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FACTORS GOVERNING LATERAL GAS MIGRATION AND SUBSEQUENT EMISSION IN SOIL ADJACENT TO AN OLD LANDFILL

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ABSTRACT

Field experiments investigating lateral gas transport and subsequent emission in soil adjacent to an old landfill in Denmark during a one-year period were conducted. A significant seasonal variation, with low concentrations/emissions of methane and high concentrations/emissions of carbon dioxide in the summer, caused by methane oxidation was observed. There was a good correlation between pressure above the barometric pressure and the methane concentration in the soil, indicating that advective flow was the controlling process. Diurnal measurements during a drop in barometric pressure showed that the fluxes of landfill gas changed dramatically within a very short time. The experiments showed that change in barometric pressure was an important factor affecting gas migration at the Skellingsted landfill in Denmark. Statistical analyses proved that soil moisture described the largest part of the variation in the carbon dioxide emissions. No methane at all emitted during the summer.

Keywords: landfill gas, lateral migration, methane emission, carbon dioxide emission, field investigation, seasonal variation, advective flow, barometric pressure, Denmark.

1. INTRODUCTION

The migration and emission of landfill gas (LFG) may potentially lead to negative effects in the surroundings (Kjeldsen, 1996). The main environmental hazards related to LFG are believed to be the explosion hazards and the global climate effects.

Many factors and processes affect landfill gas migration. Several investigations of landfill gas migration have demonstrated that both diffusive and advective transport can be important processes (Ghabaee & Rodwell, 1989; Williams & Aitkenhead, 1991; Hodgson et al., 1992; Williams et al., 1999). Diffusional fluxes are caused by variations in gas concentrations in the soil and advective fluxes are caused by a pressure gradient. Diffusional flux will always be present because the concentration of LFG in atmospheric air is very low. The pressure inside the landfill can be quite high and can result in a large pressure gradient. Changes in barometric pressure can change the pressure gradient.

In northern Europe many landfills are situated in old gravel pits with no liners, so there is direct contact between the waste and the sandy soil layers. Waste has been compacted at many landfills and heavy soils have often been used as a daily cover. This can create horizontal barriers within the waste. In the last decades, many landfills have been covered with low permeability materials (e.g. clay) to minimise the leachate production. All these circumstances encourage lateral gas migration – especially at landfill sites without liners.

Landfill gas has been measured in soil adjacent to landfills at several sites (Raybould & Anderson, 1987; Williams & Aitkenhead, 1991; Hodgson et al., 1992; Kjeldsen & Fischer, 1995; Boltze & de Freitas, 1997), and many investigations have showed that meteorological conditions have a great influence on gas transport (Williams & Aitkenhead, 1991; Jones & Nedwell, 1993; Kjeldsen & Fischer, 1995; Börjesson & Svensson, 1997; Bogner et al, 1999). Ward et al. (1996) studied the lateral migration of LFG at Foxhall Landfill. They defined the gas plume, but did not look at the factors controlling the gas migration.

The objective of this study was to investigate lateral gas migration and subsequent emissions in soil adjacent to an old unlined municipal landfill, in order to determine the most important controlling factors.

2. FIELD LOCATION

Skellingsted landfill, which is located south of Holbæk, Western Sealand, Denmark, see Figure 1a, received waste between 1971-90. In total, approximately 420,000 tonnes of waste were disposed of at the site, which covers an area of 7.5 ha. The composition of the waste is approximately 60% solid municipal waste and 40% bulky waste, industrial waste and sewage treatment sludge (Kjeldsen & Fischer, 1995).

The landfill is situated in an abandoned gravel pit located in an area of alluvial sand and gravel sediments. The thickness of the unsaturated zone in the soils adjacent to the landfill varies between 10-20 m. When the landfill was closed, it was covered with a soil layer consisting of approximately 80 cm sand and 20 cm topsoil and the landfill was planted with grass, trees and bushes.

3. METHODS

Sampling equipment was installed along two transects consisting of nine measuring stations each, at the Skellingsted landfill – see Figure 1b. Transect Field was installed in an area with pronounced crop damage – see Figure 1d. Transect House was installed close to the only still-existing house at section "C" – see Figure 1c.

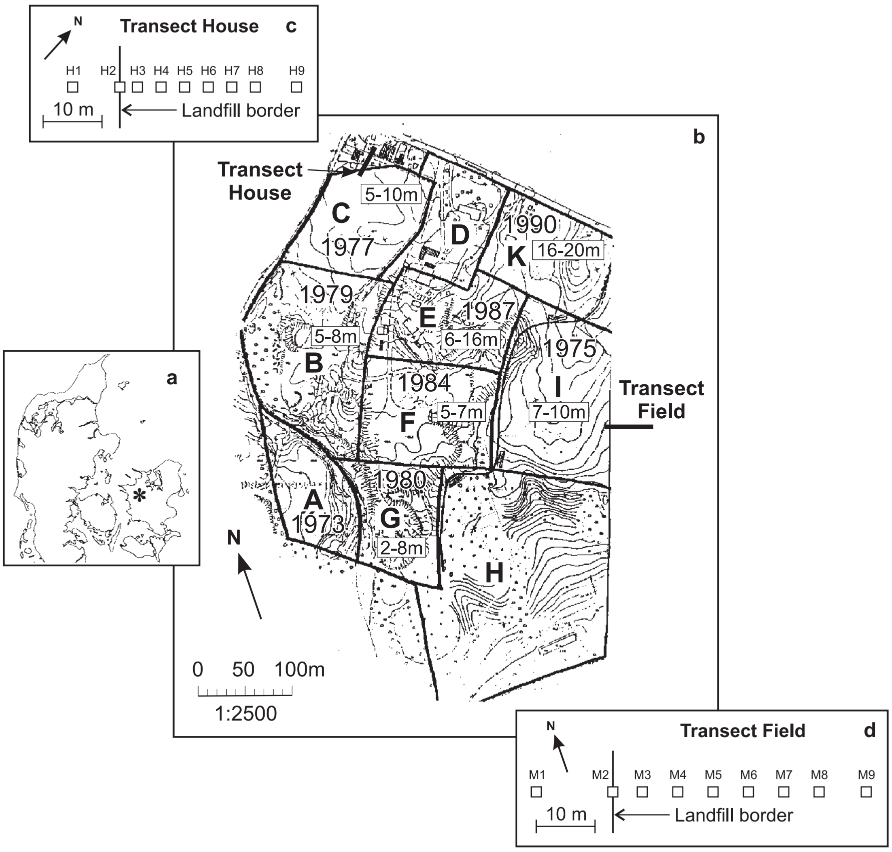

Figure 1. (a) The geographical location of Skellingsted landfill in Denmark. (b) Map showing the sections of the landfill. The year of closure and estimated waste depth in each section is given where available. (c) Detailed map of the measuring stations in transect House. (d) Detailed map of the measuring stations in transect Field. In both transects the measuring stations consisted of a flux chamber, 6 soil gas probes and 5 pairs of probes to measure the soil moisture content.

The first station (M1 and H1) of each transects were located in the top cover of the landfill. Station M2 and H2 were located at the landfill border. The subsequent 7 stations were located along a straight line at increasing distance from the landfill. Each of the 18 measuring stations consisted of a stationary flux chamber, soil gas probes and probes to measure the water content.

The soil gas probes were small steel tubes (10 mm ID) of different lengths, which were closed at the bottom and provided with slits at the lower end before being hammered into the ground. At each measuring station there were soil gas probes to measure the gas composition and the pressure difference at 10, 20, 40, 60, 80 and 100 cm below surface (b.s). Simultaneous to measuring the fluxes gas samples were taken from the soil gas probes and soil and air temperatures were measured at the station.

Simple static flux chambers were used to measure the flux of landfill gas through the ground surface. The flux chambers consisted of the top 20 cm of a metal drum (60 cm inner diameter) with a lid. The sides of the drum were pressed 6 cm down into the ground and sealed with bentonite slurry. To ensure mixing of the air in the flux chamber the lid was provided with a battery operated propeller. When flux measurements were made, the lid was placed on the drum and tightened with a clamp. Immediately after the gas composition in the chamber was analysed with a portable gas chromatograph (Chrompack Micro GC, Middelburg, The Netherlands).

The volumetric water content was measured by use of Time Domain Reflectometry, which measures the dielectric constant. The average volumetric water content over the depth was then calculated using an empirical relationship between the dielectric constant and the volumetric water content developed by Topp et al. (1980). The probes used to measure the volumetric water content consisted of steel bars (6 mm diameter) of different lengths (20, 40, 60, 80 and 100 cm) which were, two by two, hammered into the ground parallel to each other.

Measuring campaigns were conducted every second week from May 97 to May 98. Meteorological data regarding precipitation, barometric pressure and daily temperatures were obtained from the Danish Meteorological Institute from nearby measuring stations.

4. RESULTS AND DISCUSSION

4.1. Seasonal variations in gas migration

Figure 2 shows the methane concentrations at 20, 60 and 100 cm b.s. at station M6, 23 m from the landfill border, together with the temporal variation in temperature, and soil moisture content. The soil moisture content depicted at Figure 2 is the average volumetric moisture content over depth. The average soil moisture content shows the expected seasonal variation with higher moisture content in the winter. Tendencies of increasing methane concentrations at high soil moisture content were observed. The correlation between the methane concentration at 100 cm b.s. and the soil moisture could explain 63% of the variations.

The average concentrations and standard deviations were calculated for each station at 100 cm b.s. in both transects for the summer (May to October) and winter (November to April) in order to get a better overview of the seasonal variations in the data. The concentrations at 100 cm b.s. were selected for the comparison to minimise the influence of changes in barometric pressure, which decrease with increasing depth. Close to the landfill the concentration of methane was significantly lower and the concentration of carbon dioxide was significantly higher in the summer compared to the winter. The seasonal variation was caused by oxidation of methane to carbon dioxide, which is a temperature dependent process. Methane oxidation was occurring throughout the year, but more methane was oxidised in the summer.

The concentration of both methane and carbon dioxide were significantly lower in the summer further away from the landfill border. During the winter, the soil moisture content was higher especially in the topsoil and that reduced the vertical gas permeability and increased the lateral migration distance.

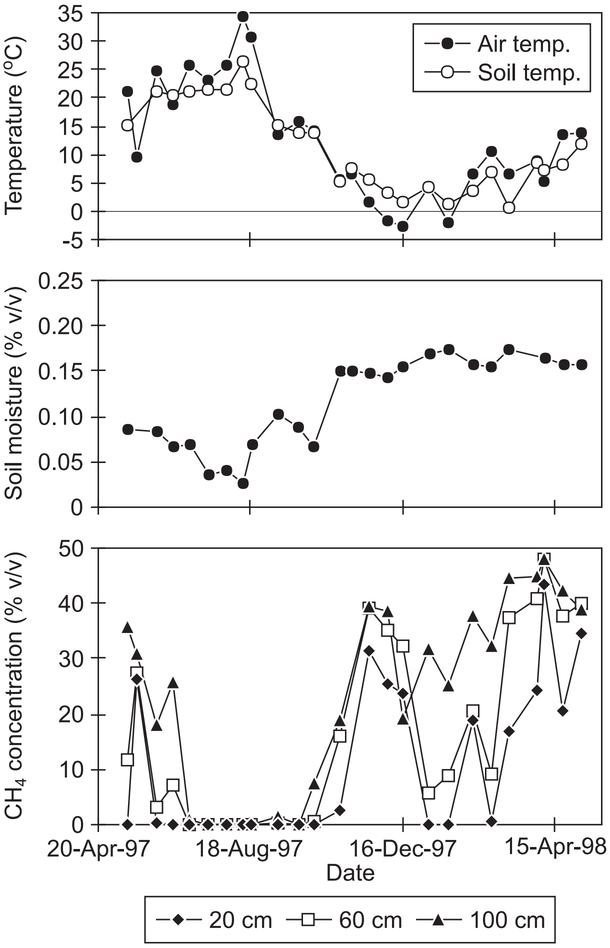

Figure 2. Methane concentrations at 20, 60 and 100 cm below surface at station M6 in transect Field, 23 m from the landfill border. Air and soil temperature (10 cm b.s. at station M6), and soil moisture content (averaged over depths at station M6) are also shown.

Pressure above barometric pressure was measured in the soil in areas, which was affected by landfill gas during the measuring period. This indicated that advective flux was important for the gas migration. That is consistent with calculations comparing advective and diffusive flux in sandy soils, which showed that very small pressures above barometric pressures would give advective flux higher the diffusive flux (Christophersen & Kjeldsen, 2000).

4.2. Seasonal variation in gas emissions

The maximal methane flux was 189 mmol/m^2/h while the average flux at each station was between <0.5 and 25 mmol/m^2/h. The maximal carbon dioxide flux was 205 mmol/m^2/h and the average flux at each station was between 5 and 69 mmol/m^2/h. The maximal methane flux is much higher than found by Maurice & Lagerkvist (1997) and Meadows et al. (1999), who also were investigating smaller and older European landfills. This can be explained by the more frequent flux analysis in the present investigations.

In order to evaluate the seasonal variations, the fluxes out through each of the transects on each measuring date were summarised by linear interpolation between the stations. Figure 3 show the summarised fluxes at transect Field. The summarised fluxes have the units mol pr. m of landfill border pr. hour. The fluxes of methane were added to the carbon dioxide flux and are depicted in the figures as LFG flux. The gas production at section "I", where transect Field started, have previously been estimated to be 8-22 Nm^3/h in 1997-98

(H.C. Willumsen, pers. com., 1999). Assuming that 40-60% of the LFG from section "I" is transported laterally out of the landfill, this gives 0.9-3.7 mol LFG/m/h. Figure 3 illustrates that these values are in the same range as the measured LFG fluxes, although the LFG fluxes measured in the winter were slightly lower.

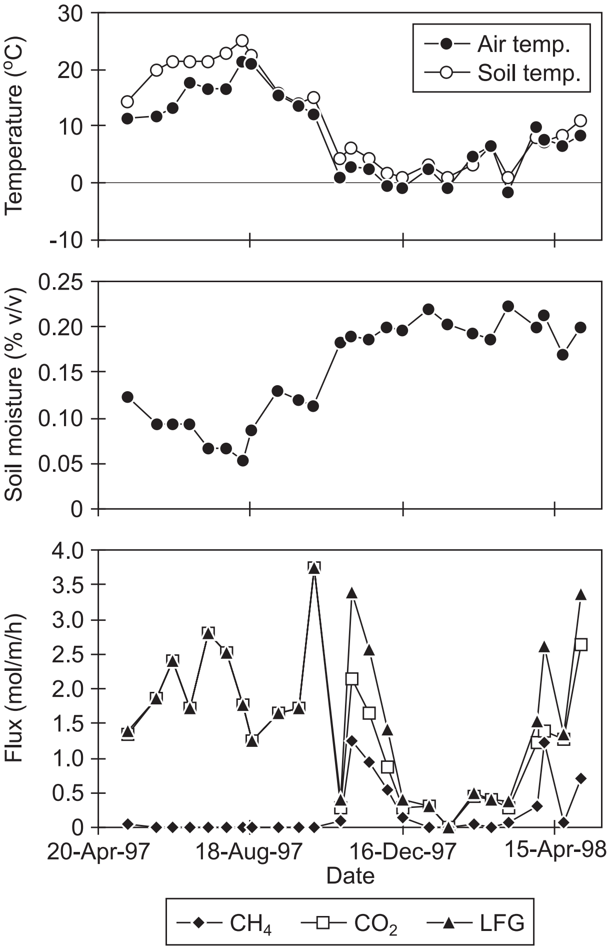

Figure 3. The summarised fluxes of methane, carbon dioxide and landfill gas (LFG) (mol pr. m of landfill border pr. hour) at transect Field as a function of time. Temporal variations in the averaged daily air temperature, the averaged soil temperature at 10 cm b.s., and the average volumetric soil moisture content are also shown.

Because the gases of interest are microbially produced and consumed, temperature and soil moisture would be expected to have a major influence. Figures 3 also show the averaged daily air temperature, the averaged soil temperature at 10 cm b.s., and the average volumetric soil moisture content. For both transects there was a significant seasonal variation in methane emissions (student t-test, P=0.02 and 0.009 for transect Field and House respectively) with higher fluxes in the winter (November to April) compared to the summer (May to October). The seasonal variation for carbon dioxide emission was the opposite with significantly higher carbon dioxide emissions in the summer compared to the winter (P=0.0007 and 0.04 for transect Field and House respectively). The higher soil temperature in the summer leads to substantial oxidation of methane to carbon dioxide. It can be seen from Figure 3 that the highest methane emissions occurred during the fall and spring. This was also observed by Maurice & Lagerkvist (1997) at a small landfill in northern Sweden. In general, the flux of carbon dioxide was higher than the methane flux. When the summarized carbon dioxide fluxes were correlated with air and soil temperatures there was a linear relationship with R^2

between 0.24 and 0.46. When the carbon dioxide flux was compared with soil moisture there was an inverse relationship with $R^2 = 0.39$ and 0.16 for transects Field and House respectively. This shows that both temperature and soil moisture have some influence on the emissions.

To obtain an estimate of the gas production the fluxes of methane and carbon dioxide were added giving the LFG flux. There appears to be a seasonal variation in the LFG flux with higher fluxes in the summer (Figure 3). At transect Field there was a significantly higher ($P=0.03$) LFG flux in the summer when the temperatures were higher and the soil moisture content lower. This has been observed at other smaller, older landfills in Denmark and it is probably caused by changes in temperature and moisture content, which can have an effect on the gas production at landfills with waste heights of less than 10 m. (H.C. Willumsen, pers. com., 2000). Methane oxidation and dissolution of carbon dioxide in infiltrating water can cause some variation in the LFG.

To evaluate the factors influencing the fluxes analyses of covariance, which can include both qualitative and quantitative variables, were conducted. In transect Field 82% of the variations in the carbon dioxide fluxes could be described with a model including the variable “station”, which tells something about the distance from the landfill, gas concentrations, soil moisture content and pressure above barometric pressure in the upper soil layers, temperature, barometric pressure and precipitation (Christophersen et al., 2000). Soil moisture content was the factor describing the largest part of the variation in the fluxes. The statistical analysis was not conducted for the methane fluxes due to many observations below the detection limit of 0.5 mmol/m^2/h.

4.3. Diurnal variations

Based upon a forecast of decreasing barometric pressure an intensive measuring campaign was conducted between October 29th 6 p.m. and October 31st 1 p.m. 1999. At transect House fluxes, soil gas concentrations and temperatures were measured approximately every three hours at stations H4, H5, H6 and H7, 7, 11, 15 and 19 m respectively from the landfill border. Figure 4 shows the methane and carbon dioxide fluxes as a function of time. No rain fell during the measurement period, and the average volumetric soil moisture content was 16%.

The drop in barometric pressure was not very pronounced (on average -0.8 mbar/h from October 29th 11 p.m. to October 31st 4 a.m.), but it clearly had an influence on the fluxes. For comparison, the gas explosion at Loscoe occurred within a depression of -4 mbar/h (Williams & Aitkenhead, 1991). The explosion at Skellingsted occurred during a drop in pressure of 0.6 mbar/h, but the pressure had been falling for 3 days (Kjeldsen & Fischer, 1995). The pressure decrease observed in this study led to an increased vertical transport of landfill gas. At station H5 the methane flux increased from below the detection limit of 0.5 mmol/m^2/h to 196 mmol/m^2/h within 14 hours, which was the highest methane flux ever measured at transect House. The carbon dioxide flux never exceeded the background level at station H7, but at stations H4, H5 and H6 the changes in carbon dioxide fluxes were dramatic: the highest measured carbon dioxide fluxes during the one year investigation period were recorded. For both the methane and carbon dioxide fluxes the increase were first observed at station H4 followed by station H5 and then station H6. This was expected due to the differences in migration distance between the landfill and the stations. In general, there was a very good correlation between the gas migration (Christophersen & Kjeldsen, 2000) and the fluxes during the diurnal measurements. An increase in the gas concentration in the soil was followed by an increase in gas emissions. These diurnal measurements clearly show that the fluxes of LFG can change dramatically within a very short time and that LFG fluxes are very dependent on changes in barometric pressure.

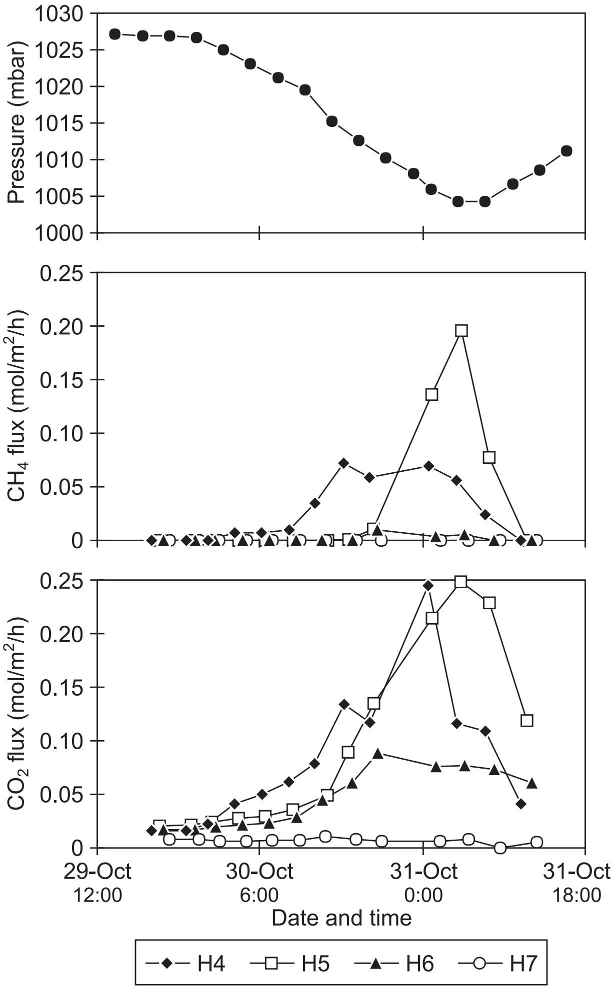

Figure 4. The flux of methane and carbon dioxide as a function of time during the diurnal measurements at stations H4, H5, H6 and H7, 7, 11, 15 and 19 m respectively from the landfill border at transect House. Barometric pressure is shown at the top of the figure.

5. CONCLUSIONS

This field investigation of the lateral gas transport and subsequent emission in soil adjacent to an old landfill in Denmark showed a significant seasonal variation in the concentration of landfill gas in the soil. Close to the landfill the concentration of methane was significantly lower and the concentration of carbon dioxide was significantly higher in the summer (May to October) compared to the winter (November to April). The concentration of both methane and carbon dioxide were significantly lower in the summer further away from the landfill border. During the winter, the soil moisture content was higher especially in the topsoil and that reduced the vertical gas permeability and increased the lateral migration distance.

The two transects with measuring stations perpendicular to the landfill border showed extremely variable emissions of methane and carbon dioxide. A significant seasonal variations in the emissions was observed, with high carbon dioxide and low methane fluxes in the summer and a lower flux of carbon dioxide and a higher methane flux in the winter. This was mainly caused by methane oxidation, which is temperature dependent. In general the flux of LFG was higher in the summer.

There was a good correlation between pressure above the barometric pressure and the methane concentration in the soil, indicating that advective flow was an important process at the Skellingsted landfill. This was confirmed by calculations comparing diffusive and advective methane fluxes in a sandy soil, which showed that advective methane flow was much more important than diffusive methane flow.

Diurnal measurement during a drop in barometric pressure showed that lateral migration and subsequent emission of landfill gas from the Skellingsted landfill was a very dynamic system. The methane and carbon dioxide fluxes changed dramatically within a very short time and the fluxes are strongly dependent on changes in barometric pressure. The advective flow increased during the barometric depression leading to a substantially higher LFG migration. The experiments showed that change in barometric pressure is an important factor affecting gas migration at the Skellingsted landfill. This finding makes it difficult to evaluate the explosion risk because it is uncertain how far methane would migrate from the landfill during a steeper decrease in barometric pressure.

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