ordinated by the Natural Environment Research Council (NERC) funded GAUGE consortia[1]. Defra partially funded the involvement of DTU and UoS under contract WR1914, "Validation of Alternative Methods for Monitoring of Landfill Methane Emissions". The comparison study included various methane quantification methods, the results of which will be presented separately. This report focuses on the results from the methane emissions located and quantified by using a mobile analytical platform and the dynamic tracer dispersion method.

The main objective of this study was to quantify the total methane emission from the Masons landfill site and to investigate temporal variations over the course of the monitoring. A secondary objective was to test the influence of tracer gas configurations and measurement distance from the landfill. Finally, an attempt to identify emissions arising specifically from non-combusted methane emitted from on-site gas engines was conducted. The measurement campaign was carried out between August 5th and 12th 2014, and included more than 130 methane plume transects.

[1] http://www.greenhouse-gases.org.uk/

2. Dynamic plume measurement using mobile analytical platform

Total landfill methane emissions were quantified using a mobile tracer dispersion method that combines a controlled release of tracer gas from the landfill with methane and tracer concentration measurements downwind of the landfill, using a mobile high-resolution analytical instrument (Börjesson et al., 2009; 2007; Galle et al., 2001; Scheutz et al., 2011). The method has been used successfully since about the late 1990s, and with new developments in analytical technology it has become a powerful tool for quantifying methane emissions from landfills (Mønster et al., 2014a; 2014b). The tracer dispersion method in general is based on the assumption that a tracer gas released at an emission source, in this case a landfill, will disperse in the atmosphere in the same way as methane emitted from the landfill will disperse. Assuming a defined wind direction, well mixed air above the landfill (causing the emitted methane and released tracer gas to be fully mixed), and a constant tracer gas release, the methane emission rate can be calculated as a function of the ratio of the integrated cross-plume concentration of the emitted methane and the integrated cross-plume concentration of the released tracer gas, as follows:

$$E_{gas} = Q_{tracer} \cdot \frac{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{gas}\, dx}{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{tracer}\, dx} \cdot \frac{MW_{gas}}{MW_{tracer}} \qquad \text{(Eq. 1)}$$

Where E_{gas} is the methane emission rate (kg h^{-1}), Q_{tracer} is the release rate of the tracer gas (kg h^{-1}), C_{gas} and C_{tracer} denote cross-plume concentrations (ppb) above the background concentration, MW denotes molecular weights and *x* corresponds to distance across the plume. The principle is shown in Figure 1, and an example on emission calculation provided in section 5.

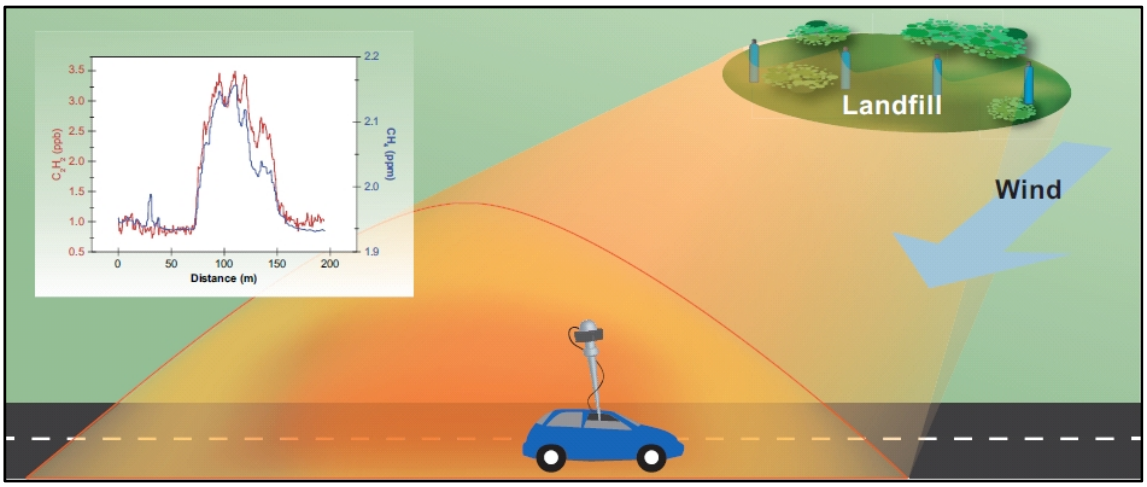

Figure 1. The principle of the dynamic tracer dispersion method for quantifying greenhouse gas emissions from fugitive sources.

The downwind measurements were carried out along public highways around Masons landfill, with distances and location varying depending on the wind direction, the degree of dispersion, the accessibility of roads and possible interference with other methane sources in the area.

The optimal distance for measuring a site's total emissions depends on the size of the emission area, the topography of the site and weather conditions such as wind speed and solar radiation (Mønster et al., 2014). The plume measurements made at Masons were at a distance of 1600 to 6700 m from the landfill. Quantifications were made by performing multiple transects across the plume and then calculating the methane/tracer ratio (Eq. 1) for each transect. In this way, a change in dilution due to a change in wind speed, or turbulence changing vertical mixing, would be the same for both gasses at each individual plume measurement. At each plume transect it was ensured that the whole plume was measured before turning the vehicle to measure the plume again. This enabled the establishment of a baseline of background concentrations to be subtracted from the measurements, in order to obtain the landfill's contribution to the plume. Each plume transect measurement took between 1 and 10 min to perform. The transect time depended on the width of the plume at the measurement distance (depending on dispersion and distance) and driving speed. The driving speed was typically 20-30 km h^{-1}, depending on road and traffic conditions.

Measurements were performed with a cavity ring-down spectroscopy (CRDS), methane/acetylene analyser (G2203, Picarro Inc., USA), with acetylene used as the tracer gas. Atmospheric air was sampled from the roof of a vehicle and brought to the analyser via an external pump, enabling a fast response time while driving. The atmospheric concentrations of methane, acetylene and water were measured with a frequency of 2 Hz and logged together with the atmospheric conditions and GPS position. The precision of methane and acetylene measurements was 0.48 ppb and 0.40 ppb respectively, making it possible to detect small changes in atmospheric concentrations whilst driving. Measured concentrations are shown in real time on a screen attached to the analyser. For more information on the CRDS, see Mønster et al., (2014a). An anemometer (All-In-One weather sensor, model 102780, Climatronics, USA.) was mounted on top of the vehicle, in order to log wind speed and direction, temperature and atmospheric pressure, and a GPS (model R330 GNSS Receiver and A101 Smart Antenna, Hemisphere, Canada) was attached to the front window, in order to log the position of the vehicle, measured within 0.20 m precision.

15.9 litre gas bottles (BOC Industrial Gases, bottle size J) filled with ~2.35 kg dissolved acetylene (98.5 % purity) were used to release the trace gas at the landfills. Flow was controlled manually with calibrated flow meters (Sho-rate, Brooks Instrument), and varied between tests. The accuracy of the flow meters was previously demonstrated in the laboratory to be better than 3%. The tracer bottles were placed in those areas with the highest methane emissions in order to simulate the emission in the best possible way. Quantification measurements were then taken downwind at an appropriate distance from the landfill, far enough to enable a mixing of the tracer gas and methane (i.e. a good correlation between tracer gas and methane) and close enough to get a good signal-to-noise ratio. More information on the instrumentation, method, influence of incorrect trace gas placement and the distance to the landfill can be found in Mønster et al. (2014a).

3. Description of Masons Landfill

Masons Landfill is located in Great Blakenham in the county of Suffolk, approximately 5 miles north of the town of Ipswich. The site has been in operation since 1992, and is licensed to receive a mixture of waste including domestic, commercial and industrial wastes, oil contaminated wastes, contaminated soils and asbestos. On average, the landfill has received between 200,000 to 500,000 t.p.a., mainly domestic, construction and industrial wastes, and soils. Since opening, the site has taken 6.3 Mt waste to the end of 2013.

The site is comprised of 11 cells, covering an area of approximately 330,000 m^2. The cells were constructed with an engineered base of 225 - 300 mm bentonite enriched soil and a 2 mm high-density polyethylene (HDPE) synthetic liner. The majority of the landfill is filled to final levels and has been restored, with just a small operational area remaining in the centre of the site. The northern parts of the site are capped and fully restored with a 1 mm LDPE liner overlain by restoration soils, and to the east, the waste has been capped with a 1 mm LDPE liner, but currently has no restoration material. Figure 2, shows an outline of the landfill, with the approximate areas of restoration, the operational area and the Gas Utilisation Plant (GUP).

An active gas management system is in operation at the landfill, comprising of a network of gas extraction wells, connected to a system of gas mains and spurs. The gas collection system directs collected gas to the Gas Utilisation Plant (GUP), which has four landfill gas engines and a flare. During the course of the tracer release experiments, either two or three of the four engines were in operation. When only two engines were operating, a flare was used to burn excess LFG. Flow through the plant during the trials, averaged 1900 m^3 h^{-1}, with an average mass of 660 kg methane h^{-1}. The GUP has a capacity of around 3 MW.

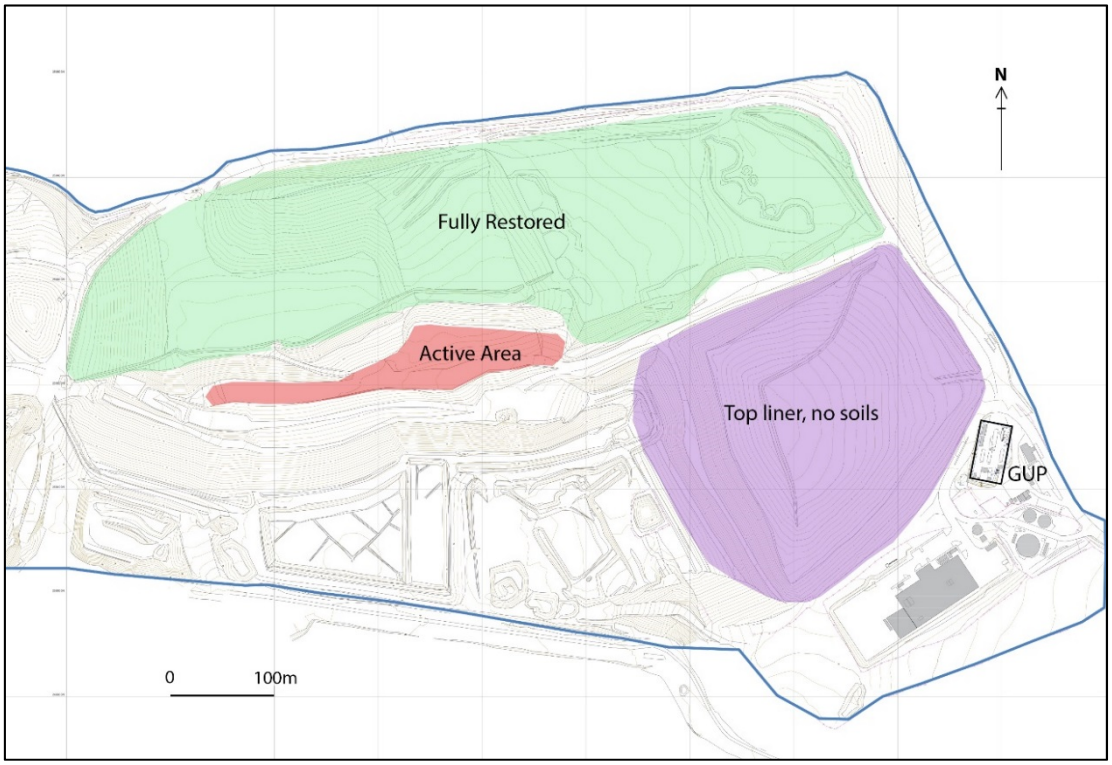

Figure 2. Plan of Masons Landfill showing fully and partly restored areas, and the active (operational) filling area. (adapted from drawing MAS4000, Viridor May 2014).

Figure 3. Photograph facing south east from the fully restored area of the landfill. The operational area where waste is being deposited can be seen to the right and foreground, and the area partially restored with a liner is shown in the centre.

4. Description of the measurement campaign.

Table 1 provides an overview of the measurements conducted during the campaign including information on measuring dates, weather conditions (average wind speed and direction and atmospheric pressure), tracer gas release (number of tracer gas release points and total release rates), and measurement transects (measuring distance and number of transects performed). On August 5th, a screening of the methane concentrations in the area surrounding the landfill was carried out, while tracer release and methane emission quantification were made on August 6th, 7th, 8th, 11th, 12th and 13th. The objective of the initial methane screening campaign was to establish background concentrations of methane and acetylene and to identify other methane sources in the area, which potentially could interfere with the quantification of the methane plume from the Masons landfill. In total, six tracer release experiments were performed, each consisting of 1 to 3 hours of measurements. On a given measurement day, measurements were performed at up to three different distances to the landfill and in different directions from the landfill, depending on the wind direction and intensity at the time of the measurement (Figure 4).

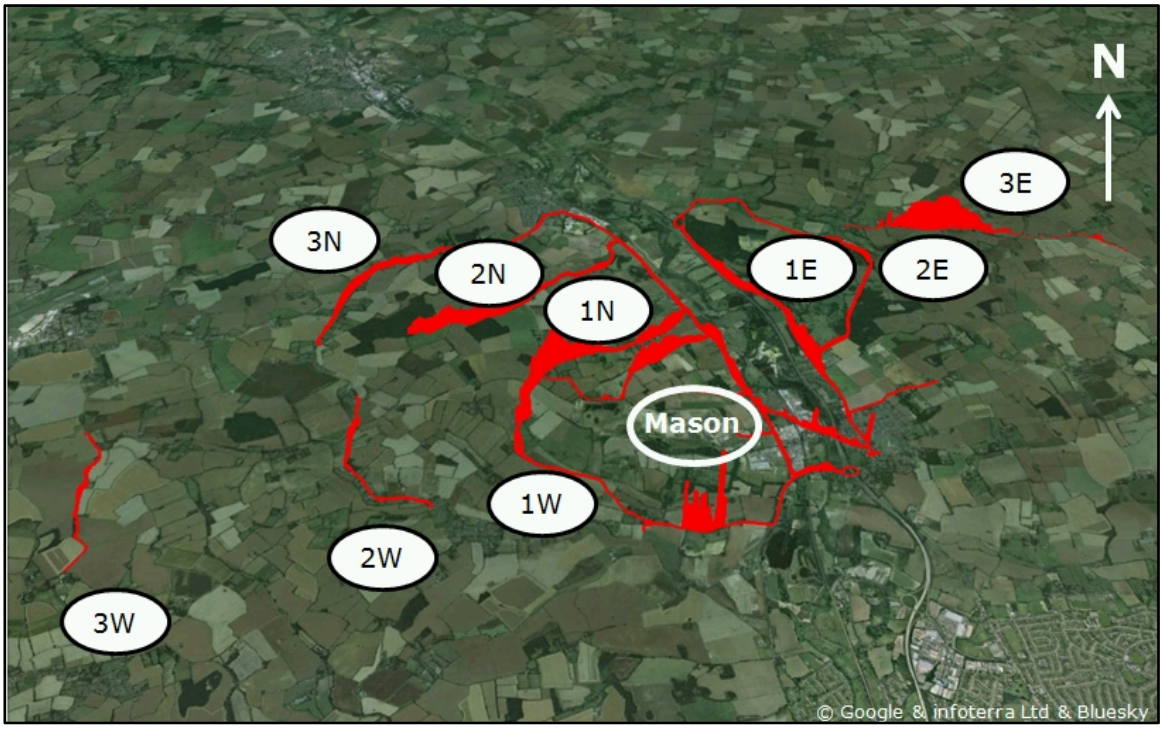

Figure 4. Geographical overview, showing the location of conducted plume transects undertaken over a period of ~ 1 week. The roads are labelled according to their relative distance and direction from Masons landfill. The methane plume heights are for illustrative purpose only and are not used for quantitative comparison.

Different tracer gas release rates and locations were trialled during the campaign in June 2014, which gave a good indication about where to place the tracer gas bottles and what the release rate should be to have sufficient tracer gas for quantification in the downwind plume. Successful quantifications were carried out on all five measuring days with a total tracer gas release

ranging from 2.6 to 3.5 kg h^{-1} from three to four tracer gas bottles. Figure 5 shows the location of the tracer gas bottles (measured with a handheld GPS), and Figure 6 shows the placement and securing of a tracer gas bottle on the ridge of the landfill between the restored and operational parts of the landfill.

The measurements were made during a period of relatively warm and sunny weather. These conditions can result in a faster plume rise, and make afternoon and evening measurements preferable for measuring methane and tracer gas at greater distances from the landfill. Figure 7 and 8 show the atmospheric pressure, local wind speed, incoming solar radiation and temperature in the period of August 3th to August 14th 2014, measured at the site's static weather station located at the weighbridge. The figures show data during the measurement period and either side of the campaign. The weather conditions (atmospheric pressure and wind speed) during the measurements are summarized and listed in Table 1. The weather data is the average measured at the landfill weather station during the actual measurement periods.

Table 1. Overview of the measurement campaign showing measuring dates, weather conditions, tracer release rates, measuring distances, and number of performed plume transects.

Date	Measuring time interval	Road*, measuring distance to the landfill (m) and total number of plume transects (*n*)	Weather conditions			Tracer gas release points (refer to Fig. 5)	Total tracer gas release rate (kg h^{-1})
			Avg. Temp. (°C)	Avg. wind speed (m s^{-1}) and dominant direction	Avg. Atmos. Pressure (mbar)		
06.08.2014	17:20-19:00	(1E) 1700-2000 (*18*)	25.0	8.0 W	1005.1	1,3,4,5	3.35
07.08.2014	18:00-22:20	(1W) 2000 (*9*) (2W) 3500-4000 (*12*) (3W) 6700 (*8*)	19.1	4.9 E	1010.5	1,2,3,5	3.48
08.08.2014	16:30-19:15	(1W/1N) 1600-2000 (9) (2N) 3000-3800 (2) (3N) 4500-5000 (6)	20.1	5.1 SE	999.2	1,3,5	2.55
11.08.2014	16:30-18:15	(1E) 1700-2000 (15)	17.6	9.3 SW	1001.8	1,3,4,5	2.6
12.08.2014	16:30-18:30	(1E) 1700-3000 (14) (2E) 2500-4200 (2) (3E) 4800-6000 (6)	18.5	9.7 WSW	1000.0	1,4,5,6	2.58
13.08.2014	08:15-09:15	(1E) 1700-2000 (13)	16.9	7.8 W	998.7	1,3,5,6	2.59

*Road name refers to Figure 4.

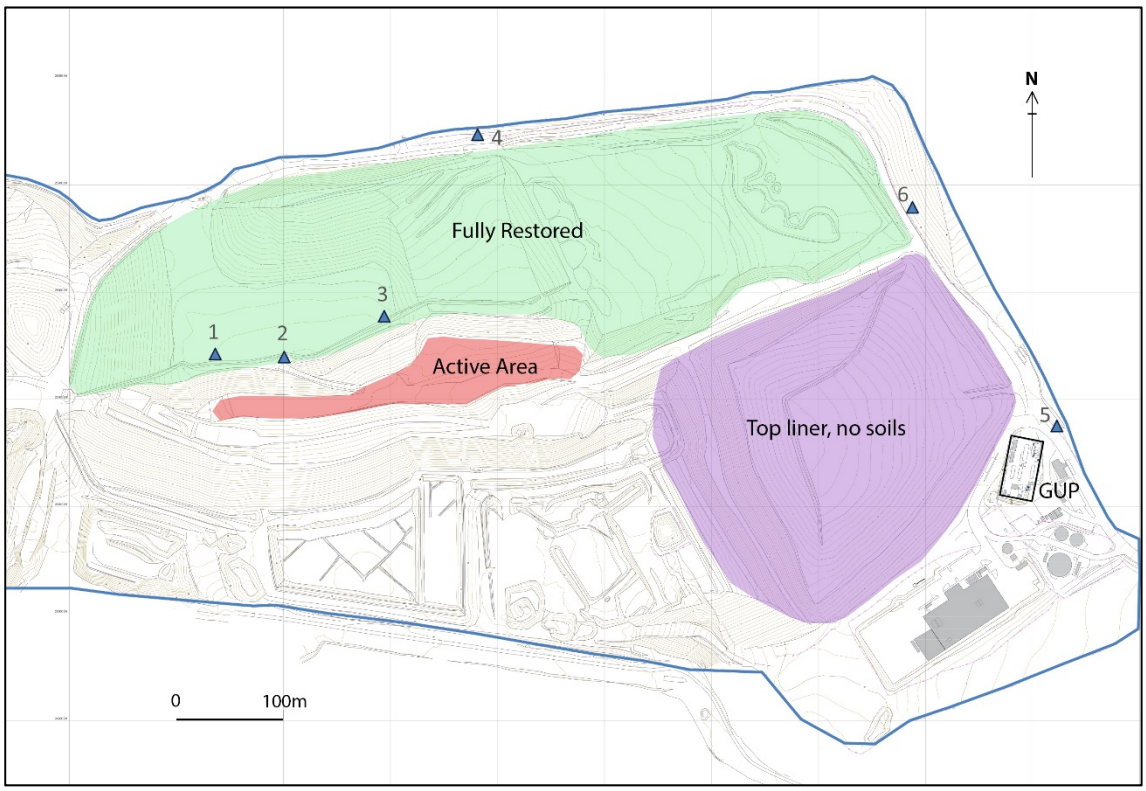

Figure 5. Plan of landfill showing location of the tracer gas bottles.

Figure 6. Tracer gas placement 3, on the ridge between the restored and the operational part of the landfill.

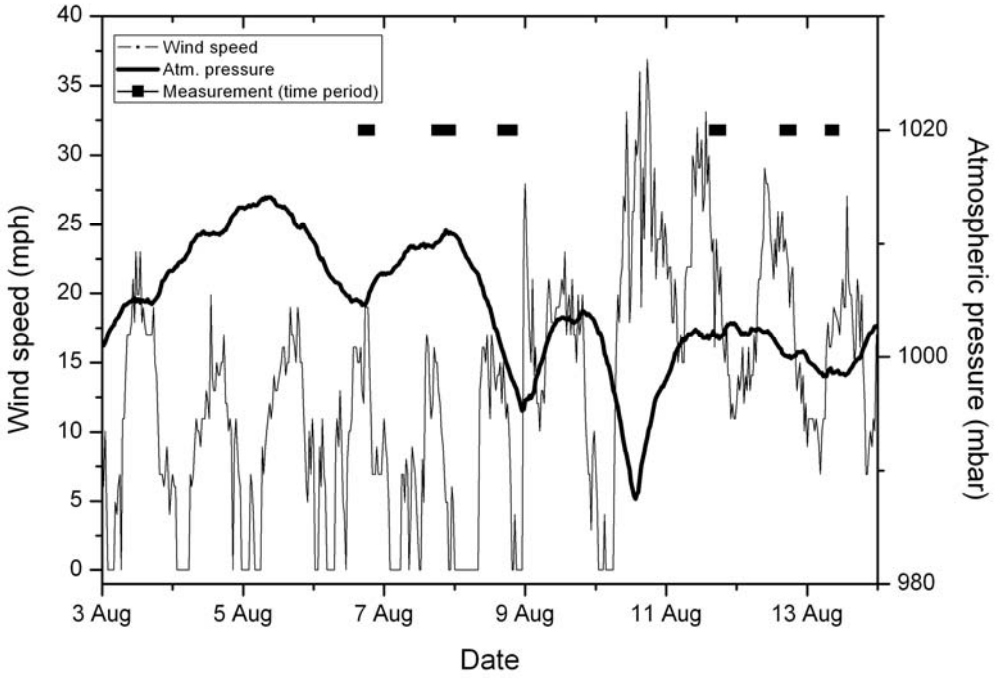

Figure 7. Atmospheric pressure and local wind speed during the period of August 3th to August 14th, 2014. Squares mark the time where emission measurements were performed.

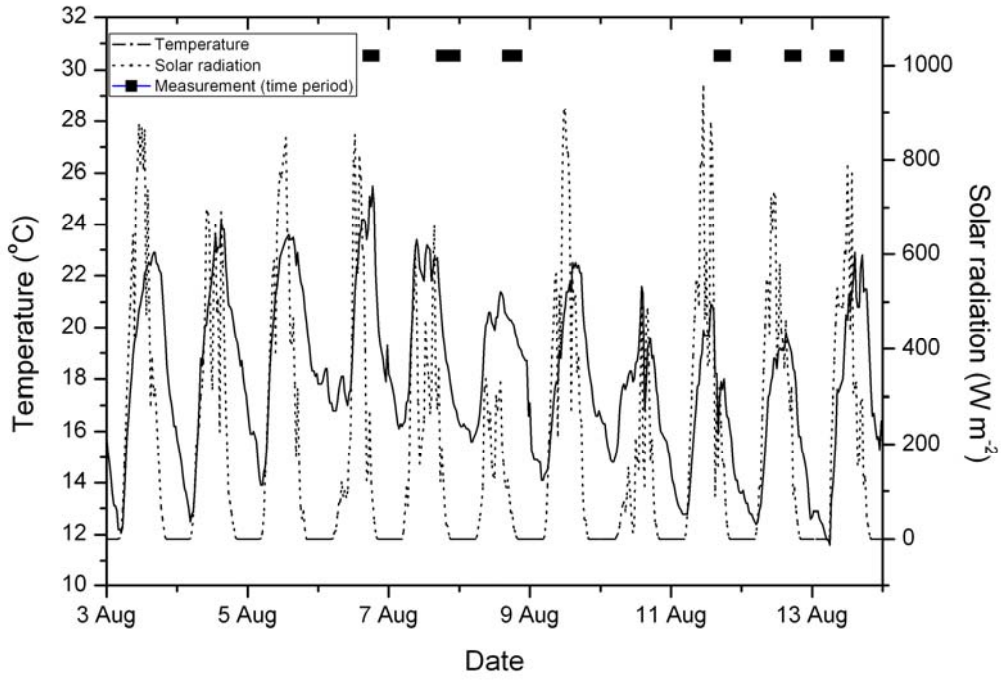

Figure 8. Incoming solar radiation and temperature during the period of August 3th to August 14th, 2014.

5. Description of the data processing.

A large number of plume transects (between 11 and 29) were performed for each tracer release (Table 1), though not all transects could be used in methane quantification. Initially, a visual screening was carried out on all measured plumes to check for interfering methane sources. In very few of the plume transects, an additional small methane source close to the measurement road resulted in a narrow, sharp additional spike in the methane concentration, which often could be removed in the data processing allowing the transect to be used (see example in Figure 9).

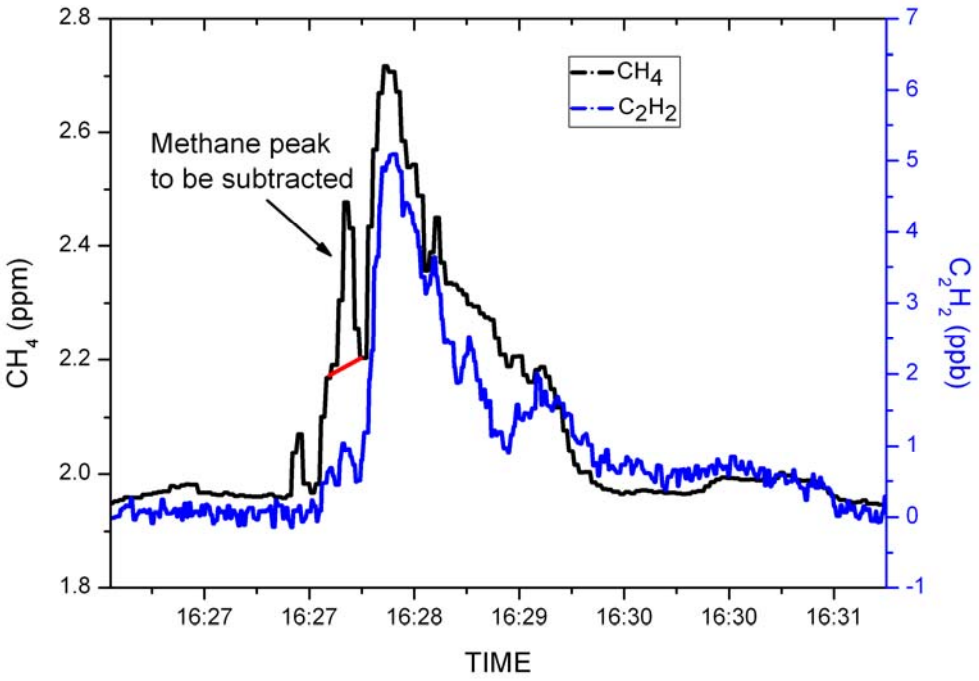

Figure 9. Methane and acetylene concentrations in the downwind plume on road 1W/1N on August 8th. The subtracted methane peak was previously identified in the background screening measuring campaign as a discrete methane source. In this case, the discrete methane source was a pile of manure, which clearly could be seen from the road as it was placed only about 50 m to the measuring road.

The release of tracer gas was controlled manually and checked periodically, demonstrating a stable release. The calculated mass of tracer release was corrected for the 98.5% purity of the acetylene in the gas cylinders. Where measurements were made late in the afternoon/evening after the landfill had closed, tracer release was left unattended on the landfill and the bottles were allowed to empty completely (except on the 7th, when the site remained open late to allow access to the acetylene bottles allowing flow rates to be monitored). To ensure measurements were made before the flow of tracer began to decrease (e.g. due to an almost empty bottle), conservative time windows for measurements were made. On two occasions, measurements were continued outside this time window, resulting in a significant decrease in measured tracer gas concentration, which again resulted in an unrealistically fast increase in the calculated emission. Such measurements were disregarded in the whole site emission rate.

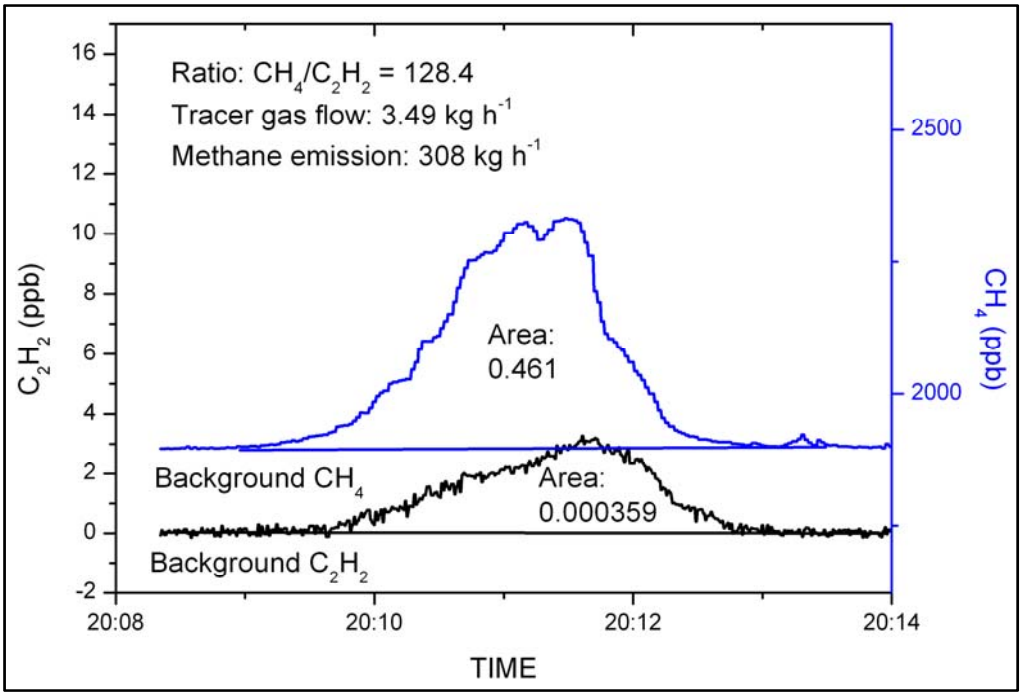

Figure 10. Example of integrated methane and tracer gas plumes and the corresponding emission calculation. Plumes were from August 7th, measured on road 3W, 6700 m from the landfill.

The plumes passing the visual screening were integrated individually to find the methane/tracer gas ratio for each plume transect, as this has been found to be the most accurate method to obtain the methane/tracer gas ratio (Mønster et al., 2014). Figure 10 shows a typical plume traverse and the corresponding emission calculation.

The integrated ratios were also calculated when the methane and tracer gas plumes were slightly off-set. The ratio of the areas can be used, as measurements were carried out far enough from the landfill for the gasses to both undergo the same atmospheric dilution.

Three examples where the tracer and methane plumes are not completely matching are shown in Figure 11. The fact that the methane and tracer gas plumes sometimes were not matching completely can be used to narrow in on the location of the main emission. By combining the information from the three plumes in Figure 11, it can be derived that the methane is mainly emitted south of the centre of the tracer gas location, which aligns with the operational area and the temporary covered part of the landfill. Ideally, the tracer gas bottles should be moved to obtain better matching of the plumes, however, for safety, tracer gas bottles were not permitted to be placed in the operational area of the landfill. For quantification of the total methane emission, the slightly shifted plumes have negligible influence on the calculated emission rate when several transects are performed and at a significant distance from the source, which was indeed the case in this study.

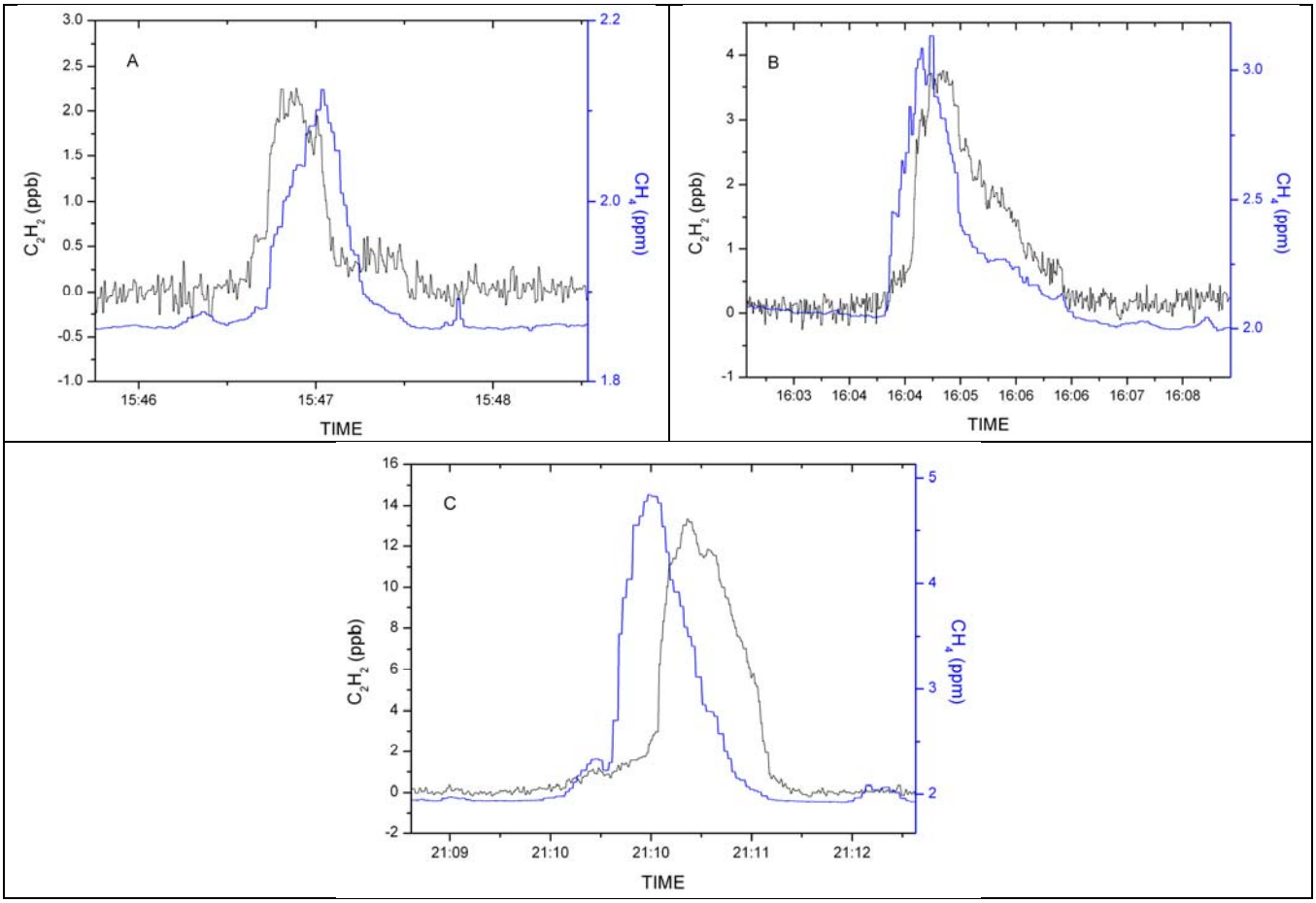

Figure 11. Plume transect data measured under three different wind directions; a) road 1E driving from north to south (Aug. 11th), b) road 1N driving from east to west (Aug. 8th), c) road 1W driving from south to north (Aug. 7th). The corresponding tracer release points and flow can be seen in Table 1.

The emission rate from the individual days was calculated by taking the average of all the emission rates calculated from the accepted plumes ratios. Where single measurements were taken, these were collated in with measurements taken in the same time of the day but at a different road. The uncertainty of the averaged emission rate was then calculated as the standard error of the mean value on a 95% confidence interval. Uncertainties from tracer release, atmospheric concentrations measurements and the background subtraction has been estimated to be below 10% (Mønster et al., 2014a) and are, if not systematic, included in the overall uncertainty.

6. Results & Discussion

6.1 Methane screening of the area around the Masons landfill

Initial screenings for methane in the area around Masons landfill were carried out in the afternoon on August 5th. Background concentrations of methane and acetylene were determined by measurements on multiple roads in the area and taking the average of the measurements where no nearby sources were present. On August 5th, the background concentrations were found to be 1.880 ppm CH_4 and 0.1 ppb C_2H_2. Figure 12, shows measured methane concentrations (above background) in the area around Masons landfill. Two other significant methane sources were found; an old, closed landfill approximately 1700 m to the south (Blood Hill Pit) and an operational landfill approximately 2800 m to the southeast (Bramford Landfill). Furthermore, a series of sharp methane concentration peaks were observed along the north-south running road, close to the village of Claydon east-southeast of Masons landfill. These peaks are likely due to methane (natural gas) leaks from pipelines along the road, and in some cases signs with warning about possible explosive atmosphere was also observed. Although the relative methane concentrations shown in the figure show higher concentrations near the old landfill and the methane leaks near the north-south going road, this does not mean that there is more methane coming from these sources in comparison to the Masons landfill, just that the measurements were made closer to the individual source.

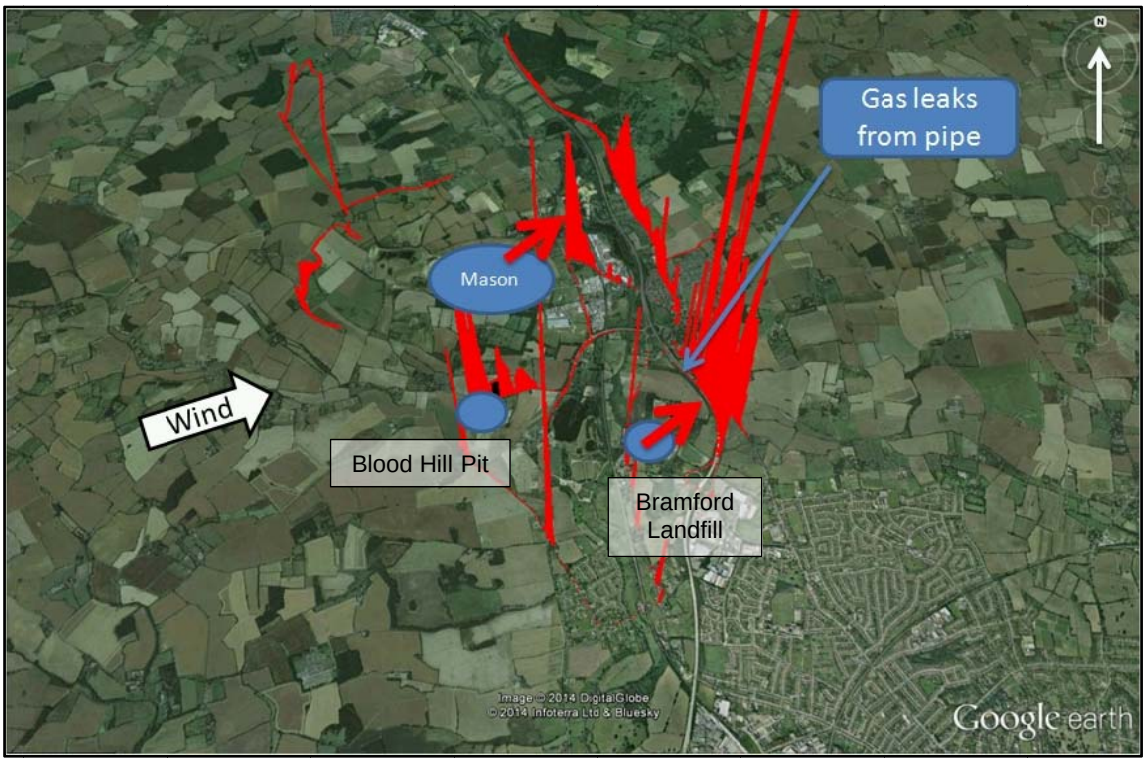

Figure 12. Atmospheric methane concentrations above background, showing sources in the area around Masons landfill. Additional blue circles mark two other landfills with significant methane emissions and the red arrow indicates the location of the downwind plume from one of the landfills (Bramford landfill).

6.2 Initial on-site methane screening of Masons landfill

Due to limited access available to the monitoring vehicle (2WD only), initial screening for methane on Masons landfill site was assumed to be similar to the screenings made in the June trial and the placement of tracer gas bottles was initially in the same locations. Figure 13, shows the relative methane concentrations above background from the measurement in June 2014. Note that North is orientated downwards in Figure 13 in order to show more clearly the full measured route. The highest methane concentrations were measured near the ridge between the operational area and the older, fully restored area with gas extraction wells, as well as downwind from here. Elevated methane concentrations were also measured downwind from the gas utilization plant.

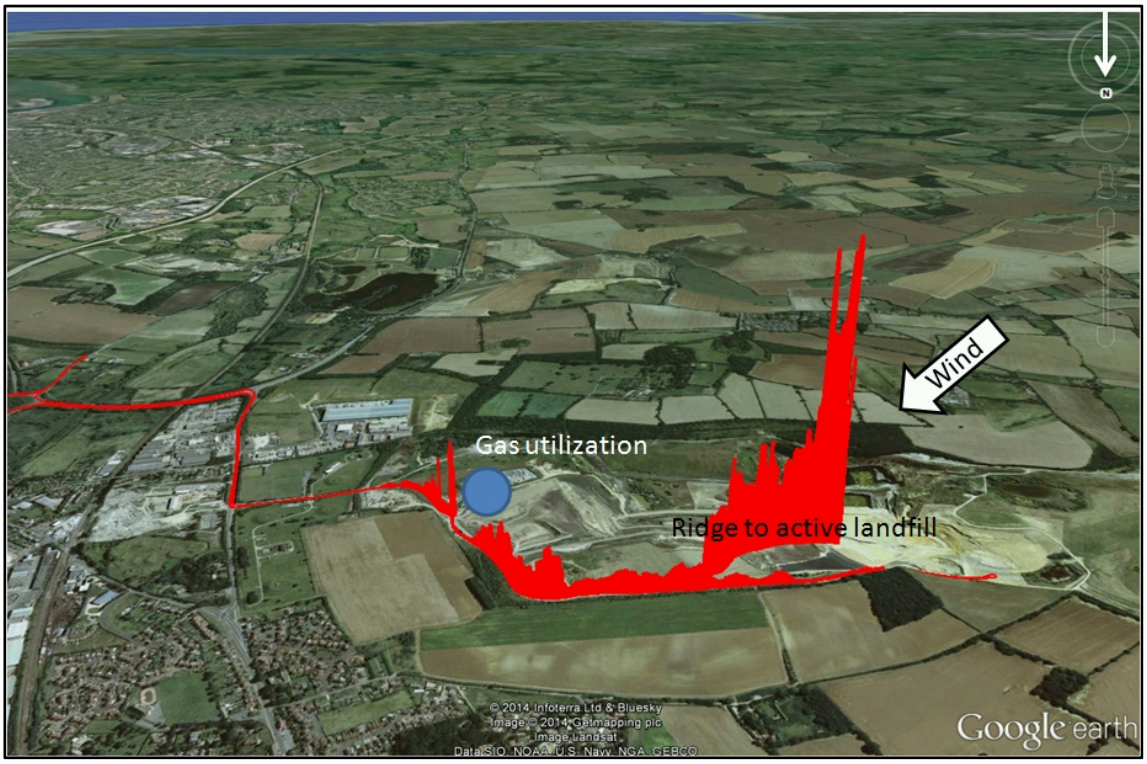

Figure 13. Relative atmospheric methane concentrations above background concentrations during screening on Masons landfill site and along the ridge, downwind from the landfill. Measurements were performed on June 10th, 2014.

6.3 Whole landfill methane emission

In the June 2014 preliminary survey, with the wind generally from the south or south-west, the highest methane concentrations were monitored on the ridge directly downwind of the operational area which, together with the temporary capped slope between the ridge and the operational area, was assumed to be the main methane emitting area of the site. Consequently, the ridge was considered to be a good location for releasing tracer. Therefore, for the first trial on August 6th, three tracer gas bottles were distributed along the ridge and one bottle placed by

the GUP (Figure 5). Due to the warm clear weather with relatively little wind, there was fast vertical rising/mixing of the emitted gasses making it difficult to measure the emissions more than a few hundred metres downwind from the landfill. Later in the day, with less sun and more calm weather, the downwind plumes were measurable much further away. The whole landfill site emission was calculated from measurements at different distances from the landfill. Figure 14 shows examples of methane and tracer gas plumes measured in three distances from the landfill, all measured the same day (road W1, W2 and W3 on 07.08.2014).

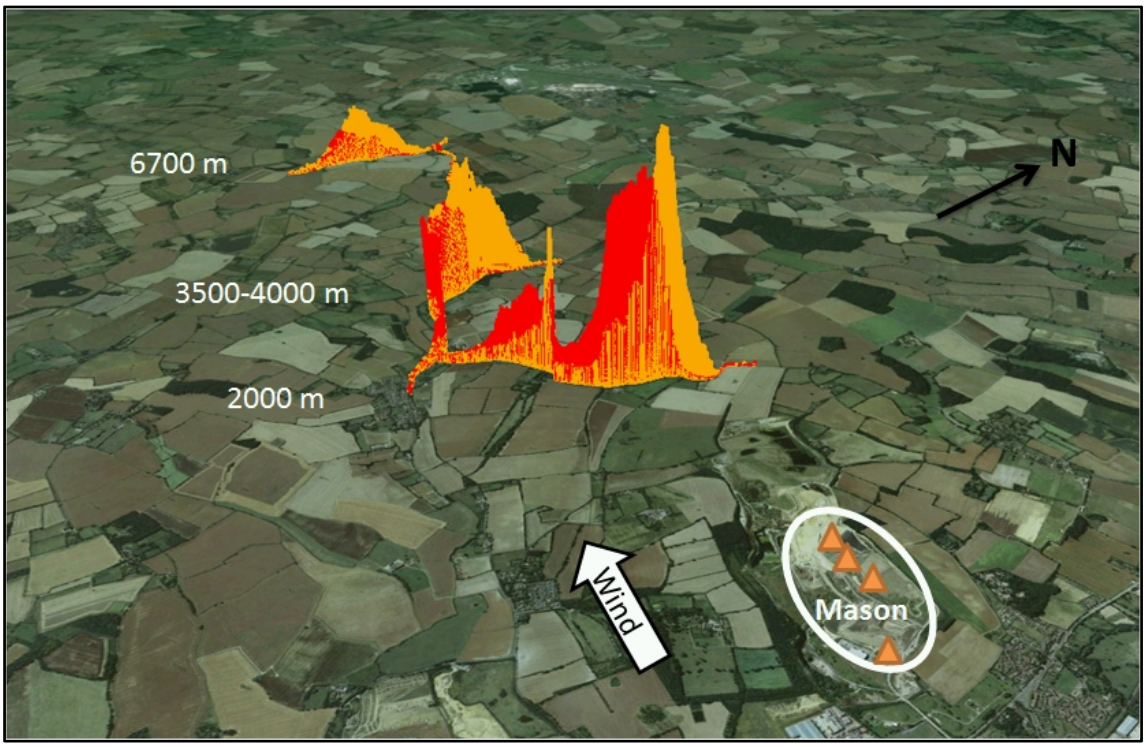

Figure 14. Relative atmospheric methane (red) and acetylene (yellow) concentrations above background measured at three different distances to the landfill on road W1, 2 and 3 on 07.08.2014. Maximum methane concentrations above background were 2620, 1290, and 590 ppb at the three measuring distances 2000m, 3500-4000m and 6700m, respectively. Maximum acetylene concentrations above background were 15.2, 9.0, and 4.6 ppb at the three measuring distances 2000m, 3500-4000m and 6700m, respectively. Yellow triangles mark the approximate placement of the tracer gas bottles (location numbers 1,2,3 and 5, Figure 5). Map data: Google, Infoterra Ltd & Bluesky.

Table 2, summarises the plume measurements carried our during the six days of quantification, Figure 4 illustrates the roads used for plume measurements at the different wind directions the different days and Figure 5 shows the location of the tracer gas bottles.

The methane emission from the whole landfill site was calculated for each plume transect on all measurement days. Table 2, shows the average calculated emission rates on the six days of measurement. There was no significant temporal emission variation within each individual measurement day, but the measured emission rates were higher on the first three days (333±27, 371±42 and 410±18 kg methane per hour) compared to the last three days (217±14,

249±20 and 263±22 kg methane per hour). The influence of factors that might affect emission rates is examined in section 6.4.

Table 2. The calculated methane emission rates (kg h^{-1}) on the six measurement days and two previous measurement days in June 2014.

Date	Measuring time interval	(Road) & Measuring distance to the landfill (m) and number of plume transects (*n*)	Number of useful transects for emission quantification	Methane emission rate[a] (kg h^{-1}) ± Standard error[c]	Overall average methane emission rate[b] (kg h^{-1}) ± Standard error[c]
06.08.2014	17.20-19.00	(1E) 1700-2000 (*18*)	18	333±27	333±27
07.08.2014	18.00-22.20	(1W) 2000 (*9*) (2W) 3500-4000 (*6*) (3 W) 6700 (*5*)	20	389±77 357±69 295±27	371±42
08.08.2014	16.30-19.15	(1W/1N) 1600-2000 (*9*) (3N) 4500-5000 (*6*)	15	390±19 441±16	410±18
11.08.2014	16.30-18.15	(1E) 1700-2000 (*15*)	15	217±14	217±14
12.08.2014	16.30-18.30	(1E) 1700-3000 (*15*) (2E) 2500-4200 (*1*) (3E) 4800-6000 (*5*)	21	274±47 293 225±21	249±20
13.08.2014	08.15-09.15	(1E) 1700-2000 (*13*)	13	263±22	263±22
11.06.2014	18.46-18:55	(1S) 1400-1700 (*5*)	5	286±14	286±14
12.06.2014	8.05-8.47	(1S) 1400-1700 (*11*)	11	323±24	323±24

[a]The average methane emission rate based on the measurements performed at each measuring distance, [b]The overall average methane emission rate based on *all* the measurements performed at each measuring time interval, [c]The uncertainty is given as ± the standard error of mean on a 95% confidence interval. Data from the June campaign is also given for comparison.

6.4 Correlation of methane emission rates with experimental, environmental (climatic) and operational factors

The measured average site methane emission rates varied from 217 kg h^{-1} to 410 kg h^{-1}. This represents a significant variation. The potential causes of this variation are explored in the section below, with further supporting information provided in Appendix I.

6.4.1 Experimental factors

The experimental error of the tracer gas release technique when applied to measuring emissions from Danish landfills has been reported to be better than ±15% (Mønster et al, 2014a).

If it is assumed that there is no short term variation in emission rates over the ~2-3 hour period of each measurement campaign at Masons landfill, then the average experimental error is calculated as ±7.4% (from Table 2). The largest variation (±11.3%) occurred for the survey undertaken on 07.08.2014, where it is noted that measurements took place over a 4 hour 20 minute interval, where the assumption that there was no real change in emission rates becomes

more uncertain. With the large number of traverses analysed (118) these data provide an upper bound for experimental error, and suggest the technique provides accuracy to at least ±7.4% of emission rates.

Emissions were measured at different distances from the landfill. Figure 15, illustrates that there does not appear to be a relationship between the measured emission rates and the measurement distance. The data points with large uncertainty are mainly due to few measurement points and/or measurements at different days. The variation in emission is, therefore, suggested to be dominated by other factors.

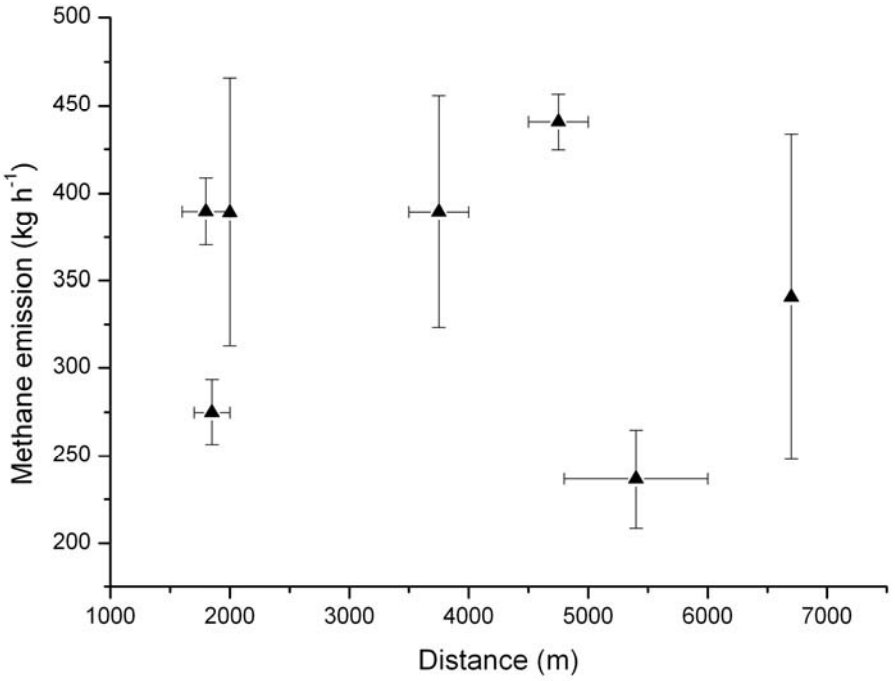

Figure 15. All measured methane emission rates as a function of measurement distance. The uncertainty on the distance is the variation in distance estimated from Google Earth and the uncertainty on the emission is the standard error of mean on a 95% confidence interval.

Figure 16, shows a wind rose of dominant wind direction and speed during each tracer release, centred on Masons landfill. Local historic (in pink) and active (brown) landfills in the proximity of Masons are also shown. The measured methane emission of a particular test day is given in the legend. The highest measured methane flux from the Masons landfill was measured on the 8th August, 410 kg h^{-1}, when the dominant wind direction was from the south east. Background screening (Figure 12), has shown that significant methane emissions are also being produced from the Bramford Landfill, which lies southeast of Masons. However, a measurement transect made between the two sites in the morning of the 8th August around 9.30 with a ESE wind direction (i.e. downwind of Mason Landfill and upwind of Bramford Landfill), reveal no significant elevated methane concentrations caused by Bramford Landfill (Figure 17). The higher methane emissions measured downwind of Masons when the wind was trending from the southeast (particularly 8th August) are not, therefore, considered to be influenced significantly by emissions from Bramford.

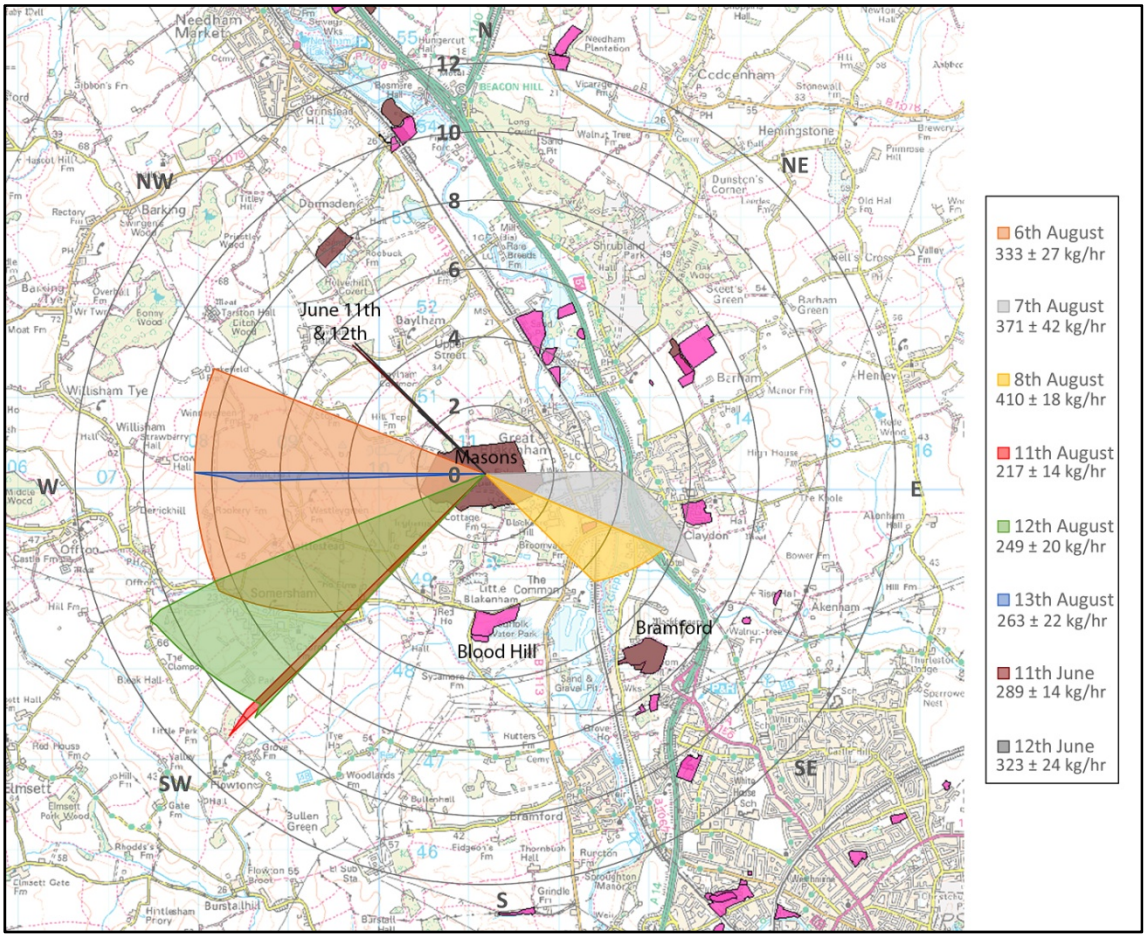

Figure 16. Wind rose of dominant wind direction and speed (m/sec) during each tracer release centred on Masons landfill, with local historic (pink) and active (brown) landfills. The map shows the direction of the wind *toward* the landfill (not away from the landfill), the methane emissions measured and the day of the test. (Contains Environment Agency information © Environment Agency and database right)

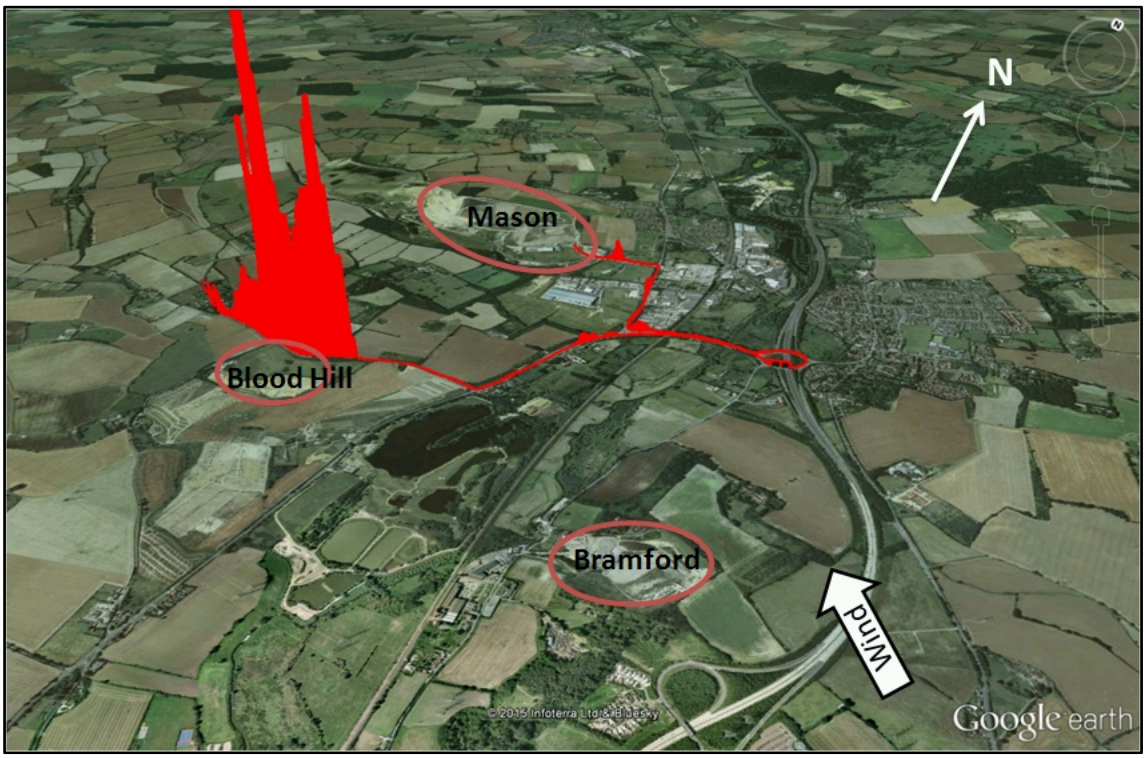

Figure 17. Methane measurements upwind from Mason and downwind from Bramford, performed at 9.30 AM on August 8th, with wind from ESE, ~7.2 m/sec, which was approximately the same speed and direction as during the emission quantification in the afternoon.

6.4.2 Environmental (climatic) factors

Table 3 shows atmospheric data alongside the calculated emission rates. Changes in atmospheric pressure are known to influence the emission of landfill gas. Figure 18 shows a comparison of the methane emission and the atmospheric pressure. The higher emissions measured during the first three days (Aug. 6th to 8th) of the campaign (333±27, 371±42 and 410±18 kg methane per hour) were in general measured during a period of an overall pressure decrease (1014 - 987 mbar) starting Aug 5th and lasting to Aug. 10th. From Aug 10th to 11th the atmospheric pressure increased again (from 987 – 1003 mbar), and remained stable for the following days (Aug. 11th to 14th). The pressure increase and the following stable pressure period could explain the lower methane emissions (217±14, 249±20 and 263±22 kg methane per hour) measured during the last three days of the campaign (Aug. 11th to 13th). However, plots of emission rates versus changes in atmospheric pressures (Appendix I) indicate a fairly weak correlation (R^2<0.31) between emission rates and antecedent pressure changes over 6, 12 and 24 hour periods.

Table 3. Calculated methane emission rates with climatic data and GUP data.

Date	Emission rate (kg h^{-1})	Std. Error (%)	Wind speed (m sec^{-1})	Direction (Degrees)	Sector	Atmos. pres. (mbar)	Overall pressure trend	12 Hour trend [a]	GUP flow rate (m^3 h^{-1})
06.08.2014	333	27	16.8	266	W	1005	Rising	Falling	1890
07.08.2014	371	42	9.5	93	E	1011	Rising	Rising	1948
08.08.2014	410	18	11.3	124	SE	999	Falling	Falling	1830
11.08.2014	217	14	20.8	225	SW	1002	Stable	Rising	1856
12.08.2014	249	20	21.8	239	WSW	1000	Stable	Falling	1830
13.08.2014	263	22	17.4	270	W	999	Stable	Falling	1780
11.06.2014	286	14	6.5	270	W	1015	Rising	Rising	2094
12.06.2014	323	24	2.5	360	N	1024	Stable	Rising	2098

[a] The 12 hour trend is the change in atmospheric pressure leading up to the start of each campaign (see Appendix I).

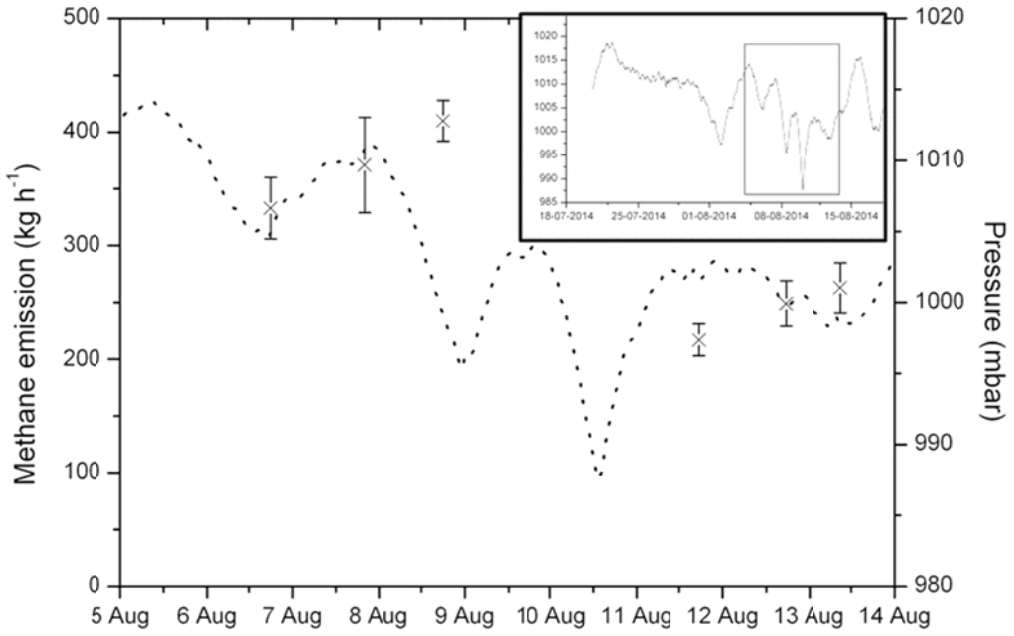

Figure 18. Comparison of the methane emission and the atmospheric pressure. Inserted graph shows a longer pressure time series.

The relationship between various other climate related parameters, including air temperature, wind speed and solar radiation, and whole site emissions are presented in Appendix I. The strongest correlation (R^2 = 0.83 if June data excluded, see appendix) is observed with changes in wind speed, with apparently lower emissions occurring at higher wind speeds (Figure 19). It should be noted, however, that it may not be the wind speed itself that is driving the change in

emissions, rather the mechanism or combination of mechanisms that are driving the changes in wind speed, for example changing atmospheric pressure. At present it is not possible to confirm that this relationship is a direct effect of wind speed on the actual emission or and indirect effect from other factors. One alternative potential factor could be an introduction of experimental bias in the tracer gas dispersion technique, which causes overestimations of measured emissions when measurements are performed under low wind speeds. However, there is no logical explanation supporting this, as insufficient mixing of tracer and methane (due to low wind speeds) and/or improper simulation of the methane source (misplacement of tracer bottles in comparison to the emitting areas) could lead to both an under or overestimation depending on the specific situation. However, at Masons landfill plume transect measurements were performed at different distances to the landfill (on the individual days), under different wind directions, using different tracer gas configurations and finally very far away from the landfill (up to 6700 m). Rather than a consistent underestimation during low wind speeds one would expect an increasing standard variation on measurements performed during periods with low wind speeds, which is not the case (as seen from Figure 19).

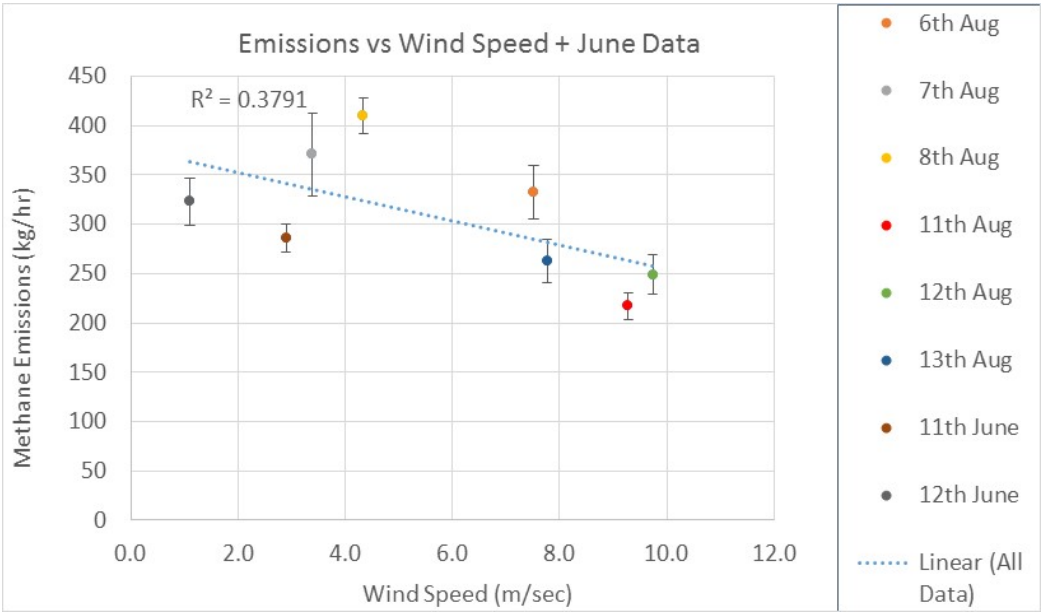

Figure 19. Calculated emission rate versus wind speed (with June data)

6.4.3 Operational factors

Operational factors are considered to relate to the operation of the landfill site, and in particular to the performance of the GUP. In theory, LFG pressure inside the landfill, and the bulk permeability of the landfill cap or cover layers will also be important, but no information was collected on these aspects during the monitoring campaign.

The GUP operates either two or three engines at a time. When two engines are running, the excess gas is diverted through a flare, such that the average hourly flow through the plant remains fairly constant. Two engines and the flare were running on the 7th and 8th of August, and three on all other measurement dates, including during the June experiments. There is no

significant correlation between the GUP flow and the off-site emission measurements, although the range in measured flow in the GUP was fairly small, between 1780-2098 m^3/hour.

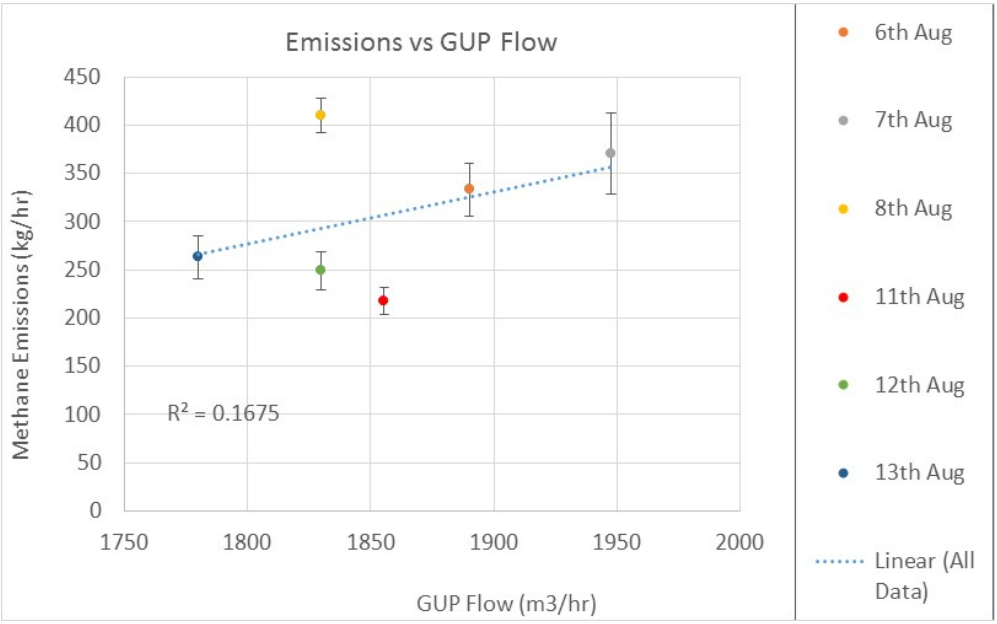

Figure 20. Calculated emission rate versus GUP flow

6.5 Non-combusted methane from on-site gas engines

The gas engines sited in the GUP may emit some non-combusted methane, either from leakage or from inefficient combustion. The location of the GUP, close to the landfill and close to the site boundary (see Figure 5) made it difficult to differentiate between any potential emissions from the GUP and emissions from the rest of the landfill. However on August 11th, the wind was from the west and was stable enough to see the individual plumes downwind on road 1E. Two tracer gas bottles were placed at the area with the assumed highest emission (location 1 and 3), one bottle was placed on the northern boundary fence (location 4) and one near the gas engines (location 5).

Figure 21 illustrates the traverse driving from south to north on road 1E and clearly shows two tracer gas plumes: one from the bottle near the gas engine and one from the three other tracer gas bottles. The methane plume is centred around the left (south) side of the tracer gas plume from the three bottles (highlighted in pink), which indicates that the main emission occurred near the tracer gas bottles at position 1 and 3. The methane plume also shows a small shoulder on the left (south) side (highlighted in blue), which correlates with the tracer gas released from bottle position 5 close to the GUP. By integrating the plumes from three useable traverses (where a split was possible), the emission from the gas engine area is estimated to be between 14 and 22 kg methane per hour. This quantification is solely an estimate. Besides the uncertainty in the plume splitting, two other factors contribute to uncertainty:

1) the methane emitting from the gas engine exhaust is from an elevated height and in the form of a warm gas, which will initially rise faster than the tracer gas release. The methane will, therefore, get more dispersed than the tracer gas resulting in an underestimation of the quantification; and
2) the site's leachate treatment facility is close to the GUP. Screenings showed some elevated methane concentrations downwind from the treatment plant, which may also contribute to the downwind plume from the "GUP area", resulting in an overestimation of the emission from the gas engines themselves.

However, the estimated methane emission rate from the gas engines of between 14 and 22 kg CH_4 hr^{-1} represents a slippage rate (un-combusted methane) of between 2.1 and 3.3 % based on a gas engine flow rate of 663 kg CH_4 hr^{-1} (Table 4). This compares to an average national UK value of 1.5 % determined by Golders in a Review of Landfill Methane Emissions Modelling for Defra (Defra 2014).

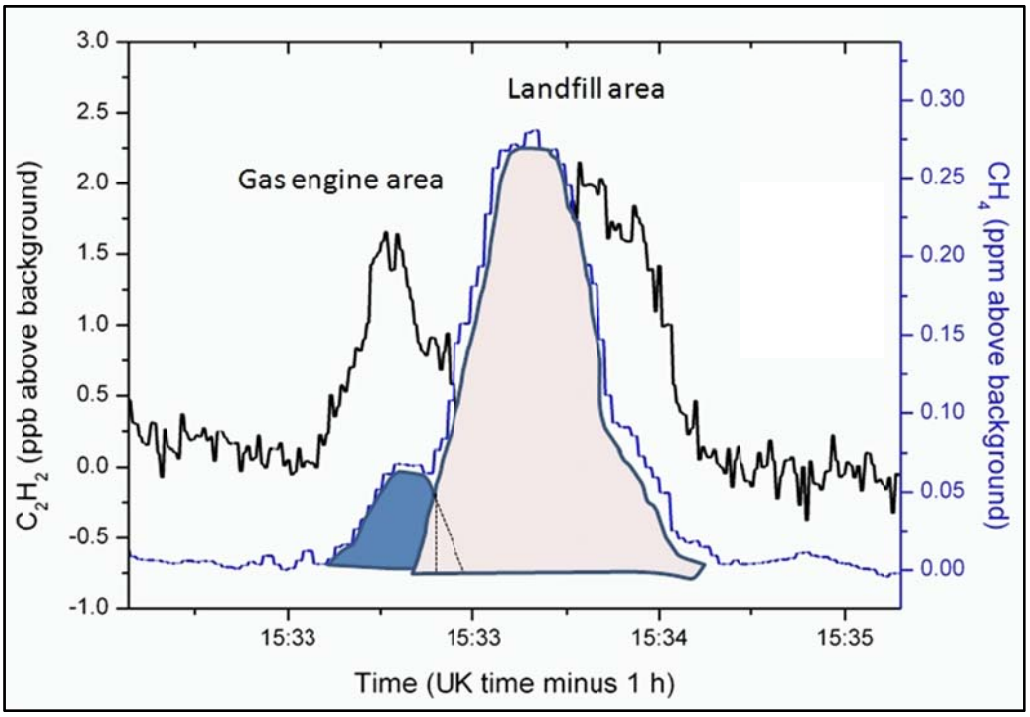

Figure 21. Methane and tracer gas concentration above background on road 1E on August 11th. The drawing shows the split of the methane plume into a part associated with the tracer gas placed near the gas engine, and a part associated with the tracer gas bottles placed at the landfill part.

6.6 Gas recovery efficiency

Table 4 shows landfill gas utilisation data for the measuring days. The values presented are daily averages collected at the GUP. Flow is measured using a thermal mass flow meter (make not given), and the gas content using a GA5000 (Geotechnical Instruments), which has a calibrated accuracy of 0.5 %. The average daily gas recovery flow varied between 1780 and 1947.5 m^3 h^{-1}, with a methane content of between 48.9% and 50.8%. The utilization rate varied

between 633 and 679 kg methane/hour at STP (1 atm, 0°C). Data from the June campaign is given for comparison.

With a methane recovery of between 633 and 679 kg CH_4 h^{-1}, the methane emitted to the atmosphere accounts for approximately 31% of the total methane generated, assuming that the methane generated is the sum of the methane recovered and the methane emitted to the atmosphere, thus not including a potential methane oxidation in the landfill cover soil.

Table 4. LFG utilisation data and calculated efficiency of recovery (June data given for comparison).

	06.08.14	07.08.14	08.08.14	11.08.14	12.08.14	13.08.14	11.06.14	11.06.14
CH_4 (%)	50.1	48.9	50.8	50.1	50.0	49.9	50.5	50.1
CO_2 (%)	35.7	34.25	35.2	34.25	35.4	36.2	37.0	36.6
O_2 (%)	1.1	1.55	1.1	1.25	1.2	1.1	0.65	0.65
Suction (mb)	-73.17	-78.54	-68.44	-68.73	-84.61	-69.29	-78	-78
Flare Flow (m^3 h^{-1})	910	887	0.00	0.00	0.00	0.00	155	159
Total site flow (m^3 h^{-1})	1890	1947.5	1830	1856	1830	1780	2094	2098
Total CH_4 collected (kg h^{-1})	670	679	663	663	652	633	754	750
Average CH_4 emission rate[a] (kg h^{-1})	333	371	410	217	249	263	286	323
CH_4 recovery efficiency (%)	67	65	62	75	72	71	73	70

[a] The average methane emission rate based on the combined measurements performed at each measuring distance.

[b] The gas collection efficiency is calculated as the collected methane divided by the sum of the collected methane and the emitted methane, neglecting methane oxidation.

6.7 Comparison of the methane emission and gas collection from the June campaign

The methane emissions from Masons landfill, during the afternoon on June 11th and morning June 12th were 286±14 and 323±24 kg CH_4 h^{-1}, respectively. During these two days the methane recovery was between 700 and 754 kg CH_4 h^{-1}, and the methane emitted to the atmosphere accounted for approximately 30% of the total methane generated. The methane emissions as well as the recovery efficiency measured in the August campaign compares very well with the emissions and recovery efficiencies measured in June.

7. Conclusion

The methane emissions from Masons landfill during the six days of the GAUGE measurement campaign were successfully quantified using the tracer dispersion method. The fair weather conditions made it necessary to perform measurements in the late afternoon and in the evening when the lower solar flux resulted in a more stable troposphere with a lower inversion layer. This caused a slower mixing of the gasses, but allowed plume measurements up to 6.7 km downwind from the landfill.

The average methane emission varied between 217±14 and 410±18 kg methane per hour within the individual measurement days, but the measured emission rates were higher on the first three days (333±27, 371±42 and 410±18 kg methane per hour) compared to the last three days (217±14, 249±20 and 263±22 kg methane per hour). This is not considered to be a result of measuring artefacts, such as wind or measurement direction, measurement distance or interference from other methane sources. Instead, the difference is more likely due to an actual change in the fugitive emission, which may be climatically driven. The higher emissions measured during the first three days of the campaign were measured during a period with an overall decrease in atmospheric pressure (from approximately 1014 mbar Aug. 5th to 987 mbar Aug. 10th). The lower emissions measured during the last three days of the campaign were carried out during a period with an initial pressure increase followed by a period of stable pressure.

For short (2-3 hours) duration tests, the average experimental error was calculated as ± 7.4 %. This may increase as the test duration increases, owing to actual changes in emission rates driven by climatic or operational controls, which would become more significant with time.

The average daily gas recovery flow varied between 633 and 679 kg methane/hour at STP (1 atm, 0°C). The methane emitted to the atmosphere accounted for approximately 31% of the total methane generated, assuming that the methane generated is the sum of the methane recovered and the methane emitted to the atmosphere. This does not, therefore, include potential methane oxidation in the landfill cover soil.

In general, the methane emissions as well as the recovery efficiency measured in the August campaign compared very well with the emissions and recovery efficiencies measured in June. The methane emissions from Masons landfill, during the afternoon on June 11th and morning June 12th were 286±14 and 323±24 kg CH_4 h^{-1}, respectively. During these two days the methane recovery was between 700 and 754 kg CH_4 h^{-1}, and the methane emitted to the atmosphere accounted for approximately 30% of the total methane generated.

8. References

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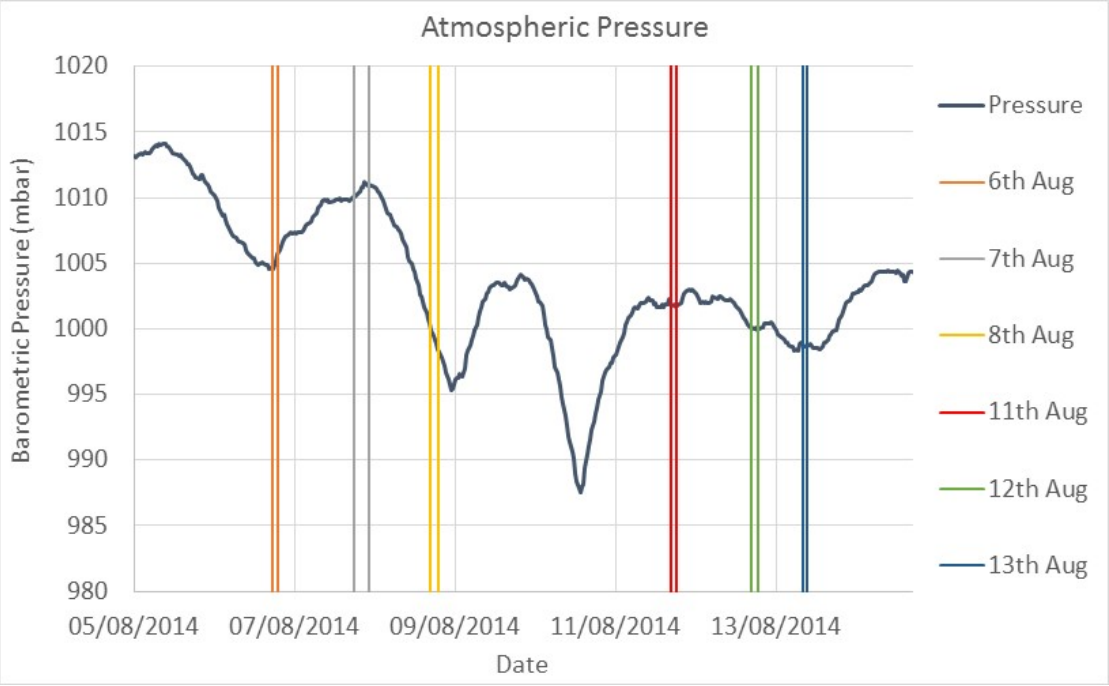
Appendix I. Investigation of factors influencing whole site methane emissions

The plots below, compare various measured parameters and the calculated methane emission for each test day. Parameters include atmospheric pressure, air temperature, wind speed, solar radiation, rainfall and flow through the GUP. Data is given firstly for the August experiments alone and a second plot is given to include the June data.

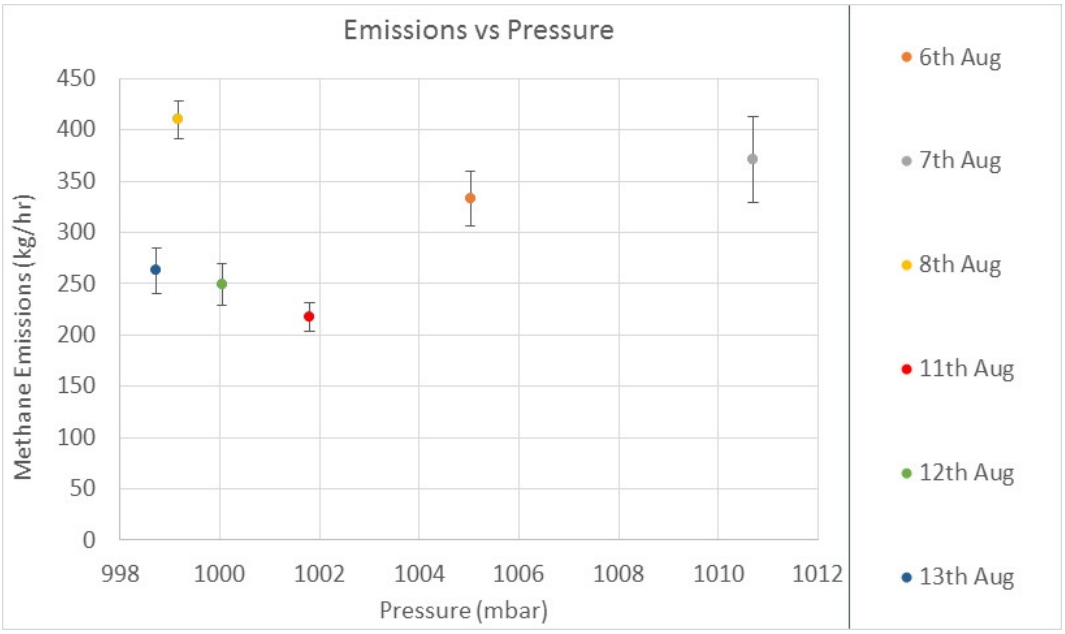
Atmospheric Pressure

There appears to be little correlation between atmospheric pressure and emissions, at least when comparing pressures at the time of the measurement. As Plot 1 shows, there were fairly significant changes in atmospheric pressure during the course of the experiment, and it is these trends that may be driving changes in emissions.

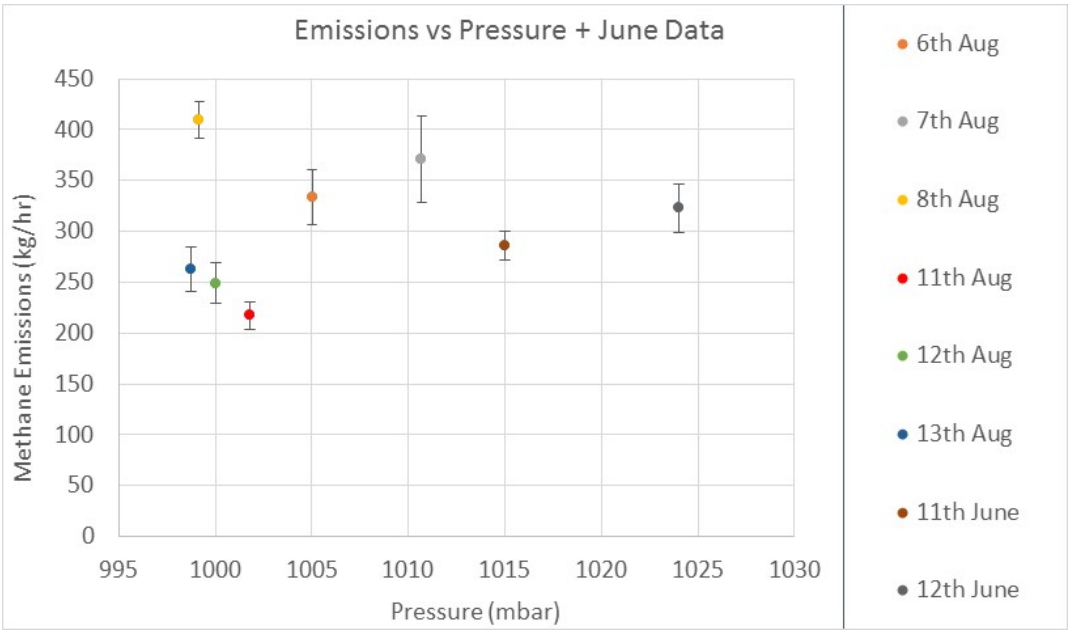
Plots 2 and 3 show the atmospheric pressure, measured at the time of the experiment, plotted with the calculated emission for each experiment. There does not appear to be any significant correlation with pressure and emission rate. However, it is more likely that changing pressure trends over time (hours to days) may be the driving force behind changes in emissions. In plot 4, the change in atmospheric pressure in the previous 6, 12 and 24 hour period before the start of the tracer tests is plotted against the calculated emission. Although there is no strong correlation, there may be a small negative relationship between increasing barometric pressure resulting in a decrease in methane emissions.



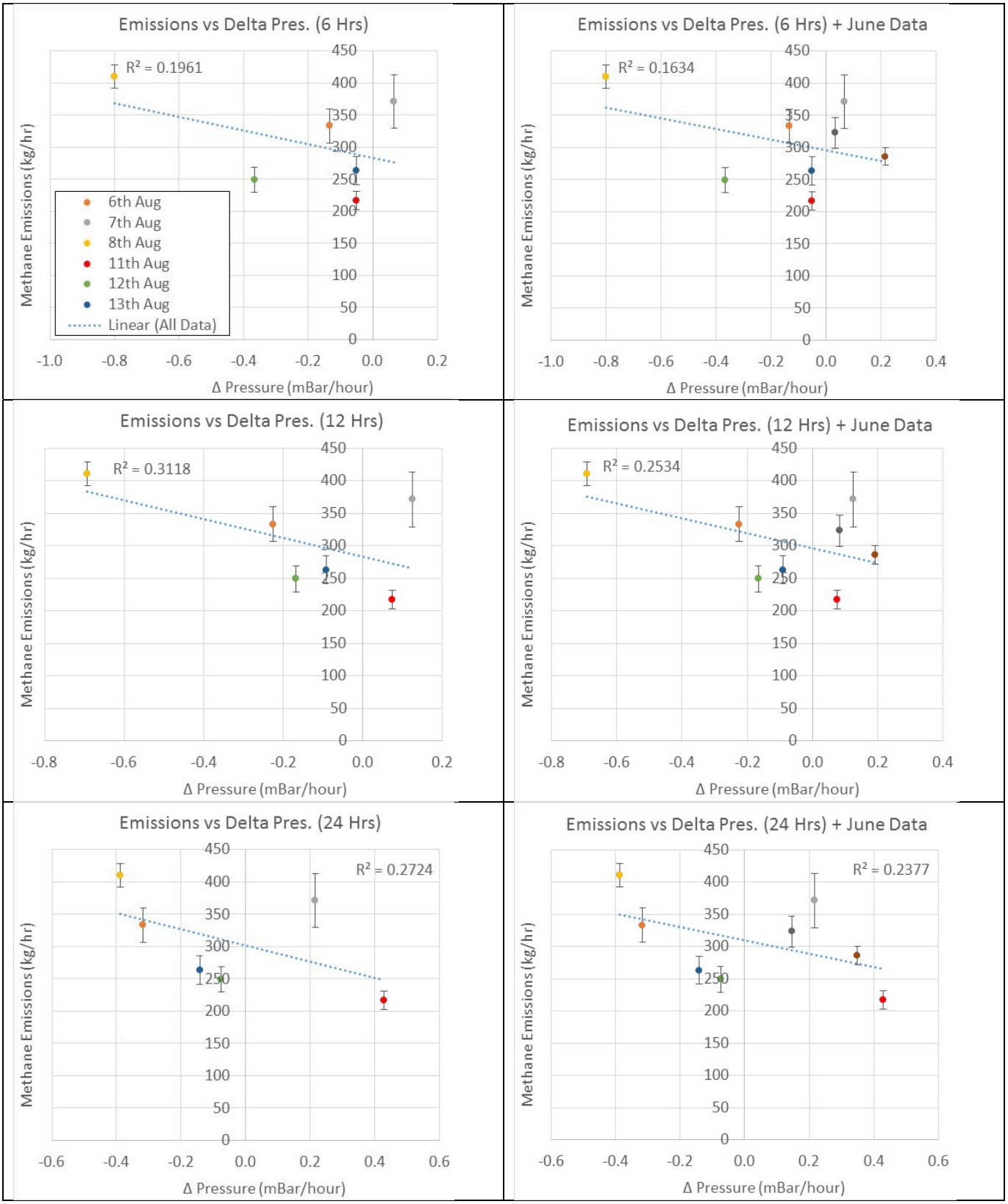
Plot 1. Relationship of atmospheric pressure to timing of measuring campaigns



Plot 2. Calculated emission rate versus atmospheric pressure at time of campaign



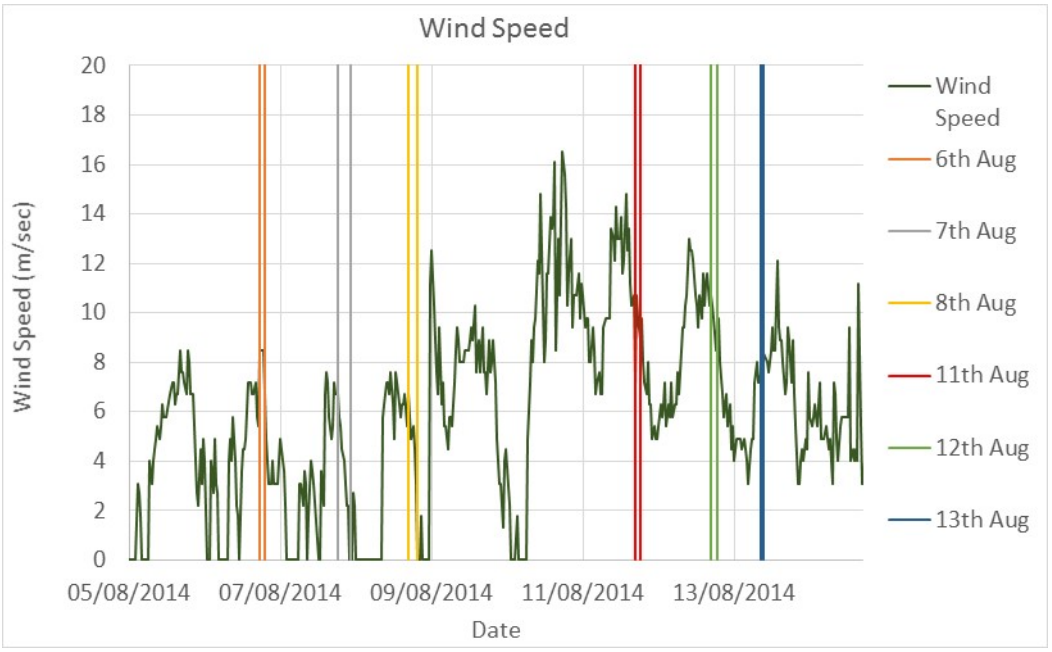
Plot 3 Calculated emission rate versus atmospheric pressure at time of campaign (with June data)



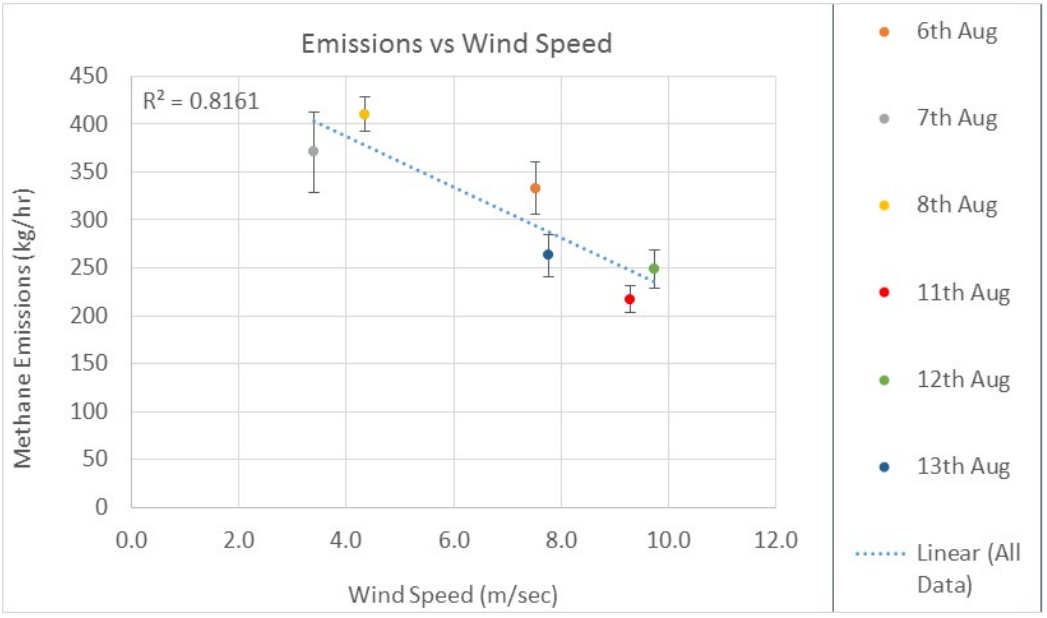
Plots 4 a to f. Calculated emission rate versus changes in antecedent atmospheric pressure over varying time durations

Wind Speed

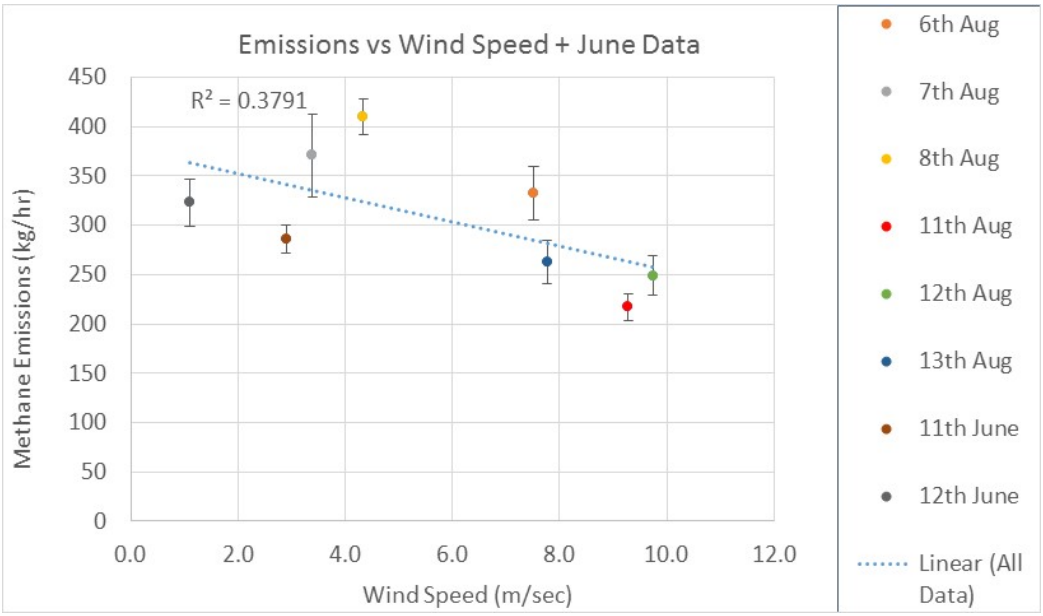
Plot 5 shows wind speed data during the period of the August experiments. Plots 6 and 7 show wind speed against the calculated emissions. The August data appear to show a fairly significant negative correlation between wind speed and emissions. The correlation is less so when the June data is included, but the trend is still present. It must be noted, however, that in general during both the June and August trials, wind speeds were fairly low.



Plot 5 Relationship of wind speed to timing of measuring campaigns



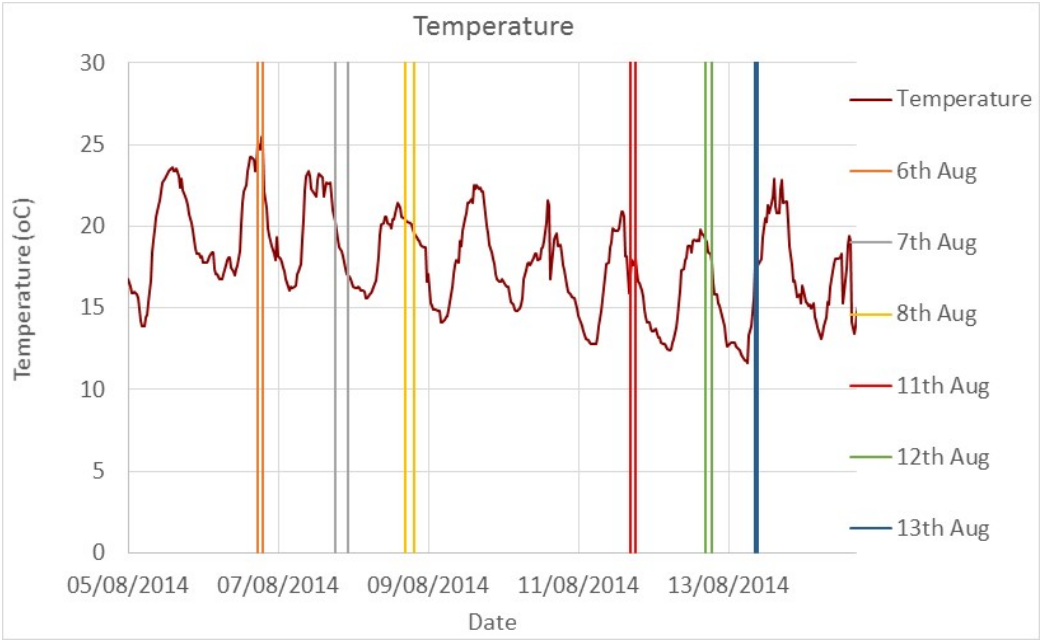
Plot 6 Calculated emission rate versus wind speed



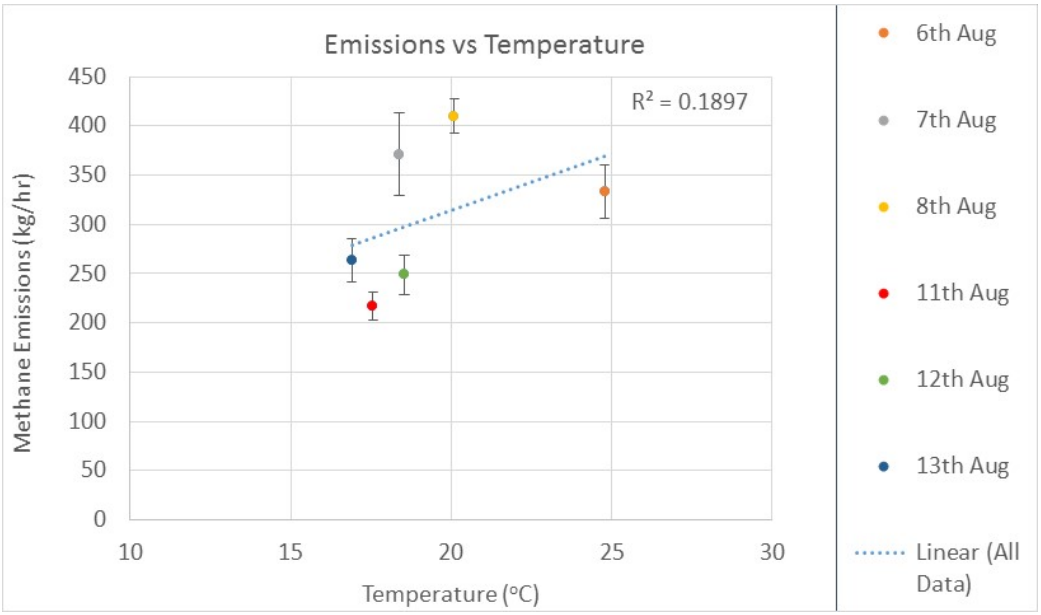
Plot 7 Calculated emission rate versus wind speed (with June data)

Air Temperature

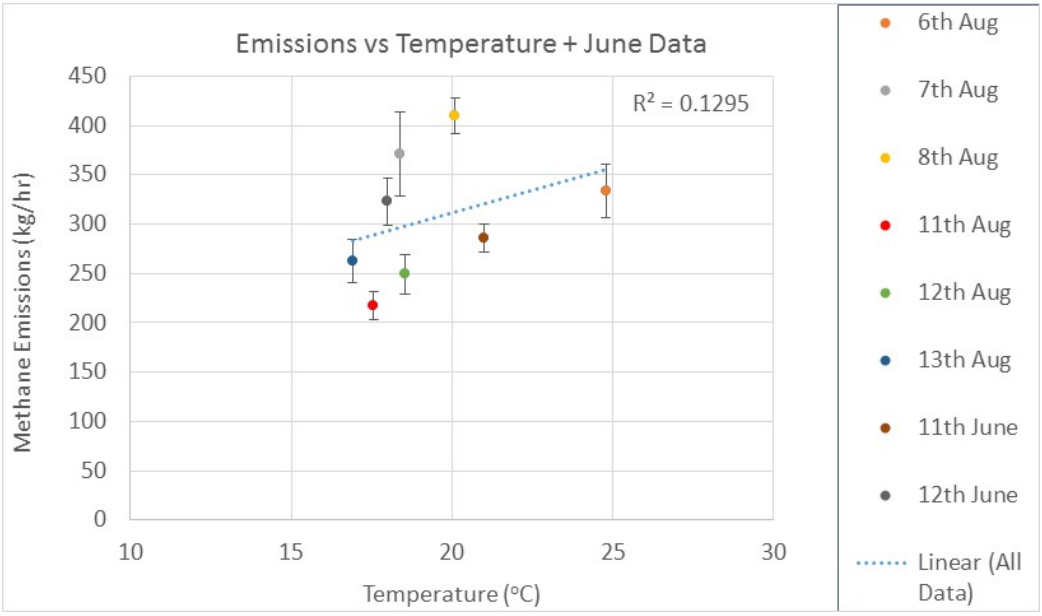
Air temperatures fell within a fairly narrow range of 17-25 ^{o}C for all the experiments, August and June. The data show a small positive correlation between increasing air temperatures and increased emissions.



Plot 8 Relationship of air temperature to timing of measuring campaigns



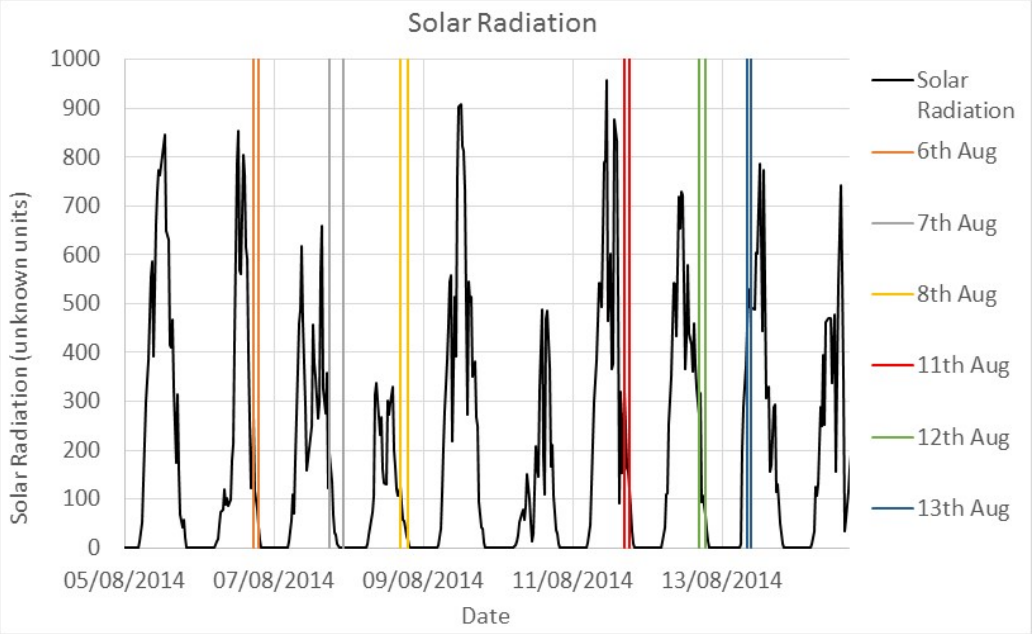
Plot 9 Calculated emission rate versus temperature



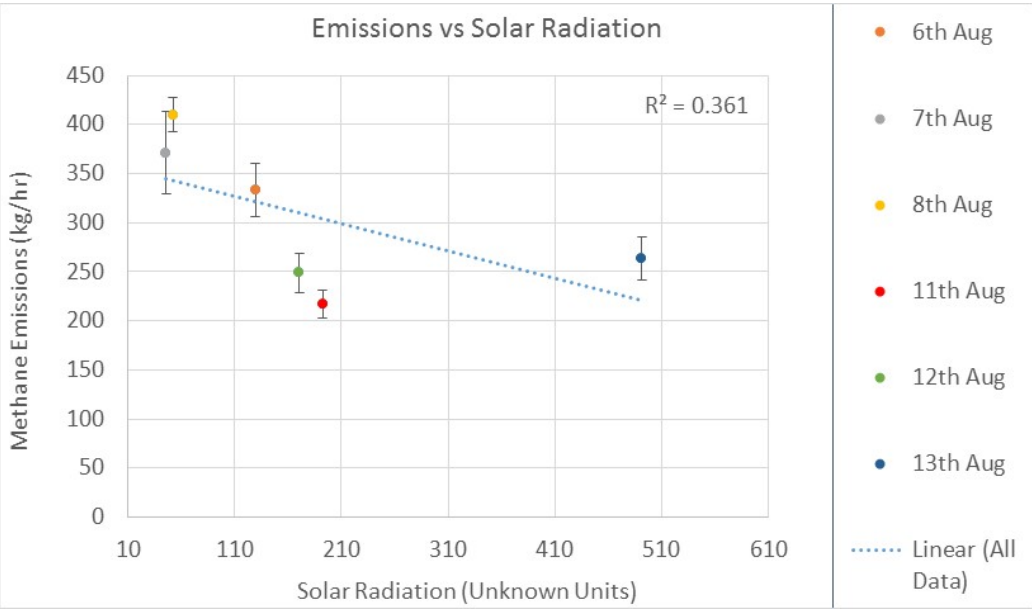
Plot 10 Calculated emission rate versus temperature (with June data)

Solar Radiation

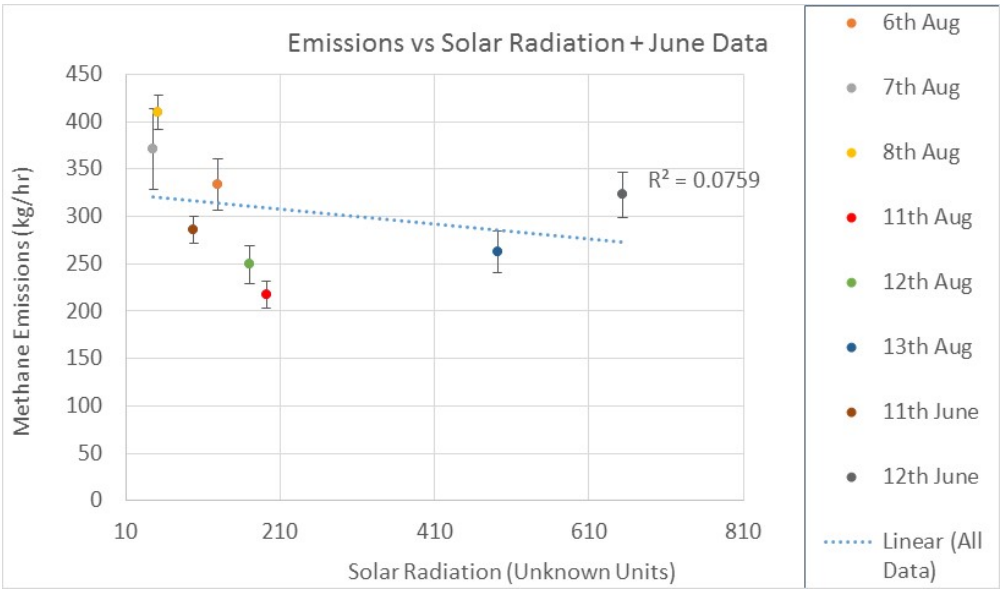
In the August study, with the exception of the final tracer release on the 13th, all other experiments were carried out in the afternoon or evening when solar radiation was declining towards sunset. The data show a small correlation with emissions, in that higher emissions were measured during periods of lower solar radiation, and decline as the intensity of the sun increases. This would, perhaps, be expected where, as discussed in the main text, bright, sunny conditions may lead to rapid vertical tracer and methane plume rise. The correlation is, however, less convincing when the June data is included.



Plot 11 Relationship of solar radiation to timing of measuring campaigns



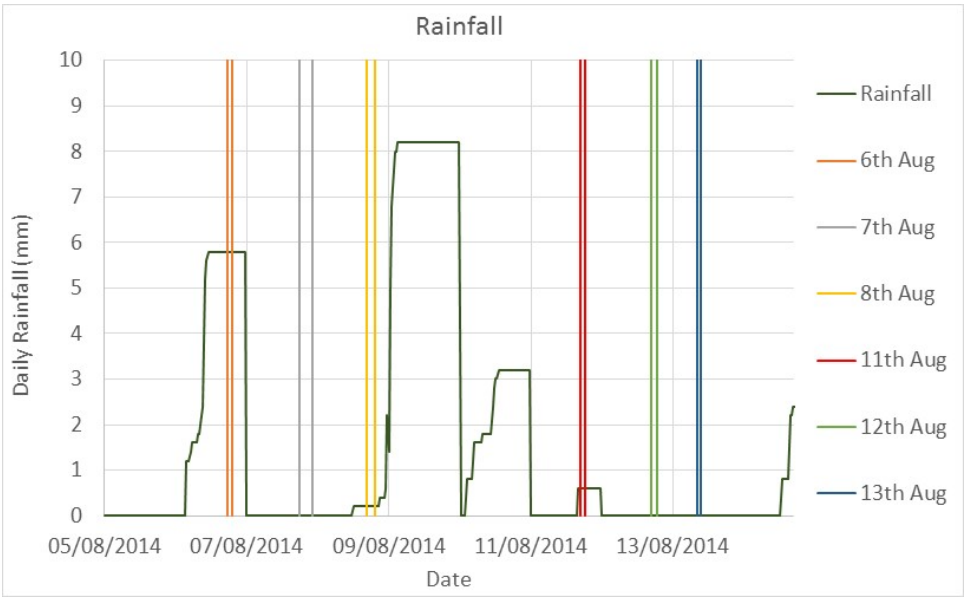
Plot 12 Calculated emission rate versus solar radiation



Plot 13 Calculated emission rate versus solar radiation (with June data)

Rainfall Data

Rainfall data is shown in Plot 14. The plot shows cumulative daily rainfall (midnight to midnight), measured in 30 minute intervals. The data show, that no campaigns were carried out during periods of active rainfall, though there had been some rain in the hours prior to the 6th, 8th and 11th August tests.

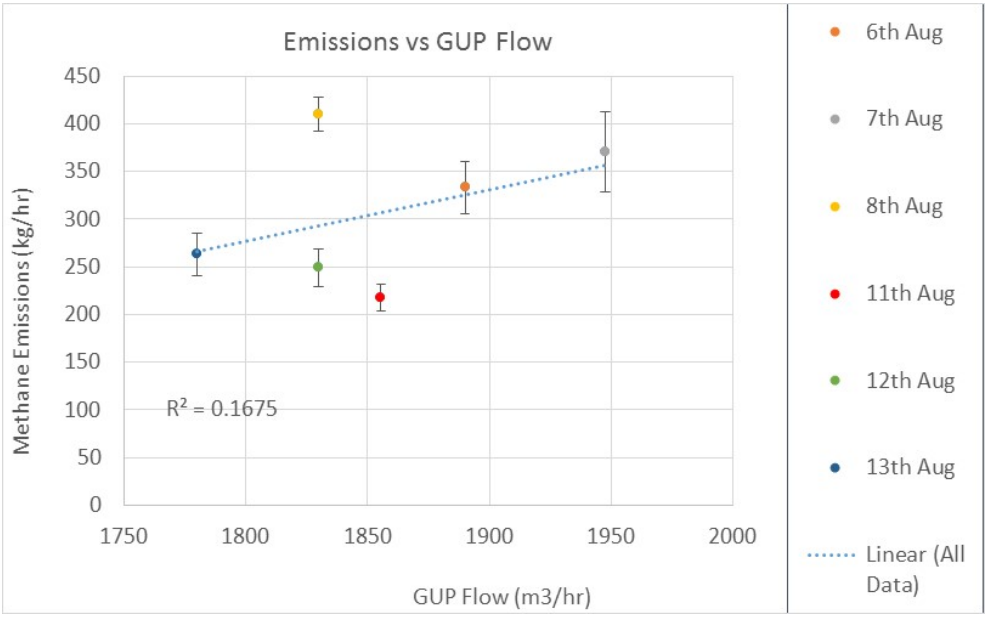


Plot 14. Daily rainfall data during August campaign

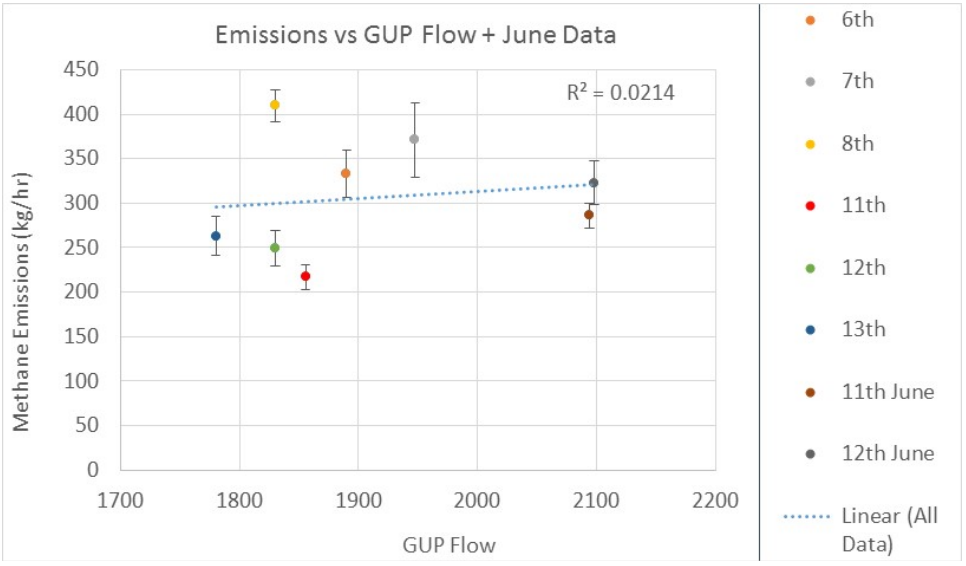
Gas Utilisation Plant

The GUP operates either two or three engines at a time. When two engines are running, the excess gas is diverted through a flare, such that the average hourly flow through the plant remains fairly constant. Two engines and the flare were running on the 7th and 8th of August, and three on all other measurement dates, including during the June experiments. There is no

significant correlation between the GUP flow and the off-site emission measurements, although the range in measured flow in the GUP was fairly small, between 1780-2098 m^3/hour.



Plot 15 Calculated emission rate versus GUP flow



Plot 16. Calculated emission rate versus GUP flow (with June data)