

# REVIEW OF LONG TERM LANDFILL GAS MONITORING DATA AND POTENTIAL FOR USE TO PREDICT EMISSIONS INFLUENCED BY CLIMATE CHANGE

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## Abstract

Methane (CH<sub>4</sub>), a potent greenhouse gas, is generated in landfills as waste decomposes. Landfills are recognized by the IPCC (Bogner *et al.* 2007) as being a major source of global CH<sub>4</sub> emissions. Inventories and modelling are widely used tools to predict future landfill gas emissions, however these models do not account for local climate variations that could be observed in the future due to the effects of climate change (Kerr 2001).

Monitoring of landfill gas composition (CH<sub>4</sub>, CO<sub>2</sub>, O<sub>2</sub>, CO and H<sub>2</sub>S) has been carried out on gas wells over the last ten years at a residential development (6.5 ha) constructed on a closed municipal waste landfill in the North Island of New Zealand. The gas extraction network at the site comprises over 40 extraction wells which are monitored weekly. There is also a dense monitoring network comprising over 1,230 monitoring points located in and below the landfill cap and within the foundations of the buildings, which is monitored monthly.

Climate at the site is temperate, with warm, humid summers and mild, damp winters. Over the last ten years, a number of extreme meteorological events have been observed (NIWA 2013a). The impacts of these events compared to typical meteorological conditions can be observed in changes in landfill gas emissions and composition at the site.

This paper presents the correlations identified between landfill gas parameters and meteorological conditions over the last ten years. The implications of this in terms of the possible influence of climate change on future landfill gas emissions has been considered for different climate scenarios (Randall *et al.* 2007, MfE 2008) considering the potential changes in rainfall and temperatures. The findings provide useful information on how landfill gas emission estimates and landfill gas collection systems can take account of the possible influence of climate change.

*Keywords:* landfill gas, climate change, methane, emission.

## 1. Introduction

Landfill gas (LFG) is a by-product of the biodegradation of organic material contained in wastes deposited in landfill sites. Landfills are capable of generating LFG for 30 years or longer. Solid inert landfills with smaller portions of organic waste can generate low quantities of LFG over a similar period. The generation of LFG is dependent on several factors. Some key factors include the type of waste, age of waste, moisture content, temperature and pH.

LFG has become of increasing interest for a number of reasons including its impact as a

greenhouse gas and associated carbon credits, and in relation to redevelopment of landfill sites and the associated implications for the safety of the occupiers and development itself.

LFG mainly comprises methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>), with a smaller proportion of hydrogen sulphide (H<sub>2</sub>S) and carbon monoxide (CO). The composition is dependent on the waste type, the stage of degradation of that waste and the climatic conditions. However, local climatic conditions are poorly considered in current LFG generation models (LandGEM or IPCC models) which use average yearly rainfall to assess specific sites (IPCC 2006, US EPA 2010). In order to

assess the effect of climate on LFG, long term monitoring data have been reviewed to identify potential correlations with meteorological parameters and consider the implications in term of potential climate change.

## 2. Conditions affecting landfill gas production

The degradation of organic material in a landfill can be summarised as a series of phases (EA 2004), starting with aerobic decomposition which consumes all O<sub>2</sub> comprised in the landfill, followed by the beginning of the anaerobic decomposition where CO<sub>2</sub> levels increase and replace the ambient N<sub>2</sub>. Following that stage, methanogenesis starts with an increase of CH<sub>4</sub> around 50-60% with a more stable CO<sub>2</sub> concentration around 40-50%. During the latest stage, when organic substrate required for microbial activity becomes limited, CH<sub>4</sub> and CO<sub>2</sub> decrease and are progressively replaced by atmospheric gas.

In practice, the idealised profiles described by the models are rarely achieved. Varying degrees of phases overlap and temporary cessation has been reported in the field. In addition, the duration of particular phases and the overall length of time taken for a body of waste to pass through the full degradation sequence varies considerably from one site to another. This reflects the influence of a wide range of factors, and amongst them are environmental factors (EA 2004, US EPA 2010 and Wreford *et al.* 2000) such as:

- The presence of moisture (unsaturated conditions) in a landfill increases gas production as it encourages anaerobic bacterial decomposition.
- Warm temperatures increase bacterial activity, which in turn increases the rate of landfill gas production. Colder temperatures inhibit bacterial activity.

The above environmental factors can be linked to climate change and will be further discussed in the following sections.

## 3. Site settings

### 3.1. Location

The 6.5 ha site is located on the North Island of New Zealand set amongst commercial and residential land uses. With easy access to the motorway and local services, the site was a prime location for redevelopment.

### 3.2. Site history and description

The site was first developed as a quarry in the 1920s, and was subsequently landfilled with

inorganic material from 1965 to 1975. In the 1980's some domestic refuse was placed.

The quarry pit extended some 3 ha, however waste was placed beyond the edges of the pit and in some places were spread thinly across parts of the site. The quarry pit is estimated to be about 18m below ground level with groundwater fluctuating between 6.3m (maximum level recorded in winter) and 12m (minimum level recorded in summer) below ground level.

The quarry pit was mainly filled with construction and demolition waste, and solid inert waste including concrete, bitumen, steel drums, rock rubble, paper, clays and soils. The site was estimated to contain approximately 800,000m<sup>3</sup> of refuse, of which 15% was estimated to display general characteristics of refuse that contains organic material.

Clay and hard fill was used as cover material and the final cover included clay and composting material as topsoil. The site was then used as a golf course in the 1990's and redevelopment of the site commenced in 2003.

### 3.3. The redevelopment

The development comprises of residential dwellings as standalone townhouses, multi-storey apartments, services buildings and recreational areas.

The buildings have been designed with vapour barriers and passive ventilation systems that can be converted to an active system if required. Monitoring points are located in multiple locations within and around the buildings. In addition, active gas extraction wells (EW) have been installed which feed into an activated carbon treatment plant. The system runs continuously and there is an alarm should the plant unexpectedly shut down.

Operation of the treatment system and design of the vapour barrier system has had to meet the requirements of the site permit.

### 3.4. Monitoring requirements

The site development permit outlines in detail the LFG monitoring system for the development. As the site has been progressively developed there has been an increasing number of monitoring points. At present there are over 1,230 gas monitoring points at the site that are monitored weekly or monthly. This includes monitoring of the extraction wells (EW) and LFG treatment plant, deep and shallow gas bores adjacent to each building (VP), gas bores within the building foundation (WP), passive vents connected to the subfloor venting system (PV) and gas bores located around the perimeter of the site (MW).

In addition, groundwater samples are taken quarterly to check contaminant levels and gauge water levels.

## 4. Local climate

### 4.1. General climate observed in the site area

The site is located in an area which has a warm-temperate climate, with warm, humid summers and mild winters. Under Köppen's climate classification (Rubel *et al.* 2010), the area has an oceanic climate (*Cfb*). The average mean temperature is 15.1°C, while the maximum recorded temperature is 30.5 °C and absolute minimum is -2.5 °C. The annual average number of ground frost days is 10 days. Rainfall occurs almost year-round with higher rainfall over winter and with an average of 1240 mm per year spread over 137 'rain days' (NIWA 2013c). Seasonal deviation from the normal mean for temperature and rainfall are presented in Figure 1.

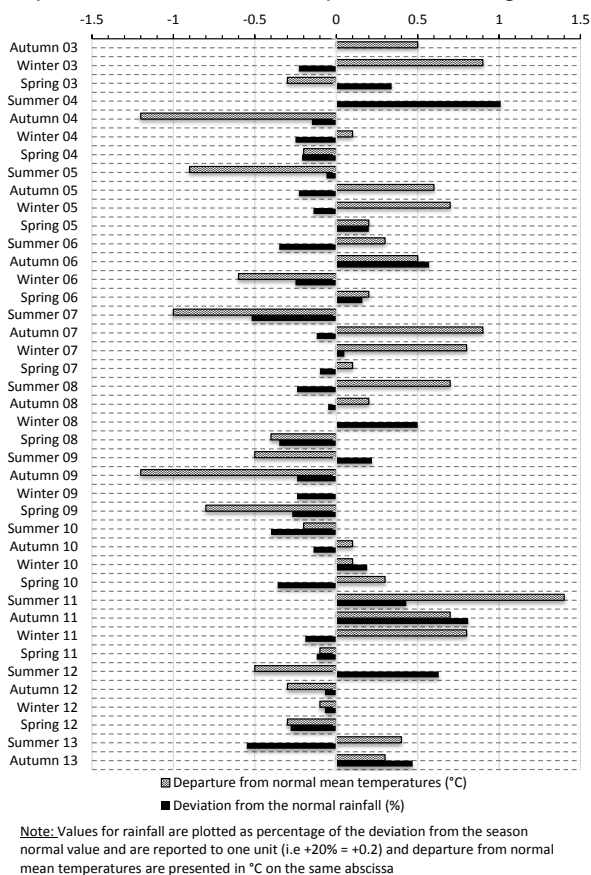


Figure 1. Seasonal deviation from the mean for temperature and rainfall between 2003 and 2013 in the vicinity of the site (NIWA 2013a)

### 4.2. Meteorological parameters selected

Daily meteorological data (NIWA 2013b) was extracted from the closest weather station (15 km away) to the site. The following daily parameters

were selected to assess the correlation with LFG generation at the site:

- cumulative rainfall (rain over 24 hours 9am to 9am),
- air temperature (dry and wet) at 9am,
- relative humidity at 9am,
- maximum and minimum temperatures over last 24 hours to 9am,
- minimum grass temperature over 24 hours to 9am,
- earth temperature at 5cm and 10cm depths at 9am,
- pressure (station and mean sea level) at 9am and
- solar radiation over 24 hours from midnight to midnight.

Cumulative rainfall 7 and 14 days prior to any gas readings were calculated from the daily values recorded.

The following monthly data was obtained from the weather station:

- number of wet days with at least 1mm of rain,
- mean daily air (min and max) and earth (at 10cm depth) temperatures,
- total rainfall, and
- maximum daily rainfall.

## 5. Landfill gas observed at the site

### 5.1. Data period

Development of the site occurred in stages from 2003 and is ongoing. In the early stages of development, between 2003 and 2005, the extraction of LFG was regularly adjusted at the treatment plant and in the extraction wells. Over that period the hourly LFG flow rate extracted ranged between 20 and 1,500 m<sup>3</sup>/h with high levels of CH<sub>4</sub> and CO<sub>2</sub> (fluctuating between 1% and 68% or 22% respectively). From 2005, gas concentrations in EWs and at the inlet of the treatment plant started to stabilise. From 2009, despite continued construction at the site, no significant adjustment of the gas extraction system was carried out and all parameters (LFG flow rates and concentrations) have remained relatively stable at approximately 500 m<sup>3</sup>/h and 1.1% methane.

### 5.2. Methodology of the assessment

Due to the significant fluctuation in data prior to 2005, the correlation between gas concentrations measured at various monitoring locations and daily meteorological data for the period 2005-2013 were assessed using Spearman's correlation coefficient. When a correlation was noted to be weak with a high level of significance, an assessment using longer averaging times, in this case monthly means, was also carried out. The assessment

highlighted correlations between gas parameters (temperature and composition), rainfall and temperature.

The selected statistical analysis of the different meteorological parameters and the LFG composition monitored on site are presented in Table 2 in Appendix 1.

### 5.3. Extraction network

Assessment of the average LFG generation over the entire extraction network provides an understanding of the general behaviour of the landfill. Using an overall average from all wells at the site avoids the potential inclusion of specific effects caused by the potential heterogeneous nature of the waste material and immediate ground conditions.

Landfill gas concentrations (CH<sub>4</sub>, CO<sub>2</sub>, CO and H<sub>2</sub>S) observed in the 47 extraction wells have been averaged for each month between 2005 and 2013 (Figure 6 in Appendix 1). The time series graph shows the effect on seasonal changes on gas composition.

Similar seasonal conditions as those projected by the climate change scenarios have been observed in the past and resulted in CH<sub>4</sub> increasing between 20% and 100% in the EWs during autumn 2006 and winter 2008. More recent warmer and wetter periods in 2011 and 2013 have showed less pronounced increases in CH<sub>4</sub> and CO<sub>2</sub>.

It can also be noted that O<sub>2</sub> concentrations vary significantly over time with peaks in concentrations linked to low recorded concentrations of CH<sub>4</sub> and CO<sub>2</sub> (particularly in winter 2007 and autumn 2012). Typically O<sub>2</sub> is displaced in the presence of significant levels of landfill gas. This observation would indicate that the gas collection system is likely to be drawing in more air through these periods or that the degradation process has slowed.

Monthly average LFG concentrations in the extraction wells, and consequently at the inlet to the treatment plant reduced over winter months. This is likely due to the typical increase in rainfall and lower temperatures during winter months inhibiting LFG generation.

## 5.4. Inlet of the treatment plant

### 5.4.1. Gas composition and rainfalls

As with the extraction wells, LFG recorded at the inlet of the treatment plant provides an overview of the general behaviour of the landfill. In addition it provides a more accurate reading of the overall LFG gas collection rate.

Statistical analysis suggests that an increase in rainfall (monthly average or cumulative rainfall over the previous 7 and 14 days) strongly correlates with

a decrease in CO<sub>2</sub> and more so with decreasing CH<sub>4</sub> concentrations.

Figure 2 summarises gas concentrations at the inlet to the LFG treatment plant and average monthly rainfall.

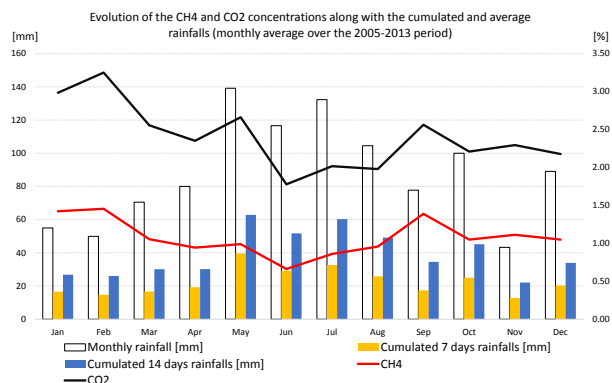


Figure 2. Monthly average of LFG concentrations at inlet to treatment plant with rainfall

The comparison of the correlations between CH<sub>4</sub> and CO<sub>2</sub> and the cumulative rainfall, indicate that the duration of rainfall, and therefore the amount of water in the waste, is a significant driver behind gas production and this occurs whatever the season. This behaviour is the driving mechanism in bioreactor landfills where moisture levels are increased to increase the rate of decomposition through anaerobic microbial activity producing more LFG.

### 5.4.2. Gas composition and temperature

Statistical analysis suggests that during warmer conditions (highlighted by an increase in air temperatures and more significantly in soil temperature at 5cm depth) CH<sub>4</sub> and CO<sub>2</sub> concentrations increase while during cooler conditions O<sub>2</sub> concentrations tend to increase. The reduction in CH<sub>4</sub> and CO<sub>2</sub> in winter leads to more air being drawn into the extraction system. Therefore, to optimise gas collection during colder months, gas extraction wells should be turned down to reduce air ingress into the system.

As observed with rainfall, the correlation is stronger with longer term average temperatures, suggesting that one day extreme events do not significantly affect gas compositions.

Figure 3 summarises gas concentrations at the inlet to the treatment plant and average monthly temperature.

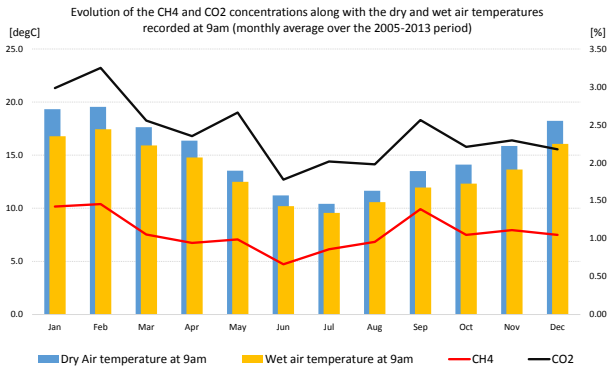


Figure 3. Monthly average of LFG concentrations at inlet to treatment plant with temperatures recorded at 9 am

### 5.4.3. Ratio $CH_4/CO_2$

The  $CH_4/CO_2$  ratio monitored at the inlet of the treatment plant was noted to be the only parameter slightly correlated with atmospheric pressure while other individual parameters (in particular  $CH_4$  and  $CO_2$ ) were non significantly correlated. This suggests that the  $CH_4$  concentration increases when atmospheric pressure decreases.

$CH_4/CO_2$  ratio is calculated to provide an indication of the likely age of waste. Newer waste typically has a  $CH_4/CO_2$  ratio of 1.5. Older waste, as in this case, is expected to have a lower  $CH_4/CO_2$  ratio.  $CH_4/CO_2$  ratio at the site varies over the years, with a ratio around 1 in more recent years, which is consistent with the later stages of waste degradation (EA 2004).

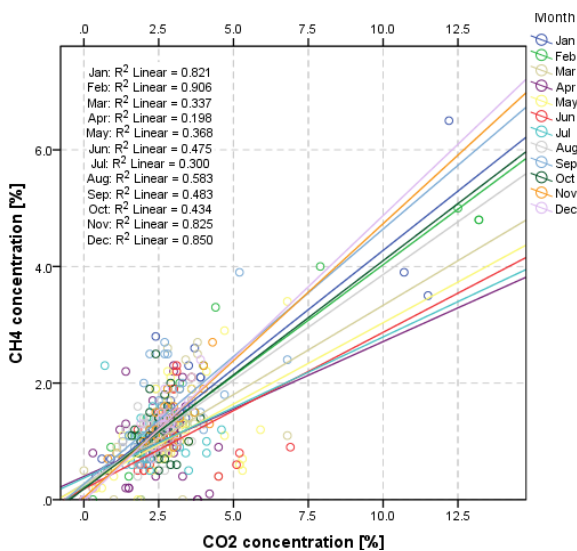


Figure 4. Monthly variation in  $CH_4/CO_2$  ratio between 2003 and 2013

The  $CH_4/CO_2$  ratio also varies over the seasons, although remains fairly stable from November to February, as illustrated in Figure 4. This is confirmed by a strong linear correlation for the 2005-2013 period (with  $r^2$  between 0.821 and 0.906).

### 5.5. Deep gas bores (VP)

Monthly gas composition in VPs was observed to vary significantly throughout the year (Figure 5).  $CO_2$  concentrations increased steadily from the start of the year and is observed to reach a peak at the start of spring, while  $CH_4$  concentrations remained relatively steady until a significant increase (+30%) between July and August. No significant correlation has been identified with meteorological conditions. It appears that the behaviour of LFG in the VPs do not follow the trend identified in the extraction network (Figure 2) which suggest that VPs are more influenced by climate as LFG is not actively extracted.

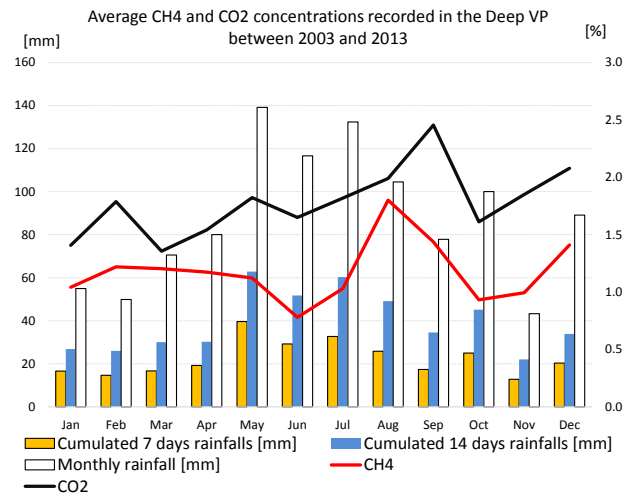


Figure 5. Monthly average gas composition observed in the Deep VP

### 5.6. Building subfloor locations (WP)

When detected, LFG monitored in the building subfloor was found to positively correlate with heavy and long rainfall events. There was a strong correlation between  $CH_4$  (and to a lesser significance  $CO_2$ ) and cumulative rainfall over the 7 or 14 day averages, but no significant correlation with daily or monthly average rainfall.

This result is supported by field monitoring on other sites (Wreford 1995) which highlight that significant cumulative rainfall can cause a shift in the LFG composition, leading to higher  $CH_4$  and lower  $CO_2$ .  $CH_4$  concentrations were generally detected in August (the coldest and wettest month) which is consistent with the LFG trend observed in the deep VP. This can potentially be explained by an increase in the groundwater table, caused by longer

term rainfall events, creating a positive pressure and pushing LFG closer to the groundwater surface. However, once the groundwater level subsides and moisture content of the waste becomes optimal, LFG generation is increased as seen in the VP and later in the extraction wells.

### 5.7. Summary

A review of variations in landfill gas composition (CH<sub>4</sub> and CO<sub>2</sub>) in the various monitoring points across the site and the effect of ambient temperature, precipitation and barometric pressure has identified a significant influence of these parameters on CH<sub>4</sub> and CO<sub>2</sub> production in the landfill. Results indicate that CH<sub>4</sub> and CO<sub>2</sub> concentrations will increase with rainfall and temperature.

Review of LFG within the different types of monitoring points has highlighted different patterns of gas migration over the seasons with:

- summer being a period when CH<sub>4</sub> and CO<sub>2</sub> concentrations remain fairly stable across the entire site;
- winter being a more unstable period, with higher rainfall, showing less CO<sub>2</sub> and CH<sub>4</sub> collected in the extraction network and more uncontrolled LFG migration to the surface (detected in the building subfloor locations).

When daily, cumulative or monthly meteorological data were compared with gas parameters across all monitoring points, it was noted that the longer the time period considered, the better the correlation with the gas parameters. This would suggest that long duration climate events (influencing temperature and rainfall) have a greater influence on the gas regime and composition than short duration (between one and 7 days) and extreme events.

## 6. Perspective in terms of climate change

### 6.1. Context relevant to this assessment

Amongst other effects, it is anticipated by the scientific community (NRC 2011, MfE 2008) that increased concentrations of greenhouse gas are expected to increase Earth's average temperature and influence the patterns and amounts of precipitation.

### 6.2. Direction and magnitude of change in New Zealand

In New Zealand, mean temperatures are expected to increase by 0.2–2.0°C by 2040 and 0.7–5.1°C by 2090 (MfE 2008) with potentially less warming in the spring season. In addition, daily temperature extremes would also vary with fewer cold

temperatures and more high temperature episodes (Parry *et al.* 2007) (along with more days above 25°C) and potential droughts (Mullan *et al.* 2005).

Mean rainfall is expected to vary with season around the country. However, heavier and more frequent extreme rainfalls events are expected (Parry *et al.* 2007). Projected changes in seasonal mean rainfall based on an average over 12 climate models indicate a wetter summer and autumn and a drier spring and winter (MfE 2008).

### 6.3. Conclusions

This paper presents the correlations identified between landfill gas parameters and meteorological conditions over an 8 year period. The implications of this in terms of the possible influence of climate change on future landfill gas emissions has been considered for different climate scenarios, considering potential changes in rainfall and temperature. Significant seasonal behaviours have been identified through this review along with the main drivers that affect the composition and migration of LFG in a closed landfill. This assessment and review also provides useful information on the key parameters that landfill gas emission estimates and gas collection systems would need to take into account when considering the possible influence of climate change.

Based on this review of LFG concentrations with different meteorological parameters, the following hypothesis can be made in terms of potential effects of a change in climate:

- Temperature is the dominant factor influencing LFG production in winter. A drier and warmer winter would lead to an increase in LFG production. In drier conditions, the level of groundwater would also be lower, reducing the amount of LFG observed in shallower monitoring points;
- Drier and cooler spring conditions would tend to reduce LFG produced from the landfill. The reduction could even be more pronounced due to the moisture deficit in the waste following a drier winter;
- Moisture content is a limiting factor in summer and autumn. Therefore increased temperatures and rainfall during that period would tend to increase LFG concentrations in the landfill.

Considering the predicted climate change for NZ, based on this site analysis, the overall emissions from landfill are likely to increase. However, the magnitude of the change has been difficult to estimate due to the heterogeneity of the site and its continuous development.

An increased number of extreme events are expected to occur in future years but only longer duration events (more than 7 days) would

significantly affect the overall LFG composition. It should be noted however that the combination of these events could lead to significant changes in LFG concentrations (i.e. periods of higher rainfall and temperature during a wet and warm summer) which could have an impact on the LFG collection system.

Overall, the analysis indicates LFG concentrations are likely to increase in NZ due to climate change and this should be accounted for in LFG collection systems, management and redevelopment of landfill sites. The magnitude of these changes should be assessed through a site specific assessment taking into account the local meteorology.

## References

- Bogner J. and al, 2007, 'Waste Management, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change' *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA
- Environment Agency (EA), 2004, 'Guidance on the management of landfill gas', LFGN03, *Environment Agency*, Bristol, UK
- Kerr R., 2001, 'Global Warming: Rising Global Temperature, Rising Uncertainty'. *Science* 292 (5515): 192–194.
- NIWA (National Institute of Water and Atmospheric Research), 2013a, Annual climate summaries from 2000 to the present. Web: <http://www.niwa.co.nz/climate/summaries>
- NIWA, 2013b, *Cliflo National Climate Database*, (query carried out on the 14/06/2013)
- NIWA, 2013c, 'Summary climate information for selected New Zealand locations - Data are mean annual values for the 1971-2000 period' in *Cliflo National Climate Database*, (query carried out on the 14/06/2013)
- Randall D.A and al, 2007, 'Climate Models and Their Evaluation' in: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.
- MfE (Ministry for the Environment), 2008, 'Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand'. *2nd Edition. Ministry for the Environment publication number: ME 870*, Wellington. xviii + 149 p
- NRC (US National Research Council), 2011, 'Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia' *US National Research Council. The National Academies Press*, Washington, DC, USA.
- Parry M.L and al, 2007, 'Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change' *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.
- Mullan A.B. and al., 2005, 'Changes in Drought Risk with Climate Change', *NIWA Client Report WL2005-23, prepared for the Climate Change Office, MfE, and the Ministry of Agriculture and Forestry*. 56p.
- Rubel, F., and M. Kottek, 2010, 'Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification', *Meteorologische Zeitschrift*, 19, 135-141
- IPCC (Intergovernmental Panel on Climate Change), 2006, 'Guidelines for National Greenhouse Gas Inventories', Prepared by the National Greenhouse Gas Inventories Programme, IGES, Japan
- US EPA, 2010, 'Landfill Gas Energy Project Development Handbook', Prepared by the Landfill Methane Outreach Program, 9/8/10
- Wreford, K., 1995, 'An analysis of the factors affecting landfill gas composition and leachate characteristics at the Vancouver landfill sit at Burns Bog', *The University of British Columbia*, December 1995
- Wreford, K. A., Atwater, J. W. and Lavkulich, L. M. (2000), 'The effects of moisture inputs on landfill gas production and composition and leachate characteristics at the Vancouver Landfill Site at Burns Bog. *Waste Management and Research*, 18: 386–392.

# Appendix 1

| LFG parameters assessed in the treatment plant inlet |                             | Cumulative rainfall over a seven days period | Cumulative rainfall over a fourteen days period | Average monthly rainfall        | Spot value of earth temperature at 5 cm depth at 9am local | Dry air temperature recorded at 9 am | Daily atmospheric pressure      |
|--|-----------------------------|--|---|---------------------------------|--|--------------------------------------|---------------------------------|
| CH4  | between individual readings | $r_s = -0.231, n=446, p < 0.001$             | $r_s = -0.359, n=446, p < 0.001$                | -                               | $r_s = 0.195, n=203, p = 0.005$                            | $r_s = 0.139, n=529, p = 0.001$      | -                               |
|  | between monthly average     | $r_s = -0.626, n=12, p = 0.030$              | -   | $r_s = -0.708, n=12, p = 0.010$ | -  | $r_s = 0.669, n=12, p = 0.017$       | -                               |
| CO2  | between individual readings | $r_s = -0.175, n=446, p < 0.001$             | $r_s = -0.250, n=446, p < 0.001$                | -                               | $r_s = 0.401, n=203, p < 0.001$                            | $r_s = 0.181, n=529, p < 0.001$      | -                               |
|  | between monthly average     | $r_s = -0.421, n=12, p = 0.183$              | -   | $r_s = -0.558, n=12, p = 0.059$ | -  | $r_s = 0.739, n=12, p = 0.006$       | -                               |
| O2   | between individual readings | -  | -   | -                               | $r_s = -0.506, n=203, p < 0.001$                           | -                                    | -                               |
| CO2/CH4 ratio  | between monthly average     | $r_s = -0.526, n=12, p = 0.079$              | -   | $r_s = 0.537, n=12, p = 0.072$  | -  | -                                    | $r_s = 0.212, n=200, p = 0.003$ |
| Gas temperature                                      | between individual readings | $r_s = -0.164, n=266, p = 0.007$             | $r_s = -0.197, n=266, p = 0.001$                | -                               | $r_s = 0.412, n=152, p < 0.001$                            | -                                    | -                               |

| LFG parameters assessed in the building subfloor locations |                             | Cumulative rainfall over a seven days period | Cumulative rainfall over a fourteen days period | Spot value of earth temperature at 10cm depth at 9am local | Minimum temperatures over 24 hours to 9am local | Maximum temperatures over 24 hours to 9am local |
|--|-----------------------------|--|---|--|---|---|
| CH4  | between individual readings | $r_s = 0.105, n=62172, p < 0.001$            | $r_s = 0.106, n=62172, p < 0.001$               | -  | -   | -   |
|  | between monthly average     | $r_s = 0.508, n = 12, p = 0.092$             | $r_s = 0.609, n = 12, p = 0.036$                | $r_s = -0.682, n = 12, p = 0.015$                          | $r_s = -0.638, n = 12, p = 0.026$               | $r_s = -0.580, n = 12, p = 0.048$               |
| CO2  | between monthly average     | $r_s = 0.545, n = 12, p = 0.067$             | $r_s = 0.503, n = 12, p = 0.095$                | -  | -   | -   |

Note: (rs) indicates the value of the Spearman correlation coefficient (n) indicates the number of pairwise cases (p) value indicates the significance (-) indicates that no significant correlation have been highlighted

Table 2: Selected statistical analysis between the different meteorological parameters and the LFG composition monitored on site.

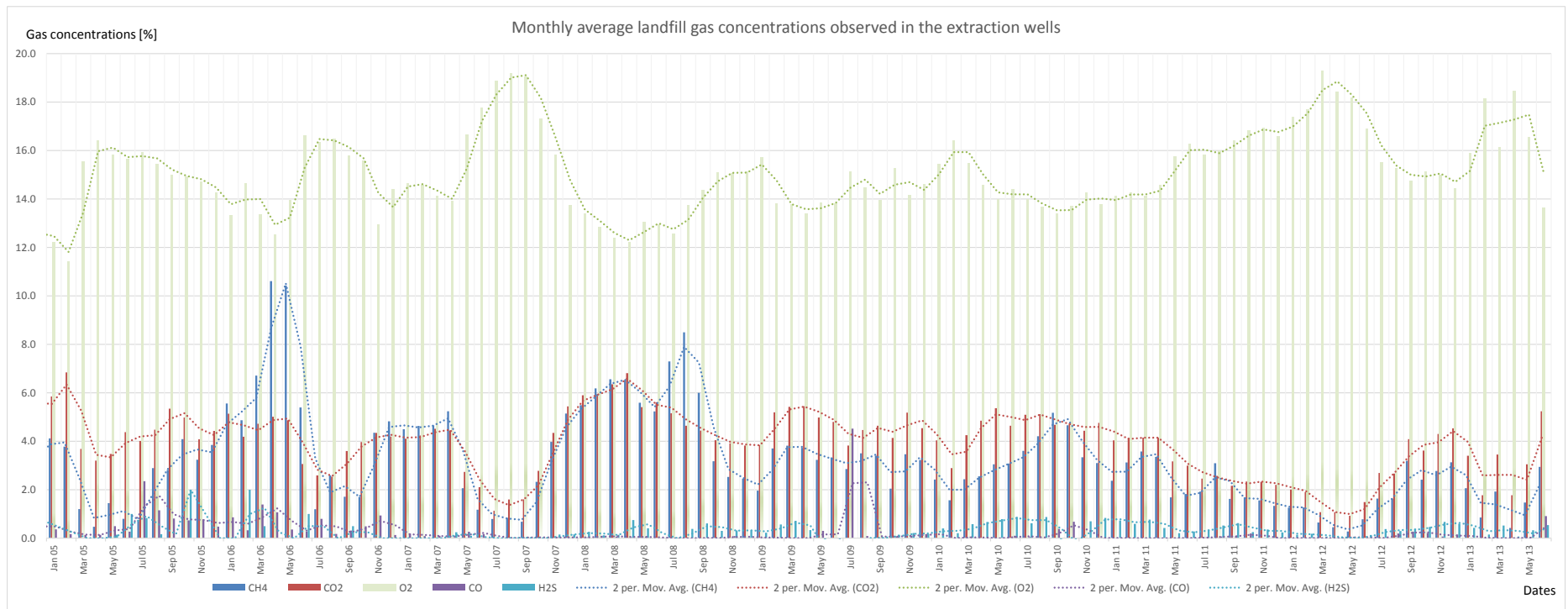


Figure 6. LFG composition from the Extraction Wells observed over time