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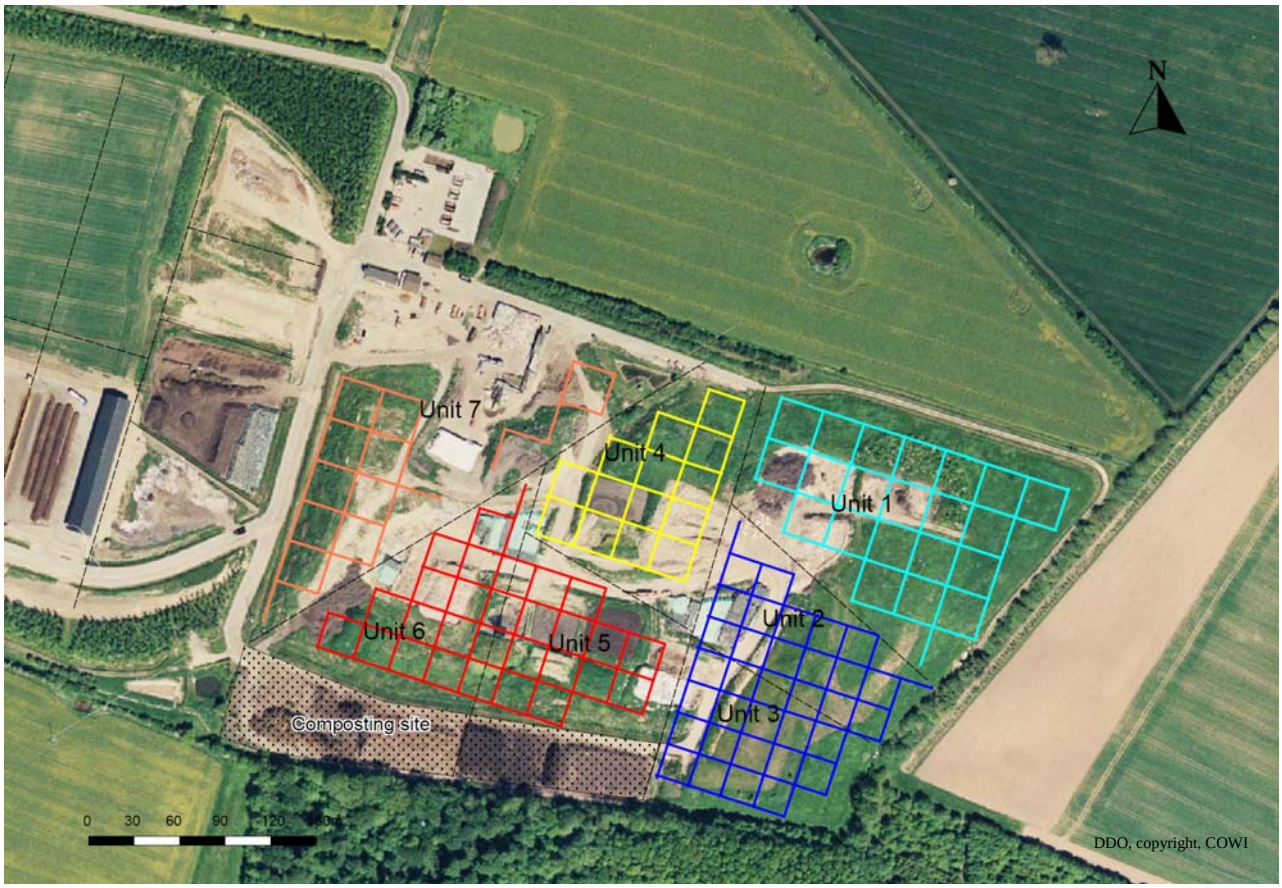

Measurement of Spatial Variability in Emissions

Institute of Environment & Resources
Technical University of Denmark

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Preface

The full title of the BIOCOVER project is *Reduction of Greenhouse Gas Emissions from Landfills by use of Engineered Biocovers*. The project is funded by the LIFE III ENVIRONMENT programme, the Danish Environmental Protection Agency, and RENOSAM and runs from August 2005 to November 2008. This report presents the outcome of Action 3.1 *Measurement of spatial variability in emissions* as described in the project application (Biocover, 2005). Fakse Landfill serves as the demonstration landfill for the BIOCOVER project. The consulting company NIRAS has contributed by providing use of a Innova photoacoustic field gas monitor they own, and the Informatics and Mathematical Modelling department at the Technical University of Denmark has contributed by lending out a high accuracy Trimble RTK GPS.

Measurements referred to in this report have been performed in the period May, 2006 to September, 2006.

Summary

Section I of Fakse landfill serves as a demonstration site for the BIOCOVER project to reduce green house gas emissions by creating optimal conditions with regards to biological methane oxidation.

In a previous report (Lemming & Kjeldsen, 2006), results of applying several models to estimate the methane production rates at the site has been described. Based on the models, the methane production rate for Section I of Fakse Landfill as of 2006 is estimated to be between 484.8 and 551.0 kg methane per day. Initial methane concentration screenings at Fakse Landfill combined with a soil cover characterization, has led to a conceptual model of the methane emission at Fakse Landfill (Lemming & Kjeldsen, 2006), which has been used to device a measurement strategy for mapping methane emissions. The following activities have been performed in this context:

- Installation of gas probes to measure landfill gas composition with regards to main components (CH_4, CO_2, O_2, and N_2) and excess pressure in the waste mass
- Measurement of methane concentrations just above ground level on random locations marked at the site, and measured for precise locations using GPS
- Locating and marking hot spots on soil cover and measurement of locations of these using GPS. Five hot spots were marked per disposal unit – 35 in all
- Measurement of methane flux through each hot spot using a flux chamber coupled with a flame ionization detector for methane measurement
- Measurement of approximate areas of groups of hot spots, where significant emission rates were observed
- Measurement of methane flux on five random locations on the soil cover using a flux chamber and sampling in evacuated glass vials for analysis of methane using a gas chromatograph
- Screening of methane concentration in the leachate collection system (inspection wells, pumping stations etc.)
- Measurement of methane emission rates through leachate collection wells using a tracer release technique

Observed methane emission rate from the leachate collection is 351 kg/d. The total methane emitting through “hot spots” in the soil cover, which have a combined area of 0.4% of the total area of the site, is measured to be 182 kg/d. Comparing these rates to the results of methane production modelling, the measurements suggest that more than half of the gas produced at the site emits through the leachate collection system, and the bulk of gas emitting through the soil cover discharges through a few relatively small areas at Fakse landfill.

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1 Introduction

The main objective of this action related to the Biocover project has been to map methane emissions from section I at Fakse Landfill where main emission pathways are identified and emission rates are measured. This has involved screenings of near surface concentrations and measurements of emission rates from locations where screenings suggested high emissions.

Previously, a conceptual model of the landfill gas emission has been setup (Lemming & Kjeldsen, 2006):

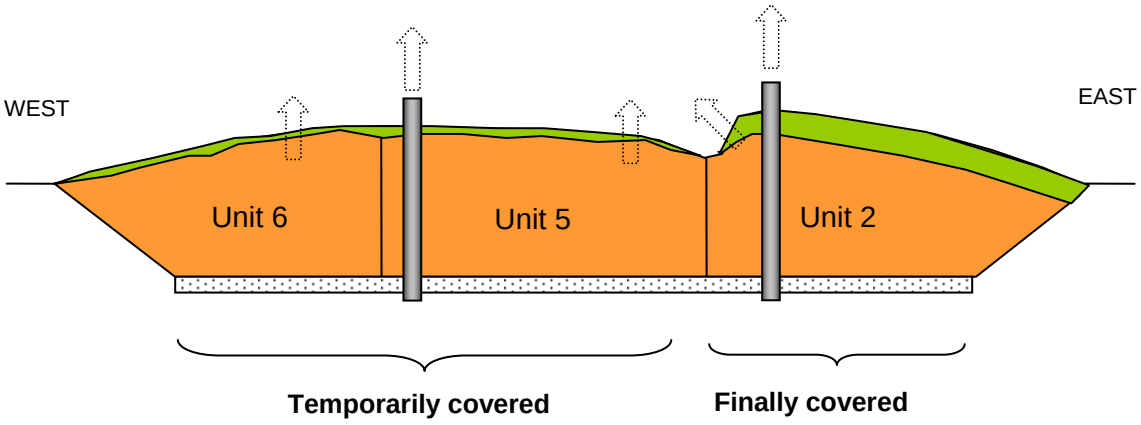

Figure 1. Conceptual model for emission of landfill gas from Fakse Landfill. The figure shows a cross section of the landfill. Arrows illustrate emission pathways: leachate wells, slopes, hot spots on temporary cover

This model has been setup based on initial methane concentration screenings, cover soil characterization and reflections considering the technical design of the landfill. Clayey soil has been used for both temporary and final covering. This leads to low permeability, which in turn leads to gas emitting in more concentrated parts of the landfill, where permeability is higher rather than more uniformly upwards through the top soil over the entire area.

Main pathways of emission were considered to be leachate “wells”, which are part of the leachate drainage system and high emission areas (hot spots) on the soil cover. These areas were believed to be found on slopes and parts of the temporary cover, where the soil cover is thin, and thereby more permeable. Furthermore, during methane concentration screenings, high concentrations of methane near remaining installations of a leachate recirculation system, which has been taken out of use in 1996, have been observed, which suggest a sizable emission through this path.

Mapping methane emissions on Fakse landfill will have importance with regards to the designing a full scale Biocover at the site (Task 5), and will be useful when conducting whole site methane emission measurements (Action 3.2)

To evaluate, if the main emission pathways have been identified, measured emission rates are compared to previously estimated landfill gas production rates. These calculations are described in the Biocover project report “Initial Characterization of Fakse Landfill”

The table 2 summarizes results from two models, which are believed to be the most applicable to Fakse Landfill out of four models used. Gas production is estimated for each of the seven disposal units of section I at Fakse landfill.

Table 2. Estimated methane production rates in 2006 using Avfalzorg and GasSim landfill gas production models.

Location	**Avfalzorg min. ($kg\ d^{-1}$)**	**Avfalzorg max. ($kg\ d^{-1}$)**	**GasSim ($kg\ d^{-1}$)**	**Range ($kg\ d^{-1}$)**
Unit 1	37	42	46	37 – 46
Unit 2	36	41	43	36 – 43
Unit 3	29	33	37	29 – 37
Sum: Finally covered units	102	116	126	102 – 126
Unit 4	77	87	87.7	77 – 88
Unit 5	75	86	97.8	75 – 98
Unit 6	61	69	76.8	61 – 77
Unit 7	170	194	137.3	137 – 194
Sum: Temporarily covered units	382	435	399.6	382 – 435
Total	485	551	525.3	485 – 551

In this report, total methane emissions measured for each of the seven disposal units are presented based on observed methane fluxes through hot spots on each unit as well as observed methane emission rates from the leachate collection system.

2 Landfill gas composition

Though not directly relevant with regards to the main objective of this action, gas probes has been installed to evaluate gas composition, which will be necessary in later studies on methane oxidation rates and thus efficiency of the biocover when established.

Method

2.5 metre gas probes, which are stainless steel tipped gas tubes with 6 perforations at the bottom, were installed. The installation of each probe is done by hand drilling through the soil cover, which has been expected to be 1.5 metres thick and subsequently ramming a 2.7 cm steel pole the remaining 1 meter. After removing the steel pole, coarse sand has been added to create a 20 cm sand filter where the perforated tip of the gas probes is to be situated. The gas probe was the inserted to the desired depth and bentonite and water was added creating a 30 cm impermeable layer above the permeable coarse sand.

9 gas probes have been installed successfully. A few additional probes have been installed, from where it is not possible to sample gas due to saturation of water in the soil. Three probes are successfully installed on unit 3, two probes on each of the units 1 and 2, one probe on each of the units 6 and 7.

Excess pressures are measured using a Thommen HM35 digital manometer capable of measuring differential pressures ranging from 0.025 mbar to 25 mbar.

Sampling of gas is done by first withdrawing approximately 500 ml gas from the probes, which have internal volumes of circa 40 ml each. Thereby the probes are flushed with landfill gas and ready to be sampled. Gas is withdrawn using a 160 ml syringe fitted with a stop valve and a septum. From the septum 5 ml samples were taken using a 5 ml syringe and stored in evacuated Exetainer^{TM} brand glass vials.

The samples have been measured for main gas components (CH_4, CO_2, O_2, and N_2) on a transportable CP-2002P Chrompack Micro GC (Chrompack International BV, The Netherlands) gas chromatograph equipped with a thermal conductivity detector and two columns. Oxygen and nitrogen are quantified on a 4 m long Molsieve 5A column and methane and carbon dioxide on a 10 m long Poraplot Q column. Carrier gas is helium and the column temperature was 40°C. Gas standards produced by MicroLab, Aarhus, Denmark ranging from 0.02 to 50 %vol. are used for calibration.

Results

When installing the probes, significantly deeper cover soil layer than the anticipated 1.15 metres (Lemming & Kjeldsen, 2006) have been found on both finally and temporarily covered parts of the landfill. In one location three meters of soil was seen. Similar observations have been done COWI at a previous landfill gas survey at the site (COWI, 2003).

Measured concentrations of main components are listed in table 3:

Table 3. Landfill gas compositions observed in samples from gas probes expressed in percent by volume, methane to carbon dioxide ratio, and excess pressure

Probe	**Methane (vol. %)**	**Carbon dioxide (vol. %)**	**Oxygen (vol. %)**	**Nitrogen (vol. %)**	**Methane / carbon dioxide (mol/mol)**	**Average excess pressure* (mbar)**
1A	62.7	36.2	0	0	1.7	8.31
1B	57.6	43.5	0	0	1.3	18.84
2B	41.5	32.9	0.8	20.8	1.3	1.23
2C	58.2	31.6	1	5	1.8	0.05
3A	64.7	39.3	0	0	1.6	0.07
3B	61	36	0.4	0	1.7	0.22
3C	63.1	37.9	0	0	1.7	0.05
6A	52.4	39.6	1.1	1.8	1.3	6.95
7A	46.5	30.8	0	18	1.5	0.01

* Average values of four measurements of excess pressure for each probe

The composition of the gas sampled is quite typical of landfill gas from landfills with relatively low production (Christensen, 1998), and are very similar to results of previous analysis of landfill gas sampled from the site (COWI, 2003), (Willumsen, 2005). In the table averages of four measurements of excess pressure are shown. As in the two studies mentioned, considerable variations between excess pressures of the different probes are seen. An explanation for this could be variations in gas production rates at different locations.

Another explanation is variations in soil cover permeability. The low excess pressure measured at the probe 3C could be so because the probe is very close to an area where emission of gas through the soil is found to be high. This could suggest a higher permeability of the soil cover at this location, so that excess gas pressure is more easily relieved.

3 Methane emission through soil cover

To serve as part of the basis for determining the most optimal locations of the biocover windows, and to evaluate the necessity of improving the existing soil cover to avoid significant bypass of the biocover windows, emission of methane through the soil cover at Fakse landfill is investigated.

Method

Equipment

To conduct field measurements of concentrations of methane a Photovac MicroFID portable flame ionization detector (FID) is used. The lower detection limit of this instrument is 0.5 ppmv methane. Accuracy of the instrument is specified to be +/- 0.5 ppmv or +/- 10% of actual methane concentration (0.5 to 2000 ppmv range). Concentrations are measured every second with concentrations displayed in real time on the instrument, and it possible to log data.

To conduct laboratory measurements of methane concentrations, a Shimadzu GC-14A gas chromatograph with a flame ionization detector is used. Gas standards ranging from 100 ppmv to 50 vol. % have been used for calibration.

Two types of flux chambers are used to measure gas flux through the soil cover: a mobile type 15.5 litre stainless steel flux chamber fitted with a simple fan for manually stirring of the air inside, and a stationary type 54.9 litre steel chamber with a 12V battery powered fan. Both types have fittings which can be used to accommodate septa for extracting gas samples, or to connect field measurement equipment such as the FID.

A Trimble 5700 RTK GPS with TSC1 controller has been used to establish locations. Locations are measured with an accuracy depending on weather conditions and other factor between less than 1 cm and 2 cm

A La Crosse weather station measuring and logging data of atmospheric pressure, temperature, wind speed and direction, and rainfall was used to monitor weather conditions.

Storing of gas samples taken in the field is done in Labco Exetainer 5.9 ml evacuated flat bottomed soda glass vials fitted with pierceable rubber septa.

Initial screening and location of hot spots

To provide basis for a qualitative analysis on the spatial variability of methane emission through the soil cover, a grid of locations for measurements of methane concentrations have been planned. The strategy which have been used for establishing this grid is described in Environment Agency, 2004

Table 4 lists areas of the disposal units at Fakse Landfill, and distances between grid points:

Table 4. Areas of disposal units, and average grid spacing

Disposal unit	**Area (m^2)**	**Average grid spacing (m)**
Unit 1	22000	28
Unit 2	11000	22
Unit 3	11000	22
Unit 4	14000	24
Unit 5	12000	23
Unit 6	13000	24
Unit 7	20000	27

Each measurement location has been marked at the site using labelled 80 cm wood poles and measured for precise location using a the GPS. This has been done to make it possible to repeat measurements at the exact same locations. Some areas of the landfill have had to be left out. These areas are in use for temporary storage of cover soil, compost and combustible waste, waste handling, and other activities.

After marking the grid of point locations for measurement, each location is measured for methane concentration just above ground level in four screening campaigns. Concentrations are measured on the grid points and hot spots using the FID coupled with a 20cm diameter funnel.

Location of hot spots has been done by systematically measuring near surface methane concentrations using the FID and funnel walking slowly along the grid between all grid points in both north-south, and east-west directions. The screening between grid points was supplemented with a screening on slopes and other features were emission through the soil cover is potentially high.

Five hot spots are marked, and measured for location using GPS on each of the seven disposal units. These locations do not comprise all locations where elevated methane concentrations are observed when screening, but merely where the concentration is highest on each of the seven disposal units.

A hot spot is in this context defined as where the observed concentration of methane above ground level is highest on each of the disposal units. This means that on hot spots on a disposal unit where emission through the soil cover is relatively low, the observed concentrations are much lower than on units where the emission is high. This approach has been chosen in order to quantify emissions through hot spots on each of the seven disposal units.

Areas of the hot spots have been established by using the FID and funnel to screen for methane concentrations above ground level. First the boundary of the areas is screened for and four marking poles are placed at this border. This is followed by screening inside the boundary to check if elevated methane concentrations are seen over the entire area. The boundary is the screened again, and the four marking poles are adjusted to form a rectangle which corresponds to the approximate area of the hot spots, which side lengths then are measured giving the area of the hot spot. In many cases the edge of the hot spots has been easy to define. In cases, particularly of the finally covered units, where concentrations of methane are low, the areas have been more difficult to establish precisely. This is also true for hot spots, where the methane concentrations are highest, since the amount of methane flowing out of the soil at these hot spots causes elevated methane concentrations in the surrounding areas. In

these cases, the boundary of the hot spots has been defined as where concentrations above ground level are 20% of the maximum concentration observed at the location.

Methane flux measurements

Quantification of the methane flux through hot spots is done by use of the mobile type flux chamber. Measurement of the concentration inside the flux chamber has been done using the FID. Time of each measurement is approximately five minutes, and the concentrations of methane in the flux chamber have been measured 6-7 time of each measurement.

Figure 5 shows an example of one flux measurement on a hot spot:

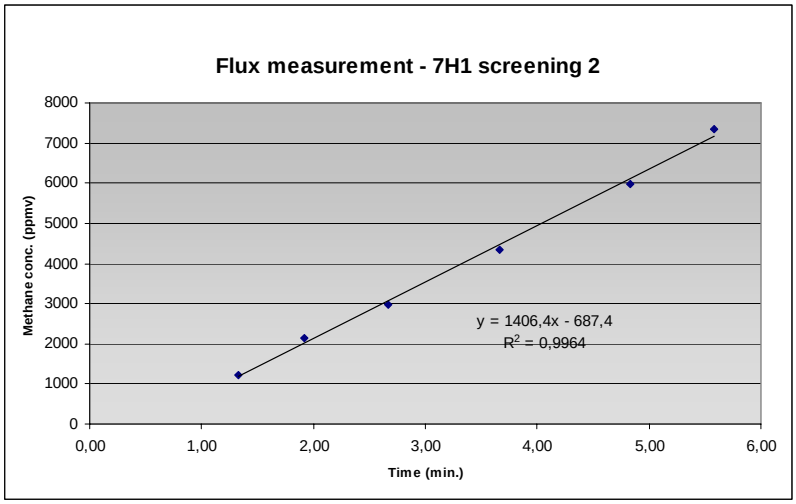

Figure 5. Data from measuring methane flux through soil cover at a hot spot using a portable flux chamber coupled with a flame ionization detector

The linear increase in methane concentration in the flux chamber is used to calculate the flux using the following formula (Environment Agency, 2004):

$$Q = \frac{V}{A}\frac{dC}{dt}$$

Where Q is the flux, V is the volume of the flux chamber, A is the area of the chamber, and dC/dt is the increase of concentration over time.

Considering an accuracy of 0.5 ppmv of the FID for concentrations of methane below 50 ppmv, the sampling period of 5 minutes, and 6 measurements over the period, the lower detection limit for measuring methane flux is estimated at approximately 0.5 ppmv/minute concentration increase inside the chamber corresponding to a methane flux of 0.1 g m^{-2} d^{-1}. This has, however, not been investigated experimentally. The lowest flux measured with satisfactory accuracy (R^2 has been found to be 0.9943) using this method has been 0.22 g m^{-2} d^{-1}.

Measurements of methane flux through the soil cover on five random locations are done using stationary flux chambers with electric fans. From these 5 ml air samples have been taken with five minute intervals over 30 minutes for each measurement. Air

samples were taken using a 5 ml syringe and stored in evacuated Exetainer^{TM} brand glass vials. Three stationary flux chambers were installed on the finally covered part of the landfill, and two were installed on the temporarily covered part. Samples have been measured for methane concentration using the gas chromatograph.

Both flux measurements on hot spots using the mobile type flux chambers, and the flux measurements on the random location using stationary type flux chambers have been done four times, to evaluate variation of emissions over time.

Results

Measurements of methane concentrations at near surface level at grid points and hot spots are shown for each of the four screening campaigns using thematic maps in appendix 1. Most observed concentrations at grid points are close to background level (below 2 ppmv), and nearly all are below 10 ppmv. The results are quite similar comparing the four campaigns. Concentrations slightly above background level (between 2 and 10 ppmv) are seen on grid points on units 4 and 5.

Increase or decrease of atmospheric pressure has been shown to affect rate of gas emissions from landfills (Czepiel, et. al, 2003), (Christophersen, et. al, 2001). Screening 1 was performed after an increase of absolute atmospheric pressure from 1010 hPa the afternoon on the previous day, to 1021 hPa overnight. Fewer grid points compared to screenings 2, 3, and 4 was measured to have methane concentrations higher than background level, which is in accordance with previous findings that emission decreases, all things equal, when there is an increase in atmospheric pressure.

The screenings of methane concentrations at ground level can be used for a qualitative evaluation of the spatial variability of methane emissions through the soil cover. The data supports the conceptual model described in the introduction, since quite low concentrations of methane at ground level are measured at the grid points, which are random locations on the soil cover, but very high concentrations (several thousand ppmv) are measured at some of the hot spots on the landfill. These hot spots have been found to be concentrated on slopes on the landfill soil cover, which has been expected. Figure 6 shows measured locations of grid points and hot spots at the site.

The total area of the hot spots has been measured to be 381 m^2 in all using the method described. The greater share of the area is on the temporarily covered part of the landfill.

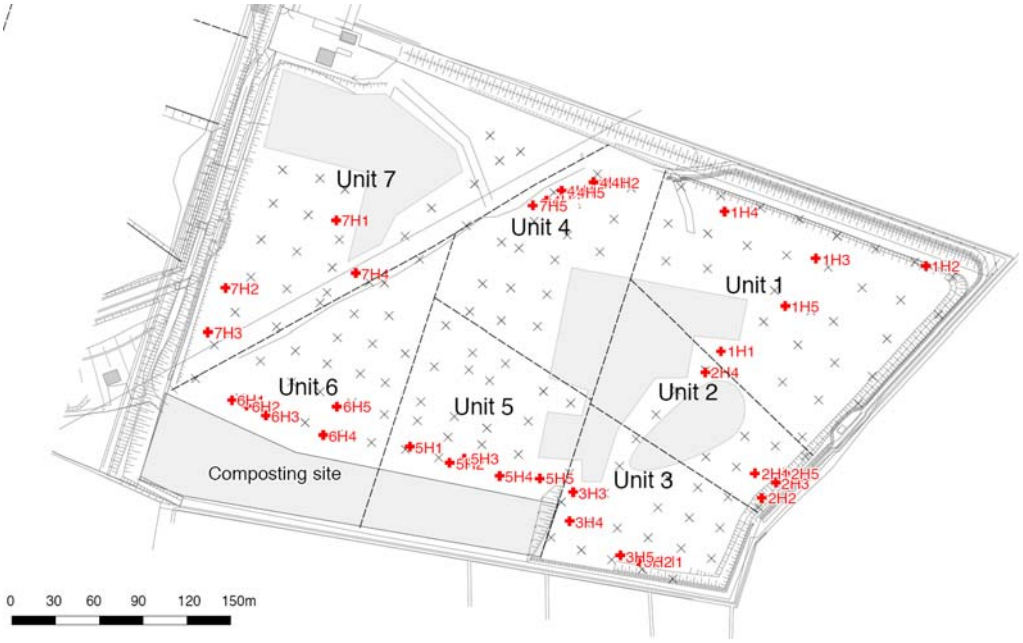

Figure 6. Measured locations of grid points and hot spots marked at the site. Grid points are shown as grey crosses, and hot spots are shown as red crosses. Areas on the site shown in grey are areas used for storage and handling of compost, combustible waste, and cover soil among other uses. Grid points have not been marked on these areas

Figure 7. Hot spot on soil cover. In many cases a change in vegetation, or lack of vegetation has been observed a these zones of high landfill gas emission. The picture on the right shows the flux chamber coupled with the FID

As is seen on figure 6, the hot spots are mostly clustered together. Many are found on a long slope on unit 5 and 6 facing the composting site on section I. Large hot spots on a slope on unit 7 facing section II of Fakse landfill, where vegetation on some of the area is absent, and gas can be smelled oozing out of the soil.

The flux measurements can be used to quantify emissions. Appendix 2 shows results of flux measurements of the four campaigns in thematic maps.

Table 8 lists methane fluxes observed listed in groups of hot spots as well as the total area of each group. The emission of methane from each of the ten groups of hot spots is calculated as the average flux measured on the hot spots in the group multiplied

with the total area of the hot spots in the group. An average value of the fluxes observed the four campaigns is listed in the table, and used when calculating the methane emission.

Table 8. Average fluxes measured, total areas, and methane emissions of groups of hot spots.

Group	**Location**	**Id.**	**Average methane flux (4 campaigns) ($g\ m^{-2}\ d^{-1}$)**	**Area (m^2)**	**Methane emission ($kg\ d^{-1}$)**
1	Various locations on unit 1 and 2	1H1, 1H2, 1H3, 1H4, 1H5, 2H4	4.8	6.0	0.03
2	Near leachate pumping station on unit 2	2H1, 2H2, 2H3, 2H5	13.9	10.0	0.1
3	Slope on unit 3	3H1, 3H2, 3H5	13.4	34.5	0.5
4	Small slope on unit 3	3H4	322.1	4.0	1.3
5	Slope on unit 5 and 3	3H3, 5H1, 5H2, 5H3, 5H4, 5H5	71.3	55.5	4.0
6	Slope on unit 6	6H1, 6H2, 6H3, 6H4, 6H5	70.5	53.0	3.7
7	Slope on unit 7	7H2, 7H3	556.7	89.5	49.8
8	Slope on unit 4	7H5 4H1, 4H2, 4H3, 4H4, 4H5	179.6	98.5	17.7
9	Slope on unit 7	7H1	3934.2	25.0	98.4
10	Near electrical pole on unit 7	7H4	1314.2	5.0	6.6
		Total	**648.1**	**381**	**182.1**

Overall these measurements show that a large fraction of landfill gas produced in the waste mass emits through these hot spots. Considering an estimated methane production of 484.8 to 551.0 kg CH4/d as described, between 33% and 38% of emits through the hot spots. In appendix 2, flux rates measured at each of the four campaigns are shown. Comparing results of the campaigns, each of the hot spots do not vary much with regards to the categories used in the thematic maps. Some variation is seen however. The hot spots on unit 7, where the highest flux rates are measured, variations in flux rates cause considerable variations of the total methane emission, when comparing campaigns against each other. Methane emission from group 7 is observed to vary between 22.5 and 88.7 kg d^{-1}.

The total area of the groups of hot spots is approximately 0.4% of the total area which is 103000 m^2.

Most of the emission (97%) through hot spots is observed on temporarily covered units (unit 3, 4, 5, 6, and 7), which match the conceptual model described in the introduction.

Table 9 lists observed methane fluxes measured using the stationary flux chambers at random locations on the soil cover.

Table 9. Measurements of methane flux using stationary flux chambers on random locations.

Location	**Cover type**	**Screening 1 ($g\ m^{-2}\ d^{-1}$)**	**Screening 2 ($g\ m^{-2}\ d^{-1}$)**	**Screening 3 ($g\ m^{-2}\ d^{-1}$)**	**Screening 4 ($g\ m^{-2}\ d^{-1}$)**	**Average ($g\ m^{-2}\ d^{-1}$)**
Unit 1	Final	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Unit 2	Final	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Unit 3	Final	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Unit 6	Temporary	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Unit 7	Temporary	15.5	42.7	1.1	3.3	15.7

b.d.l: below detection limit

As seen in the table above, methane emission above detection limit was only observed at the location on unit 7, which is temporarily covered. The methane flux is very low compared to the flux measured at the hot spots on unit 7.

4 Methane emission through leachate collection system

Initial screenings of methane concentrations at Fakse Landfill have suggested that a significant amount of methane is emitted to the surroundings via the leachate collection system at the site. A previous study (Fredenslund et. al, 2006) has shown that a high percentage of landfill gas (LFG) generated in the waste mass can be emitted through the leachate collection system.

Significant emission through the leachate system after installation of the biocover at the site would serve as a bypass, and thereby decrease the overall efficiency. Therefore it was found important to quantify emissions through the leachate collection system, in order to evaluate the necessity of modifications to reduce emissions of LFG through this path.

A technical description of the leachate collection system at Fakse Landfill is given in the report D 2.4.1: "Initial Characterization of Fakse Landfill".

A screening of methane concentrations in all installations of the leachate collection system, where from gas can be emitted was performed using a portable flame ionization detector. High concentrations inside most inspection- and collection wells have been observed. Concentrations observed have in many of these cases been above 5 vol. %, which is the upper detection limit of the instrument used for the initial screening. In other installations such as pumping stations and other wells, concentrations were measured to be near or at background level (below 2 ppmv). High concentrations of methane have been measured near two installations which are a part of a leachate recirculation system on disposal unit 1 that has been taken out of use in 1996. Based on this finding, it was decided to perform one methane emission measurement on all 14 leachate inspection- and collection wells in section I at the site, as well as the two leachate recirculation wells.

To avoid effects on the gas emission rates caused by rise or fall of barometric pressure, which is known to be potentially very important, all measurements have been performed under stable weather conditions.

Method

To measure methane emission rates from the leachate collection system, a continuous tracer release method was used on desired locations. The principle of this method is to continuously release a gaseous tracer (carbon monoxide) at a constant known rate near the source of the methane emission (bottom of leachate wells), and subsequently compare measurements of concentrations of tracer and methane in the plume downwind after background concentrations of tracer and methane have been measured. Concentrations of carbon dioxide have also been measured.

The basic equation for calculating emission rates through these measurements of concentration is derived from the assumption that the ratio between flow rates of methane and tracer is equal to the ratio between observed concentrations measured downwind.

$$\frac{Q_{CH_4}}{Q_{CO}} = \frac{C_{CH_4}}{C_{CO}} \Leftrightarrow Q_{CH_4} = Q_{CO} * \frac{C_{CH_4}}{C_{CO}} \qquad (1)$$

Where Q_{CH4} is the flow rate of methane (l/min), Q_{CO} is the flow rate of carbon monoxide tracer, C_{CH4} is the concentration down wind of methane (ppmv), C_{CO} is the concentration of carbon monoxide tracer (ppmv).

This relationship assumes perfect mixing of LFG and carbon monoxide tracer, and that background levels of methane and carbon monoxide are negligible. To take background levels into account, an approximate compensation is introduced, so that

$$Q_{CH_4} = Q_{CO} * \frac{C_{CH_4,t} - C_{CH_4,background}}{C_{CO},t - C_{CO,background}} \qquad (2)$$

The tracer release system consists of a CO-gas bottle fitted with a two stage gas regulator and a simple flow meter. The tracer release rate used has been 2.7 l/min, and carbon monoxide has been added through 4 mm internal diameter tubing to the bottom of each leachate well.

Figure 10. Methane emission measurements from leachate wells.

To measure methane, carbon monoxide, and carbon dioxide an Innova 1312 Photoacoustic Field Gas monitor is used. The instrument has been set to measure at maximum sampling rate, which in the used configuration is app. one measurement every 54 seconds. The detection limits on this instrument with regards to all monitored gases are below 1 ppmv.

The reason behind the choice of carbon monoxide as tracer gas has been, that a highly reliable method for measurement of this gas has been available and CO can be measured using the same instrument that measures methane. The risk of significant background levels of carbon monoxide imposing error on the flow calculations is avoided by measuring background levels of carbon monoxide in each case. Being able to measure both gasses on the exact same amount of sampled air eliminates error caused by fluctuations in concentrations downwind due to change of wind speed or direction when sampling.

If no apparent opening on the well was seen such as cracks in the concrete or gas vents, the carbon monoxide tracer has been added through tubing running through a drilled hole in the iron manhole cover with the same diameter as the tube, and Glisseal® vacuum grease was used for sealing. This has been done to avoid changing conditions of gas emission from the wells by creating passage, which is not there under operating conditions. If, however, visible openings, which enable gas to pass

through without restraint were seen, tracer gas is added through tubing inserted by way of these openings or by partly opening the manhole cover.

Placement of the point of sampling is determined in each case, and evaluated during measurement considering observed concentrations. Two concerns have had to be taken into account. First, it has been necessary to measure relatively close to the emission source so that significant margins between the concentrations of both methane and tracer and background levels of these gasses were observed, and to minimize influence on measurements from other nearby sources of methane. Secondly, some distance was desired, since this will ensure a high degree of mixing of tracer and methane in the plume downwind from each location. In general, one meter was found to be an adequate distance.

In figure 11 an example of results is shown:

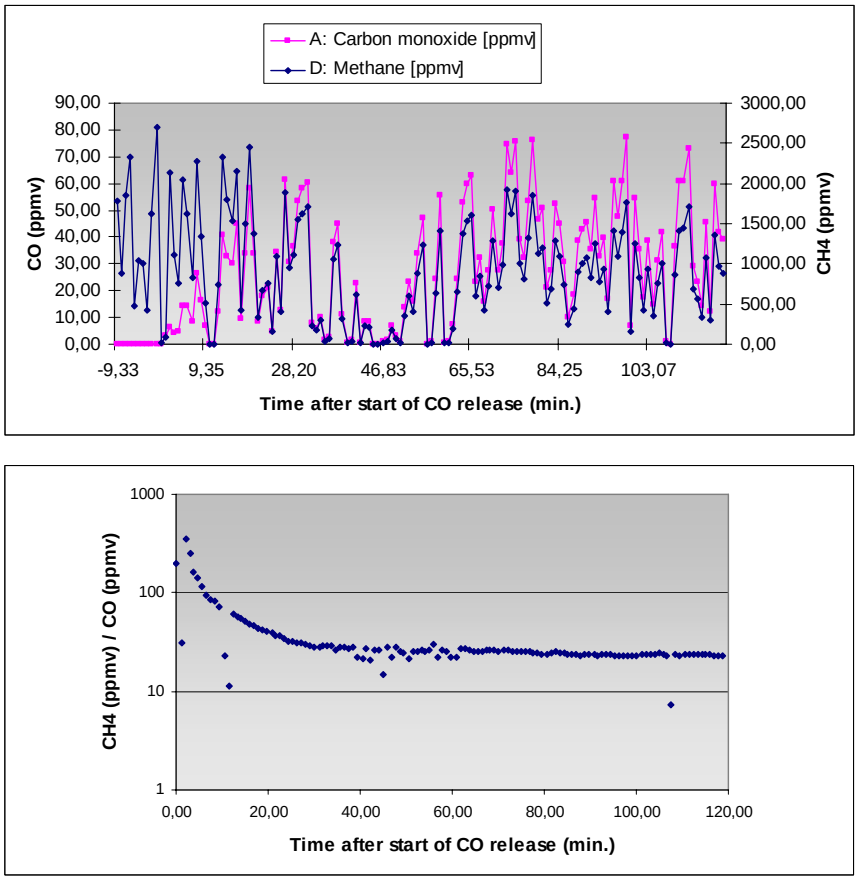

Figure 11. Example of data from methane emission measurement at a leachate well. The top graph shows observed concentrations of both methane and carbon monoxide tracer as a function of time. The bottom graph shows the ratio between the concentrations as a function of time. Note that the scale of the y-axis on the bottom graph is logarithmic.

As seen in the figure above, the measured concentrations fluctuate a lot. This is probably mainly caused by changes in wind speed and direction. The ratio between concentrations however shows a clear tendency of a very high methane concentration compared to carbon monoxide concentration just after start of tracer release, which falls, and ends at a relatively constant value. Breakthrough is seen in this case to be app. 30 minutes after start of tracer release.

Outliers seem to be where absolute concentrations are very low. This could be explained by bursts of wind directing the plume away from the point of sampling, so that the ratio between methane and carbon monoxide does not represent the mixing ratio in the well. When calculating methane emission rate, data sets where either methane or carbon monoxide concentrations are below 10 ppmv are disregarded.

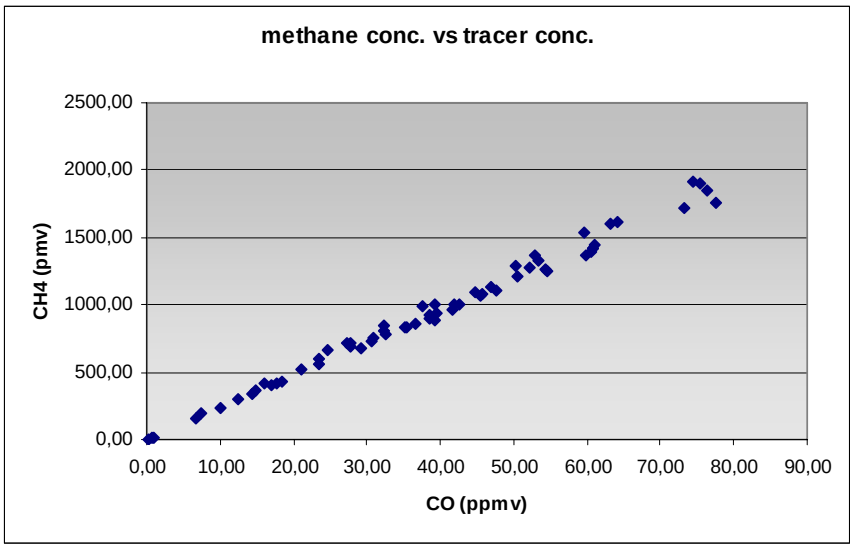

Figure 12. Ratio between methane and carbon monoxide concentrations for t >60 minutes after tracer release.

The figure above shows methane concentration as a function of carbon monoxide concentration after 60 minutes of tracer release. Factors such as fluctuation of methane emission rate in the period of measurement, methane and tracer not entirely mixed, error due to background levels of methane or carbon monoxide causes deviations from a straight line. In this example, after compensating for background levels using equation 2 and disregarding data points were concentrations are below 10 ppmv, the average ratio between methane and carbon monoxide (ppmv) after breakthrough is found to be 28.7 with a standard deviation of 1.9. This corresponds to a methane emission rate of 76 kg methane per day for this location.

Results

In all cases, background levels of carbon monoxide were found to be below the detection limit of the instrument used (0.4 ppmv). Therefore it was not possible to compensate for background carbon monoxide levels. The error, which might be caused by this, can only have minor importance to the accuracy of the final results. The background levels of methane were generally low – app. 2 ppmv, but in one case, were the well is situated close to methane emission hot spots, a background level of 15 ppmv was observed.

In general, the breakthrough time was found to vary between app. 30 minutes to 3 hours. This variation can be explained by varying emission rates and varying depth of the leachate collection wells.

Table 13 lists observed methane emission rates for each location of measurement.

Table 13. Observed methane emission rates. At locations D2 and D5 the emissions were to low to measure using the described method. The wells D2….D15 are named as in COWI, 1997. R1 and R2 are used to denote two remaining wells from the leachate recirculation system. R1 is located in the far north-eastern corner of disposal unit 1, whereas R2 is located west of R1

Well	**Methane emission rate (kg/d)**	**Well**	**Methane emission rate (kg/d)**
D2	Not measurable	D10	15
D3	4	D11	76
D4	20	D12	36
D5	Not measurable	D13	13
D6	39	D14	27
D7	1	D15	10
D8	40	R1	38
D9	25	R2	9
		Total	**351**

Emissions from wells D2 and D5 were not measurable using the described method. These emission rates are believed to be lower than 1 kg CH_4/day, which is the lowest rate measured.

Comparing the observed emission rates to the estimated production rates listed in the introduction, these measurements show that overall, more than 50% of the methane is emitted through the leachate collection- and inspection wells.

5 Discussion

Based on the measurements of emission through the leachate collection system and emission hot spots on the soil cover described in the previous sections methane emissions can be listed for each of the seven disposal units.

Table 14. Estimated methane production and measured emissions listed for each disposal unit, and entire site.

Location	Estimated methane production ($kg\ d^{-1}$)	Emission through hot spots in soil cover ($kg\ d^{-1}$)	Emission through leachate wells ($kg\ d^{-1}$)
Unit 1	37 – 46	0.03	50
Unit 2	36 – 43	0.1	20
Unit 3	29 – 37.0	2	1
Unit 4	77.0 – 88	18	79
Unit 5	75 – 98	4	39
Unit 6	61 – 77	4	111
Unit 7	137 – 194	155	50
Total	**485 – 551**	**182**	**351**

Overall, it is seen that the total emission (533 kg/d) measured from the leachate collection system, leachate recirculation system, and hot spots on the soil cover is within range of the estimated total methane production. Methane concentration screenings on grid points also show slightly elevated methane concentrations on some parts of the temporary cover which is likely due to emission through the cover, which have not been quantified.

Comparing emissions from the different units, variations are observed in the distribution of gas emitted through leachate wells and soil cover. This can be explained by variations in permeability of the soil cover. Where relatively high permeable zones exist, as is the case on disposal unit 7, more gas is emitted through the soil. On the finally covered disposal units 1, 2, and 3 very low emission through the soil cover is observed, which is in coherence with the conceptual model shown in figure 1.

The emissions and estimated productions listed in table 14 are subject to some uncertainty. Gas emissions from landfill are known to vary significantly over time, and emissions through soil cover vary spatially. To improve accuracy, conducting more flux measurements at the high emission hot spots on disposal unit 7 can be relevant.

It is not certain that gas produced in a disposal unit emits at the same location, since lateral transport of gas is likely due to the low permeable soil cover at the site. This can explain the low emission observed on disposal unit 3, so that gas produced in this disposal unit is emitted through, perhaps, the leachate recirculation system on disposal unit 1.

The results described in this report are comparable to measurements done by COWI, 2003 and Willumsen, 2005 at Fakse landfill. COWI, 2003 concluded, however that most gas at the site is oxidized in the soil cover, since only negligible methane fluxes through the soil cover were observed. Methane oxidation was not quantified in COWI, 2003 which conclusion is in contrast to the methane balance shown in table

14. The dominating methane emission through the leachate system, and the high degree of heterogeneity of methane flux through the soil cover, where most gas is emitted through a very small fraction of the soil covers area, causes traditional flux chamber measurements to be too uncertain used alone in this case.

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Appendices

Appendix 1 Screening of methane concentrations at grid points and hot spots

Screening 2


N
Screening II: Methane concentrations
5000 to 10000 ppmv
1000 to 5000 ppmv
100 to 1000 ppmv
10 to 100 ppmv
2 to 10 ppmv
0 to 2 ppmv
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Composting site
0
30
60
90
120
150m

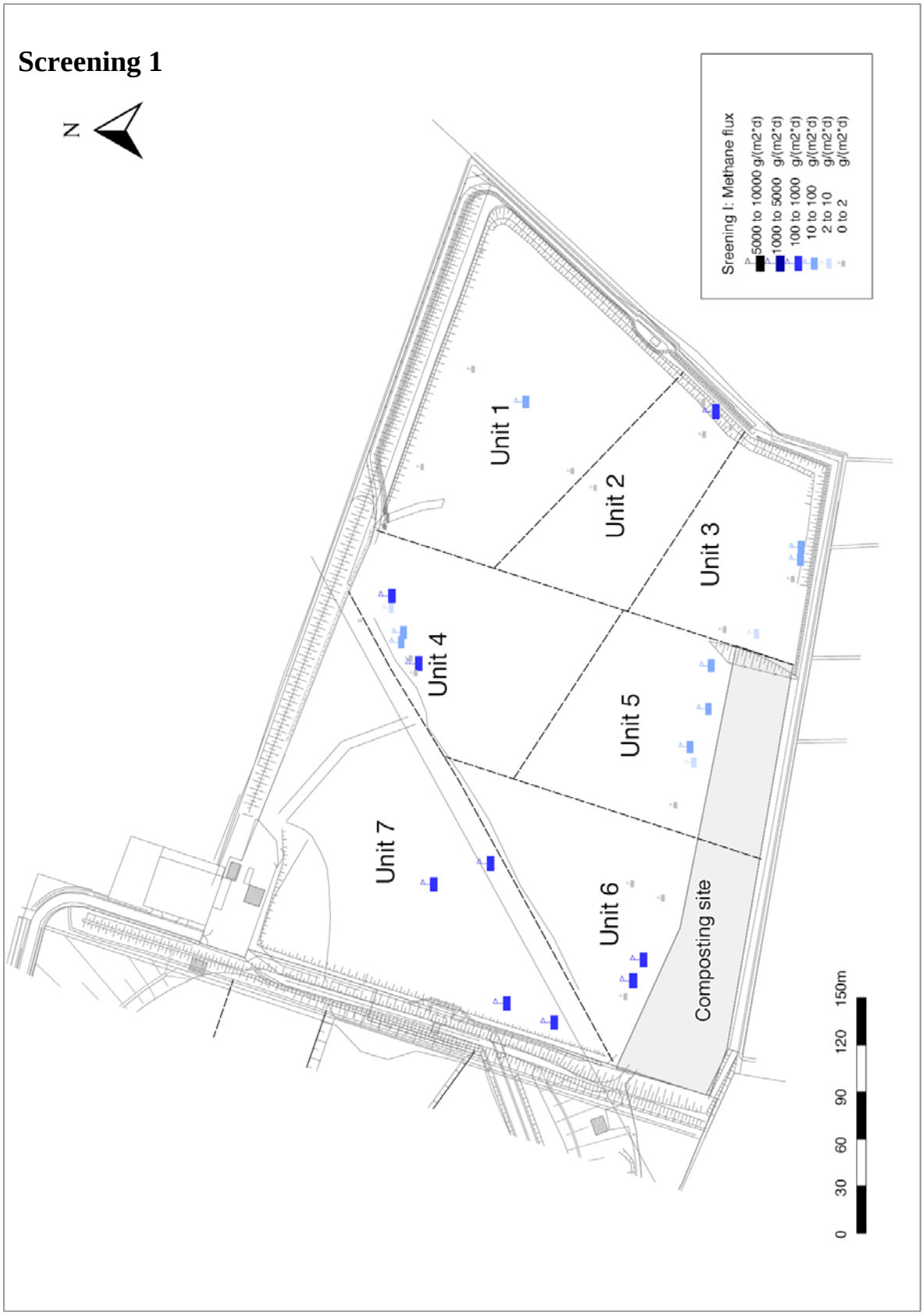
Screening 3


N
Screening III: Methane concentrations
5000 to 10000 ppmv
1000 to 5000 ppmv
100 to 1000 ppmv
10 to 100 ppmv
2 to 10 ppmv
0 to 2 ppmv
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Composting site
0
30
60
90
120
150m

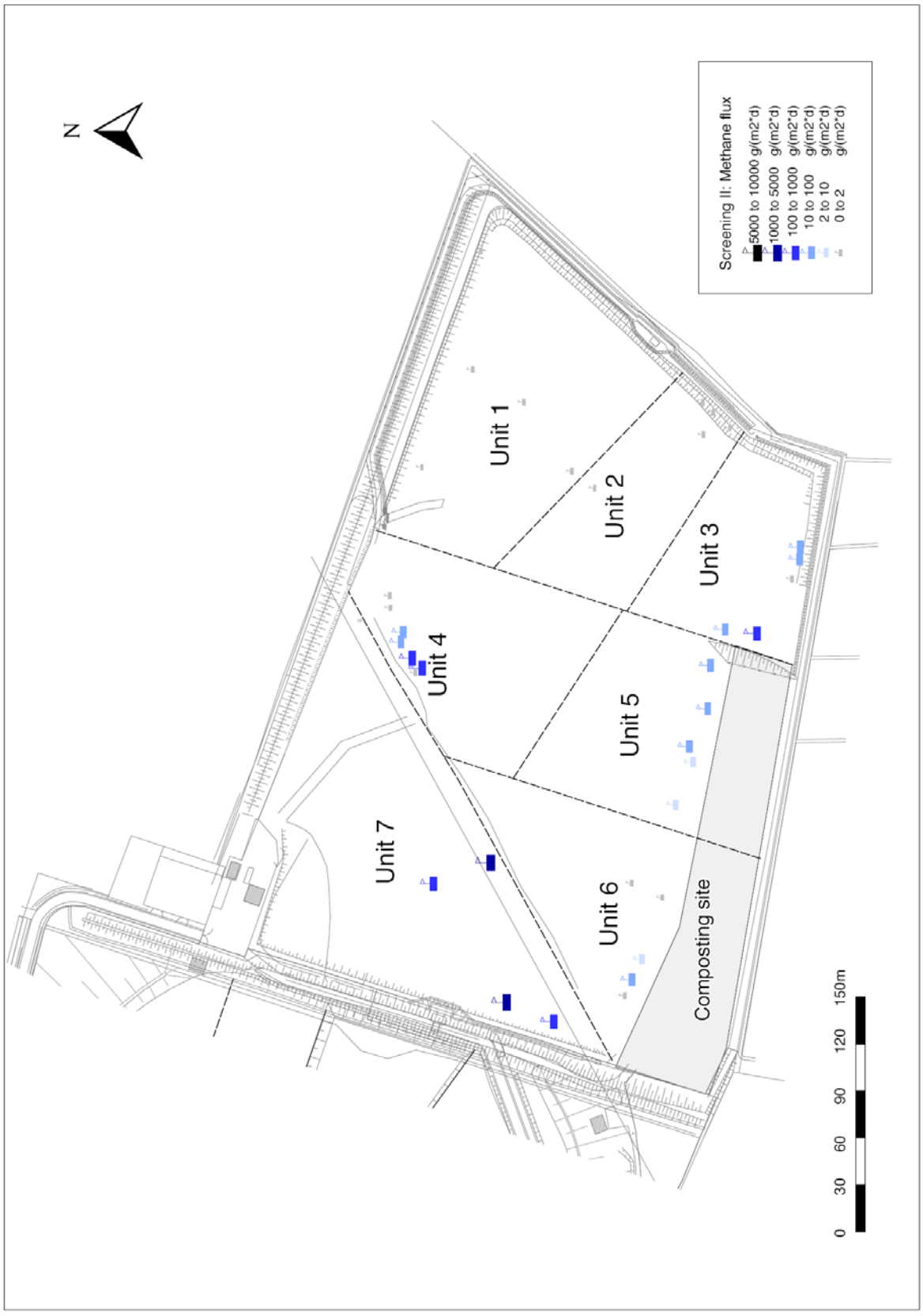
Screening 4


N
Screening IV: Methane concentrations
5000 to 10000 ppmv
1000 to 5000 ppmv
100 to 1000 ppmv
10 to 100 ppmv
2 to 10 ppmv
0 to 2 ppmv
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Composting site
0
30
60
90
120
150m

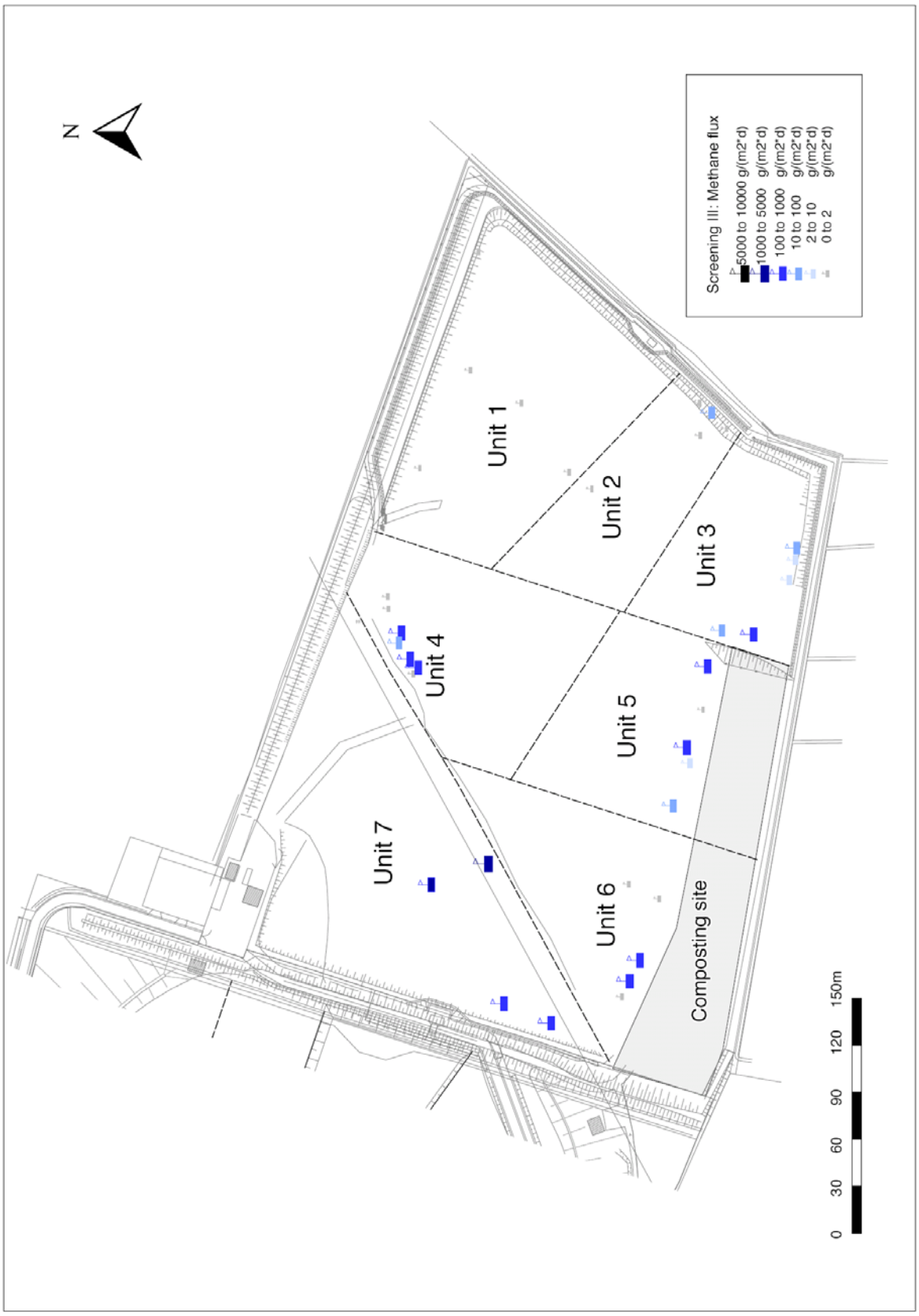
Appendix 2 Flux measurements at hot spots



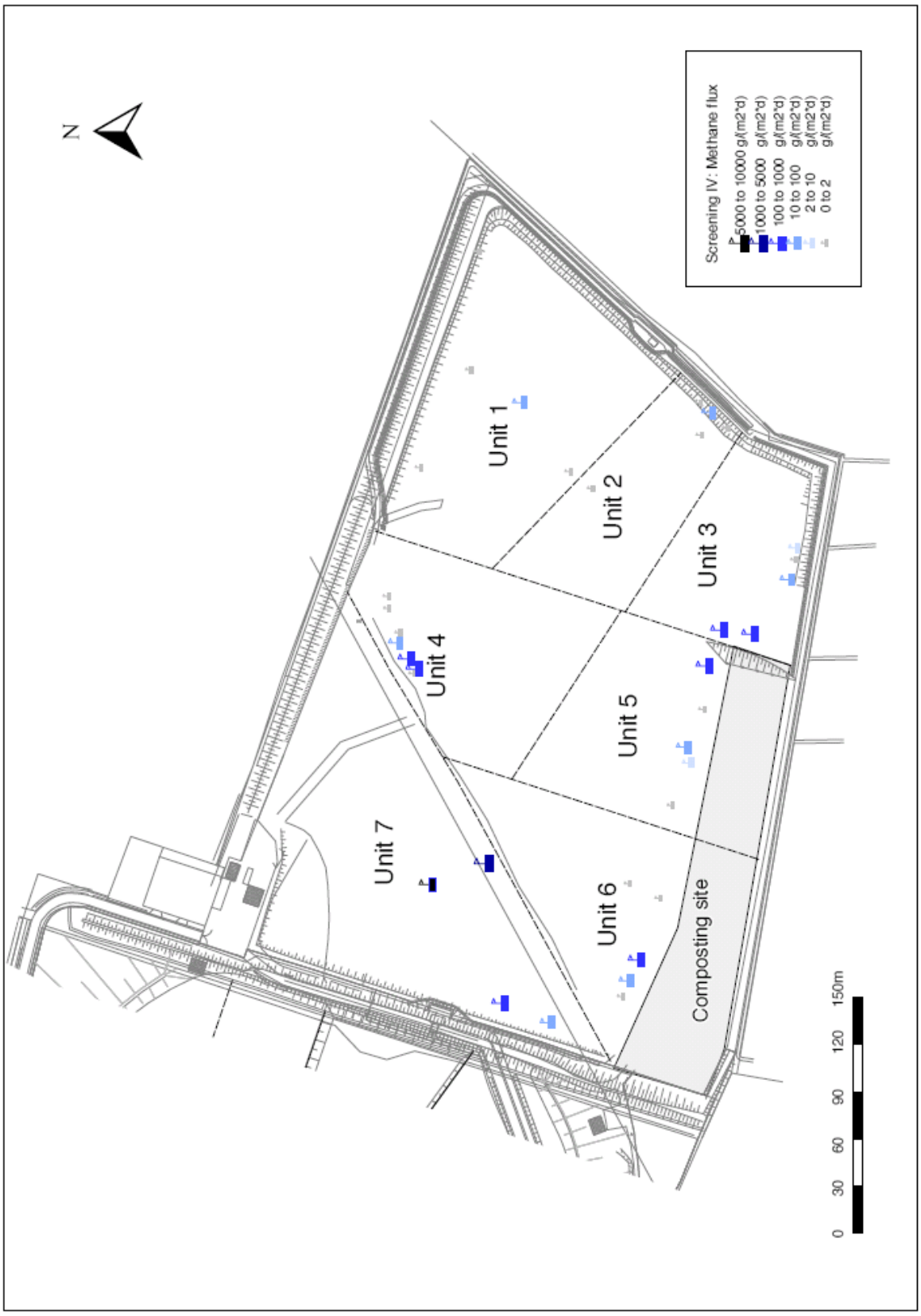
Screening 2


N
Screening II: Methane flux
5000 to 10000 g/(m2*d)
1000 to 5000 g/(m2*d)
100 to 1000 g/(m2*d)
10 to 100 g/(m2*d)
2 to 10 g/(m2*d)
0 to 2 g/(m2*d)
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Composting site
0
30
60
90
120
150m

Screening 3


N
Screening III: Methane flux
5000 to 10000 g/(m2*d)
1000 to 5000 g/(m2*d)
100 to 1000 g/(m2*d)
10 to 100 g/(m2*d)
2 to 10 g/(m2*d)
0 to 2 g/(m2*d)
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Composting site
0
30
60
90
120
150m

Screening 4


N
Screening IV: Methane flux
5000 to 10000 g/(m2*d)
1000 to 5000 g/(m2*d)
100 to 1000 g/(m2*d)
10 to 100 g/(m2*d)
2 to 10 g/(m2*d)
0 to 2 g/(m2*d)
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Composting site
0
30
60
90
120
150m