LFG emission measurements in arctic climatic conditions

Seasonal variations and methane emissions mitigation

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Abstract
Landfill gas emissions were measured at three landfills in Northern Sweden. A seasonal variation of the emissions could be observed. Variations in the methane oxidation are believed to at the origin of those variations i.e. low temperatures and low water content in the soil reduce the methane oxidation activity.

1 Introduction

Northern Scandinavia has a low population density, and the long distances between the cities lead to the construction of relatively small landfills. With a 6-month long winter, temperatures down to between minus 30-35°C during winter, and a temperate summer, the climatic conditions in this region also lead to low temperatures in the top cover of the landfills as well as in the landfill interior (Lagerkvist 1991).

LFG (Landfill gas) emissions are highly variable (Börjesson & Svensson 1997, Maurice et al 1995). Several processes may be at the origin of those variations:

- The amount of LFG available for emission may be influenced by the LFG production, the degradation activity, and the abstraction levels if the site is equipped with an LFG collection.
- The LFG flow may also be influenced by the air pressure variation, and the soil conditions, e.g. the water content in the pore volume or frizzing of the soil. Emissions may be delayed when the air pressure increases or the gas pore volume decreases.
- The LFG quality depends on the waste composition, but also on the methane oxidation activity that will decrease the methane concentration in the emitted gas.

Those processes result in diurnal, seasonal, and spatial variations of the emissions that lead to difficulties when measuring and estimating the emissions.

LFG emissions from such landfills situated in arctic regions are difficult to estimate because of the long winter period. The cold temperatures and snow cover make both the measurement procedures and the estimation of LFG emissions difficult.

Even in cold climate areas, the surface of bio-active landfills will rarely cool down much below 0°C and the seasonal temperature variations in the waste is fairly small compared to the atmospheric temperature variations. In a test cell studied in North Sweden, the temperature was observed to be fairly constant at a 4-meter depth (Lagerkvist 1991). Börjesson & Svensson (1997), measuring LFG emissions during a one-year period on a landfill in Southern Sweden, recorded lower methane emissions during both the winter when snow covered the landfill surface and during the summer. These low emission levels were explained by the formation of an ice layer preventing gas emissions during the winter and by the oxidising activity during summer.

This article presents results from three projects that were conducted at different landfills in Northern Sweden and Finland. The aspects that have specially been studied are:

- Strategies to measure LFG emissions from snow covered landfills
- Methane and carbon dioxide emissions
- Seasonal variation of the emitted LFG quality
- Oxidation capacity of the soil cover

2 Methods

2.1 Presentation of the sites

- *Site 1:* LFG emissions from a test cell were monitored for a one-year period, from February 1996 to March 1997, at the landfill of the city of Luleå, in Northern Sweden (65.6 N – 22.0 E). Methane and carbon dioxide emissions and temperatures in the top cover of the test cell were measured monthly. LFG probes were also used to sample gas in the soil profile (see Bergman et al 1993). The test cell contains a 3-meter thick layer of waste below a 1.2-meter thick soil cover. Temperature probes were installed in the cell and the cover.

- *Site 2:* LFG emissions from the city of Kemi landfill, in Northern Finland (65,7 N – 24,7 E), were measured on three occasions. The measurement campaigns took place during the late summer, the winter, and the spring. The soil cover on the slope of the landfill was very thin and sometimes missing. The variations of the LFG emissions were investigated. The oxidation capacity of the soil was also measured in laboratory experiments.

- *Site 3:* The seasonal variation of the mitigation of the methane emissions in a biofilter was investigated at the landfill in the city of Umeå, also in Northern Sweden (63.8 N, 20.3 E). Field measurements were done in the biofilter during the period August 1998 to March 2000. The biofilter (2 x 5 x 1 m) was filled with soil (Maurice & Lagerkvist 1999) and the LFG was collected on the top of the landfill over an area of about 150 m^2. A pump redistributed the gas into a 5-meter long pipe dug at a depth of 1 m in the filter with a flow of 6 l/min. The second part of the filter is a reference that does not receive any LFG, neither from the pipe nor from the landfill below.

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2.2 Measurement strategy and techniques

LFG emissions were measured using the static chamber techniques (Bergman *et al* 1993; Maurice *et al* 1995). During the winter, several strategies were tested to measure the LFG emissions. Measurements were done at the top of the snow cover and at the soil surface after removing the snow. Gas samples were analysed using an infrared acoustic multi-gas monitor during the first investigations while gas chromatography was used for the more recent investigations.

2.3 Laboratory measurement of methane oxidation

The "Methane Oxidation Capacity" (MOC) of the investigated soils was assessed by the pressure decrease induced by the oxidation (Maurice & Lagerkvist 1999) and was investigated in batch tests. A soil sample of 15 g is placed in a 330-ml glass bottle. The bottle is closed, 50 ml of air is extracted and 50 ml of oxygen and 25 ml of methane are added to the bottle. The pressure in the bottle is automatically registered for about one week.

3 Results

Site 1: The results from the LFG emission monitoring done at the test cell are presented in table 1. Methane emissions were only observed during the late winter when the soil surface was frozen. During the summer and autumn no methane emissions could be detected. However, carbon dioxide emissions were observed throughout the entire year. In May, just after the snow-melting period, a high peak was registered. The emission rate increased during the summer from 300 to about 700 mol/m^2/year. During the autumn and winter, the emissions have been low with the exception of the measurements made in February 1997.

In March 1996, the snow layer was about 40 cm thick on the test cell and the soil surface, where large temperature gradients occur, was frozen.. During sunny days, the soil surface is warmed up while the soil underneath is still frozen. In the summer, temperatures as high as 25 °C are reached.

Table 1 Results from the gas emission measurements during the period 7 March 1996 to 21 February 1997. Gas emissions in m^3/m^2 year

Datum	7/03	17/05	25/06	27/06	30/07	28/08	10/10	23/10	27/11	18/12	21/02
	CO_2 emission rate										
Numb. obs.	9	11	12	6	10	8	3	3	3	3	12
Mean	0,2	20,1	6,8	8,8	14,5	16	1,5	1,8	8,2	3,8	16,8
Std. Dev.	0,1	11,3	6,4	6,4	6,6	4,3	1,3	1,1	6,6	3,0	6,5
Min.	8	401	66	122	246	507	21	41	43	25	288
Max.	16	2169	1121	826	1007	1120	131	133	616	287	1197
	CH_4 emissions										
Numb. obs.	9	11	12	6	10	8	3	3	3	3	12
Mean	0,4	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	1,0
Std. Dev.	0,5	-	-	-	-	-	-	-	-	-	0,8
Min.	0,04	-	-	-	-	-	-	-	-	-	0,3
Max.	1,6	-	-	-	-	-	-	-	-	-	2,7

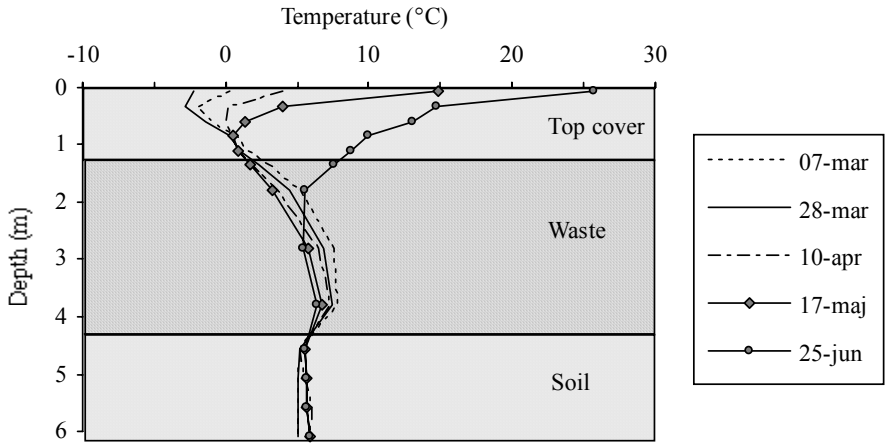

Figure 1 Temperature profile in the test cell during the first half of the year.

Site 2: LFG measurements were done on three separate occasions at Kemi Landfill: end of the summer, end of the winter, and early spring. In April, melting water had been accumulating on the top of the site. Therefore, measurements were not possible at points 1-00, 2-00, and 2-25. On the slopes of the landfill, the snow cover was between 50 and 100 cm thick. No water accumulated on the slopes and the soil was thawing at points 1-30 and 1-35. Methane emissions were measured at three points and could further be observed at five more points. One month later, no methane emissions could be observed. Methane emissions were also measured during the August-measurement campaign. They were measurable at each sample even though they were one order of magnitude lower than the carbon dioxide emissions.

Carbon dioxide emissions, significantly higher ($p<0.01$) in May compared to April, could be observed during each measurement campaign. The emission levels were of the same order of magnitude on the three occasions.

Table 2 Results from field measurements of LFG emissions in m^3/m^2 y.

Date	**1999-08-20**		**2000-04-17**		**2000-05-15**		**MOC**
Sample	**CO_2**	**CH_4**	**CO_2**	**CH_4**	**CO_2**	**CH_4**	**mol/y kg TS**
1-00	5.95	0.21	Water	Water	5.68	<0.2	3.59
1-10	4.29	0.12	2.71	0.69	3.61	<0.05	5.31
1-20	6.92	0.89	2.16	<0.2	3.20	<0.05	13.24
1-30	2.07	0.47	1.58	<0.2	4.77	<0.05	3.96
1-35	4.45	0.12	2.24	<0.2	2.73	<0.05	2.39
2-00	5.95	0.21	Water	Water	5.68	<0.05	3.59
2-25	6.12	0.04			5.17	<0.05	6.64
2-50	2.56	0.12	1.61	0.58	3.30	<0.05	3.95
2-75	34.05	0.23	2.11	<0.2	3.85	<0.05	6.47
2-100	4.95	0.62	2.32	0.56	2.87	<0.05	1.66
2-125	9.64	0.19	1.89	<0.2	3.39	<0.05	5.25

<0.2: Traces of methane could be observed during the analysis but the levels were too low to calculate the emission level.

<0.05. No trace of methane could be observed in the LFG. The detection limit of the measurement method is 0.05 m^3/m^2 year

The results of methane oxidation tests show an oxidation capacity between 1.66 and 13.24 mol/y kg TS (se last column in table 2).

Site 3: The LFG injection in the biofilter began at the end of February 1999. Only in the sample taken above the gas pipe where LFG is released (see table 3) could methane emissions be observed. Carbon dioxide was observed at the four sampling points, but the emissions were highest on the samples taken close to the pipe, *i.e.* samples 1 and 2 (see table 3).

LFG emission measurements from sample 1 revealed that methane was emitted.

- Methane emissions were observed at the end of the winter after the gas injection started.
- During the first part of the summer, no methane emissions could be observed.
- During late summer and autumn, a methane emission peak was observed.
- Carbon dioxide emissions were high from May to November.

The methane content of the collected LFG varied between 5 and 10 % during the investigation period and the carbon dioxide content varied between 10 and 20%.

Table 3 LFG emission measured at the 4 sampling points in m^3/m^2 y.

Sample	LFG emissions measurement											
	1998		1999								2000	
	Sep	Oct	Nov	Feb	Mar	Apr	May	Jun	Aug	Oct	Nov	Jan
1, soil												
CO_2	6.9	3.4	2.8	<0.05	1.1	0.3	7.2	10.3	24.2	16.4	12.0	1.8
CH_4	<0.05	<0.05	<0.05	<0.05	1.5	0.1	<0.05	<0.05	8.0	7.4	<0.05	1.0
2, slag												
CO_2	7.3	4.3	<0.05	<0.05	0.5	<0.05	3.8	7.5	9.4	13.3	17.8	<0.05
CH_4	<0.05	<0.05	<0.05	<0.05	0.4	<0.05	<0.05	<0.05	0.3	0.1	<0.05	<0.05
3, soil												
CO_2	17.0	0.9	<0.05	<0.05	0.1	<0.05	2.1	5.7	7.5	4.2	2.4	
CH_4	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.1	<0.05	<0.05	
4, slag												
CO_2	3.6	0.9	<0.05	0.1	<0.05	<0.05	<0.05	3.1	5.8	3.8	6.8	
CH_4	<0.05	<0.05	<0.05	<0.05	0.1	<0.05	<0.05	<0.05	0.1	<0.05	<0.05	

Table 4 Results from the MOC batch test. The experiments were made with two replicates.

Sample	Depth	TS	LOI	Oxidation start	Oxid rate	St.dev
	cm	%	% TS	day	mol yr^{-1} kg^{-1}TS	
1	10	92	7,5	1,5	8,1	1,98
1	30	88	8	1,5	4,2	0,57
2	10	89	6,7	2	2,85	0,21
3	10	81	8,3	2	5,9	0,42
3	30	81	10,7	2,5	4,55	1,63
4	10	89	7,8	2,5	2,8	0,00

The results of the methane oxidation capacity are in the same order of magnitude as those obtained with the soils from the landfill at Kemi (see table 2 & 4).

4 Discussion

LFG emissions were measured with static chambers. When the soil surface was covered with snow, attempts were made to measure the emissions on the top of the snow cover and to compare it with the emissions measured from the ground surface.

It appeared that the best way was to remove the snow and measure directly at the landfill surface. LFG emissions also occur through the snow cover; however, the snow cover is disturbed when walking to the sampling point and when installing the chamber. Moreover, the snow built a hard top crust due to the melting/freezing succession at the end of the winter. Below the crust, dry and fluffy snow works as gas drainage and any channel done by the footsteps from walking on the site will lead the LFG into the atmosphere. Consequently, emissions through the cover will be affected by those preferred pathways. Measurements through the snow cover were, therefore, abandoned and the chambers were placed directly on the soil surface. This also makes it possible to verify if an ice layer has formed on the soil surface.

LFG probes were not usable during winter. They have to be installed before the soil freezes, and there is a greater risk that water will get inside the probe and turn to ice when the winter begins. Sampling will then be impossible with ice in the tubes. Inserting the probes after the soil froze was also not possible because of damages caused to the probe by the hard soil.

The first site is a test cell filled with a 3-metre waste and a 1-meter thick soil layer. Compared to the second site, the waste layer is thinner than the municipal landfill of Kemi. Therefore, the LFG production may be expected to be lower at site 1 than at site 2. Site 3 is a biofilter receiving emitted gas colleted from a 150 m^2.area, at the top of the landfill. It is not directly comparable to the previous sites concerning emission levels. However, it is a useful object to study methane oxidation because it is possible to steer the LFG flow is possible

During the first study, LFG emissions occurred independently of the season, but the gas quality varied. The vegetation and organic content of the soil were low at the test cell and it is possible that the main contributor to carbon dioxide emission is from the LFG emission directly or through methane oxidation. During the summer high carbon dioxide emissions have been recorded while no methane emissions occur. This indicates an efficient methane oxidation.

LFG emission rate and quality varied between the different seasons. There seems to be two emission peaks, one in the spring and one in the autumn. The carbon dioxide emission rate varied between 11 and 897 mol /m^2 /year while the methane emission rate was between <1 and 46 mol /m^2 /year. The LFG emissions from the test cell were estimated to about 432 mol carbon dioxide /m^2 /year and to about 8 mol methane /m^2 /year. Methane was completely oxidised in the top soil, except for during a part of the winter when the soil was frozen.

Climatic influence on the waste temperature was noticeable down to about a 3-meter depth in the test cell. The snow layer works as a thermal protection preventing frost from penetrating deeply into the soil. Also, as the waste temperature only varies a few degrees, the LFG production is probably fairly constant. Since the winter is fairly dry in Luleå, no ice cap formation on the soil surface was observed as in South Sweden (Börjesson and Svensson 1997). The occurrence of methane emissions only during the late wintertime when the soil was frozen leads to the conclusion that methane oxidising organisms must be inhibited during

this period. This may be a combined effect of low temperature and drought. Judging from the emissions, however, the methane oxidation seems to be almost complete during warmer (and wetter) periods.

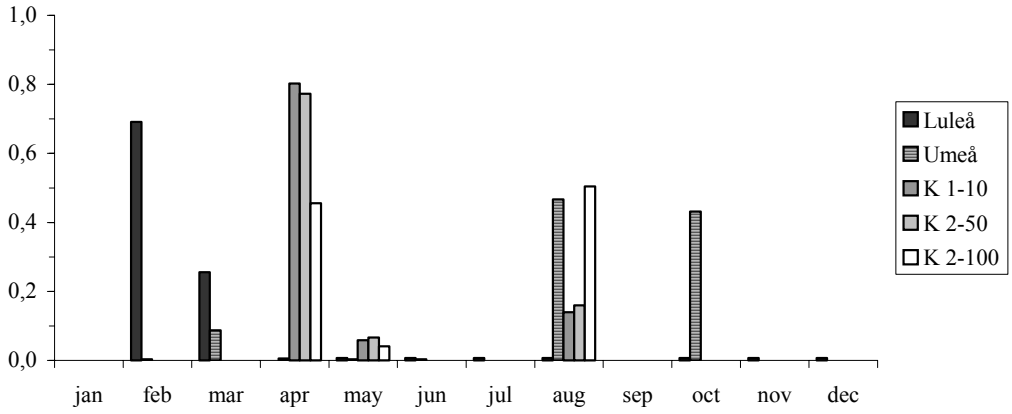

Figure 1 Repartition of the measured methane emissions along the year for the 3 sites.

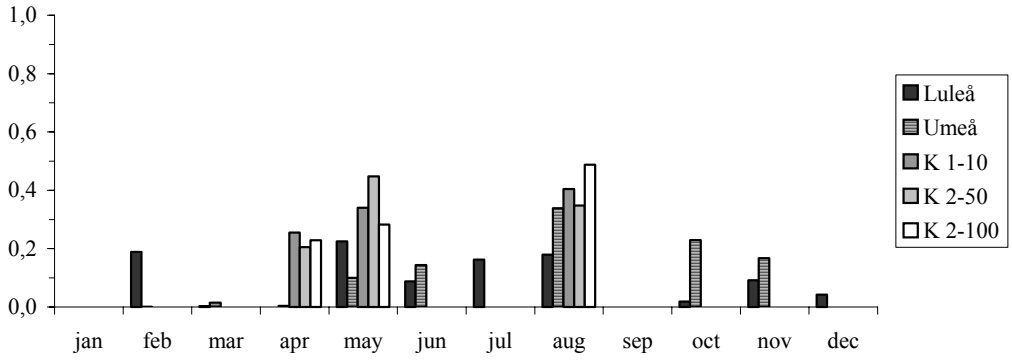

Figure 2 Repartition of the measured carbon dioxide emissions along the year at the sites.

The distribution of the LFG emissions over the year are presented in figures 1 & 2. Each bar represents the measured emission share compared to the total emissions from the studied point. No assumption is made on how long each time period is for each measurement represented. In Northern Scandinavia, the year may basically be divided in two main seasons, i.e. a winter period (when the soil is frozen and snow covered) and the chilly summer where spring and autumn could be included. Figure 1 shows that the main methane emissions were observed during the late winter (February-April) and during the late summer in August, at both sites in Umeå and Kemi. In October, methane emissions were also observed at Umeå. Carbon dioxide emissions are more regular throughout the year with higher emissions during the summer (see figure 2).

The same pattern could be observed at site number 2, in Kemi, where a seasonal variation of the quality of the emitted LFG could be observed, i.e. methane emissions occurred during the winter period while most of the methane was oxidised during the summer period. However, during the late summer, methane emissions could also observed when the soil dried and in the biofilter at Umeå where these emissions occurred again at the end of the summer. The combination of drying due to the summer temperature and the effect of the heat generated by the oxidation are likely to reduce the oxidation capacity. The microbiological activity requires soil moisture and is optimal at about 30% water content. Furthermore, water evaporation opens more pores to transport gas and may result in a faster transport of the methane through the soil cover.

5 Conclusions

The efficiency of methane oxidation is believed to be at the origin of the methane emissions' variation. During the winter, the upper part of the landfill cover freezes, and the microbiological activity is reduced. The formation of an ice layer on the top of the soil surface could also influence the LFG emissions.

- Measurements should be done directly at the soil surface and the eventual snow cover should be removed beforehand.
- A seasonal variation of the methane emissions could be observed, thus requiring monitoring during the different seasons in order to obtain a better estimation of the LFG emissions from landfills.
- A reduced methane oxidation activity in cold soils is likely to be one of the reasons for those variations.
- At low emissions rates, the main methane emission may occur during wintertime because of the greater mitigation effect of methane oxidation during summertime.
- A combination of summer temperatures and the heat from methane oxidation leads to a drying of the soil and a subsequent decrease in the oxidation of methane.

Methane oxidation is a biological process, sensitive to low soil temperatures and drying of the soil. The efficiency of the mitigation of the methane emissions that could be obtained is reduced when the environmental conditions in the soil become less favourable. To avoid such a decrease in efficiency, excessive cooling or drying must be avoided and the development of new cover designs is needed to achieve this.

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