Reduction of Greenhouse Gas Emissions from Landfills by Use of Engineered Biocovers: Full Scale Studies

Fredenslund, Anders Michael; Kjeldsen, Peter; Scheutz, Charlotte

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Technical University of Denmark

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Anders Michael Fredenslund

DTU Environment
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PhD Thesis
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The thesis will be available as a pdf-file for downloading from the homepage of the department: www.env.dtu.dk

Address: DTU Environment
Department of Environmental Engineering
Technical University of Denmark
Miljoevej, building 113
DK-2800 Kgs. Lyngby
Denmark

Phone reception: +45 4525 1600
Phone library: +45 4525 1610
Fax: +45 4593 2850

Homepage: http://www.env.dtu.dk
E-mail: reception@env.dtu.dk

Printed by: Vester Kopi
Virum, April 2010

Cover: Torben Dolin

ISBN: 978-87-91855-92-4

Preface

This thesis was submitted as part of the requirements for obtaining a PhD degree from the Technical University of Denmark (DTU). The study was carried out from January 2006 to December 2009 at the Department of Environmental Engineering at DTU under the supervision of Professor Peter Kjeldsen and Associate Professor Charlotte Scheutz. The study was funded jointly by DTU and the research project, "Biocover – Reduction of greenhouse gas emissions from landfills by use of engineered biocovers", which in turn was financed by the EU LIFE-Environment program, DTU, FASAN I/S, Danish Environmental Protection Agency, Reno-Sam and COWI.

The thesis comprises a summary of the subject "Reduction of greenhouse gas emissions from landfills by use of engineered biocovers: Full scale studies" and the four journal papers:

I Fredenslund, A.M., Scheutz, C., Kjeldsen, P., 2010. Tracer method to measure landfill gas emissions from leachate collection systems. Waste Management. DOI: 10.1016/j.wasman.2010.03.013

II Scheutz, C., Samuelsson, J., Fredenslund, A.M., Kjeldsen, P., 2010. Quantification of multiple methane emission sources at landfills using a double tracer approach. Submitted to Waste Management.

III Fredenslund, A.M., Lemming, G., Scheutz, C., Kjeldsen, P., 2010. Mitigation of methane emission from Fakse landfill using a biocover system 1: Baseline study. Manuscript

IV Fredenslund, A.M., Pedersen, G.B., Scheutz, C., Kjeldsen, P., 2010. Mitigation of methane emission from Fakse landfill using a biocover system 3: Design and performance. Manuscript

In this thesis, the papers are referred to by their Roman numerals. The papers are not included in this www-version but can be obtained from the library at DTU Environment. Contact info: Library, Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, DK-2800 Kgs. Lyngby, Denmark or library@env.dtu.dk.

In connection with this study, there have been several publications, which are not included in this thesis. In addition to the papers listed above, I was main- or coauthor on six technical project reports and seven conference contributions.

Professor Peter Kjeldsen and Associate Professor Charlotte Scheutz are thankfully acknowledged for their supervision. I wish to thank the management and employees at Fakse landfill for their cooperation with regards to implementing and improving the biocover system at the site and for their hospitality. I thank my co-authors for their collaboration as well as many friends and colleagues at the Department of Environmental Engineering – especially Gitte Bukh Pedersen & Kåre Press-Kristensen. Most of the illustrations and figures included in this thesis were prepared by Torben Dolin, whom I gratefully thank.

Special thanks to Tina and our wonderful children, Filippa and August. I thank my parents: Anna for her love and support during this busy time and Aage for inspiring me to enter the field of engineering.

March, 2010

Anders Michael Fredenslund

Summary

Methane emissions from landfills constitute the most important source of greenhouse gas emissions from the waste sector. Compared to many other sources of greenhouse gas emissions, landfills constitute point sources, and mitigation of these emissions are potentially cost efficient. Production of landfill gas (LFG) consisting mainly of methane (55-60% v/v) and carbon dioxide (40-45 % v/v) is a result of degradation of organic matter within the waste mass which lasts for several decades, also after landfilling of waste has ceased. Microbial methane oxidation has been observed in landfill top covers in many studies under many climatic conditions. The relative significance of methane oxidation, and thus reduction in impact on global warming has been observed to vary, and to be dependent (among other factors) on the physical properties of the cover material. Therefore, it may be possible to engineer a landfill soil cover to maximize methane oxidation, and thus reduce the site's impact on the environment with regards to release of greenhouse gases.

This thesis concerns a study on implementing a so-called biocover system in full scale at Fakse landfill, Denmark, to facilitate methane oxidation with the objective to significantly reduce methane emissions from the site. The biocover system was evaluated with respect to mitigation efficiency primarily through measurements of the site's total methane emission before and after implementing the biocover system. The biocover system installed at Fakse landfill consisted of ten biocover "windows". These windows were areas of the existing soil cover, where the low permeable cover soil had been excavated and replaced with 15 cm gravel "gas distribution layer" overlaid by a 1 m layer of active material, which consisted of composted yard waste. The combined area of the biocover windows was 5000 m^2, whereas the total area of the site was approximately 12 hectares. Before the biocover system was designed and constructed, a baseline study on LFG emissions from Fakse landfill was performed. This study had several objectives, one of which was to establish total methane emission from the site for the purpose of comparison with similar measurements after implementation, thereby enabling assessment of the system's overall methane mitigation performance. The total emission before implementation was measured during two campaigns. The method used to determine total emissions was to continuously release a gaseous tracer from the landfill surface, while performing concentration measurements downwind from the landfill using a high precision, mobile detector. The results of these measurements were similar. During the first campaign the emission from the

site was measured to be 749 kg CH4 d^{-1}, while the emission was measured to be 732 kg CH_4 d^{-1} during the second campaign. As another part of the baseline study of emissions, methane emissions were mapped at the site. As has also been seen in other LFG studies, the emission through the soil surface was found to be occurring very inhomogeneously. At most of the surface no emissions were seen, but locally very high flux rates were measured using a static flux chamber. Emission rates were measured from identified emission "hot spots" during four campaigns. The average total emission from these hot spots was found to be 182 kg CH_4 d^{-1}, but large temporal variation was seen. Using a tracer method developed in connection to this study, the LFG emission from a leachate collection system at the site was assessed. Adding emission rates measured once from each of 16 leachate "wells" at the site, it was estimated that 351 kg CH_4 d^{-1} was emitting through this pathway. This amount corresponded to half of the measured total emission. As a result of the baseline study, measures were taken to reduce emissions through the leachate collection wells and some of the slopes as a part of installing the biocover system. The total emission measurements and laboratory studies on methane oxidation performance of the compost biocover material (part of a related study) were the basis for dimensioning the biocover windows.

Performing emission measurements during a one year period after installation of the biocover system at Fakse landfill was done to evaluate the system's efficiency with regards to methane oxidation, and thereby reduction of greenhouse gas emissions from the site. Flux chamber measurements repeated during the monitoring period on 12 locations of the biocover windows indicated high oxidation efficiencies at these locations. In addition, soil gas profiles indicated methane oxidation took place within the biowindows. By measuring the total methane emissions from the site it was, however, concluded that most of the emissions measured before implementation of the biocover was still occurring after installing and improving the system. The overall efficiency seemed to be increasing over time, and the lowest emission was measured during the last performed measurement campaign, which suggested a reduction in methane emissions of approximately 29%. Mapping emissions at the site showed that significant emissions were occurring through the leachate collection system, in spite of several measures taken to seal off this pathway. Also, high methane emissions were observed at hot spots on the biocover windows, indicating that the load was unevenly distributed to the biocover area leading to overload in parts of the system resulting in reduced efficiency.

Dansk sammendrag

Emissioner af metan fra lossepladser er den største kilde til udledning af drivhusgasser fra affaldssektoren. Begrænsning af disse emissioner er potentielt omkostningseffektivt, da emissionerne sker inden for relativt afgrænsede områder. Lossepladsgas (LFG) dannes ved nedbrydning af organisk stof i det deponerede affald og består hovedsageligt af metan (55-60 % v/v) og kuldioxid (40-45 % v/v). Gasproduktionen varer i flere årtier, og dermed efter deponering af affald er ophørt. Mikrobiel metan oxidation er blevet observeret i lossepladsers afdækningslag i en række undersøgelser under forskellige klimatiske forhold. Omfanget af metan oxidation, og derved reduktionen af emissioner af drivhusgasser er observeret at variere kraftigt, samt at være afhængig (blandt andre faktorer) af de fysiske egenskaber af dæklaget. Derfor bør det være muligt at designe afdækningslag med henblik på at maksimere metan oxidation, og derved reducere udledningen af drivhusgasser.

Dette studie omhandler en undersøgelse af implementeringen af et såkaldt biocover system i fuld skala på Fakse losseplads i Danmark, for at øge metan oxidationen. Effektiviteten af systemet evalueredes primært på baggrund af målinger af total metan emissioner før og efter implementeringen.

Biocover systemet på Fakse losseplads bestod af ti biocover "vinduer", hvilke var områder i det eksisterende jorddække, hvor den eksisterende lav permeable afdækningsjord var blevet udgravet, hvorefter et 15 cm grus "gas distributionslag" blev installeret overlejret af et 1 m lag af aktivt materiale, (komposteret haveaffald). Det samlede areal af biocover vinduerne var 5000 m^2, mens det samlede areal af lossepladsen var 12 hektar. En undersøgelse af LFG emissioner fra Fakse losseplads blev udført før biocover systemet var designet og konstrueret. Denne undersøgelse havde flere formål, hvoraf den ene var at kvantificere den samlede metan emission, til brug som sammenligningsgrundlag for lignende målinger foretaget efter implementeringen af biocover systemet. Den samlede emission før gennemførelsen blev målt i to kampagner. Den anvendte metode til bestemmelse af samlet emission, var at kontinuerligt frigive et luftformigt sporstof fra lossepladsen, mens der blev målt koncentrationer nedvinds af sporstof og metan med en præcis, mobil detektor. Resultaterne af disse målinger var ens. Under den første kampagne blev den total metan emission målt til 749 kg CH_4 d^{-1}, mens emissionen blev målt til 732 kg CH_4 d^{-1} ved den anden kampagne. Som en del af de indledende undersøgelser før implementering af biocover systemet, blev metan emissioner kortlagt. Som det

også er set i andre LFG undersøgelser, blev emissionen fundet til at ske særdeles inhomogent. På det meste af overfladen var der ingen emission, men lokalt blev meget høje emissioner målt ved hjælp af flux kammer målinger underbygget af koncentrations screeninger. Emissioner blev målt fra identificerede "hot spots" i løbet af fire kampagner. Den samlede emission fra disse hot spots blev fundet at være 182 kg CH_4 d^{-1} (gennemsnit af fire målekampagner), men der blev observeret en høj variation af fluxrater over tid. LFG emission fra et perkolat opsamlings system på stedet blev kvantificeret ved hjælp af en sporstof metode udviklet i forbindelse med dette studie. På baggrund af denne måling blev det anslået, at emissionen gennem perkolat opsamlingssystemet var 351 kg CH_4 d^{-1}, hvilket svarede til halvdelen af den målte totale emission. Som et resultat af kortlægningen af emissioner, blev der truffet foranstaltninger for at reducere emissionerne gennem perkolat opsamlings brønde og nogle af skrænterne som en del af installationen af biocover systemet. Målingerne af den totale metan emission og laboratorieundersøgelser af metan oxidation i kompost biocover materialet (en del af et tilknyttet studie) var grundlaget for dimensionering af biocover vinduerne.

Biocover systemet blev evalueret i en et år lang periode efter systemet var færdiggjort. Resultater af flux kammer målinger gentaget i overvågningsperioden på 12 steder på biocover vinduerne påviste høje metan oxidation effektiviteter disse steder. Gas profiler prøvetaget samme steder påviste også metan oxidation. Men fra målinger af total metan emission fra lossepladsen blev det konkluderet, at størstedelen af metan emissionen målt før etablering af biocover systemet fandt sted efter, hvilket altså tydede på en langt lavere samlet effektivitet sammenlignet med målinger udført specifikke steder på biocover vinduerne. Den samlede effektivitet syntes at være stigende over tid, og den laveste emission blev målt i de sidste udførte måle kampagne, hvilken tydede på en reduktion i metan emission på ca. 29 %. Kortlægning af emissioner på stedet viste, at store emissioner stadig fandt sted gennem perkolat opsamlings systemet, på trods af flere foranstaltninger gjort for at reducere denne emission. Derudover blev der fundet, at en del metan emitteredes gennem ”hot spots” på selve biocover vinduerne, hvilket tydede på en ujævn belastning af disse, og dermed en reduceret samlet effektivitet.

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1 Introduction

Landfilling of waste remains the most used method for waste management. In the European Union, 1.3 billion tons of waste is produced annually (European Communities, 2005). Approximately half of the municipal solid waste is landfilled, though this fraction varies significantly between member states. Degradation of organic matter causes emissions of landfill gas (LFG), which main constituents are methane (CH_4) (55-60% v/v) and carbon dioxide (CO_2) (40-45% v/v), while many other gaseous constituents are present in lesser concentrations. LFG is the most important contributor to climate change from the waste sector due to the amounts of CH_4 emitted globally (Bogner et al., 2007). CH_4 is regarded as the second most important greenhouse gas after CO_2 due to the amounts of anthropogenic emissions released and a relatively high global warming potential (GWP). GWP is a commonly used term to compare the relative impacts of different greenhouse gases, and refers (in simple terms) to a compound's ability to absorb infrared radiation of 1 kg released relative to that of 1 kg released CO_2 over a given period of time (IPPC, 1990). The GWP of CH_4 is 25 over a period of 100 years (Forster, P, 2007). Resent research shows that the relative importance of green house gases changes, when taking atmospheric chemical interactions into account. The actual importance of CH_4 as a greenhouse gas is thereby potentially higher than used in carbon-trading schemes or the Kyoto Protocol (Shindell et al., 2009). The atmospheric concentration of CH_4 has risen from approximately 715 parts per billion (ppb) in pre-industrial times to 1774 ppb in 2005. This is by far the highest concentration of CH_4 during the last 650,000 years, which has been determined from ice core studies (IPPC, 2007). The major anthropogenic sources leading to this increase in atmospheric abundance of atmospheric CH_4 are: energy production, landfills, ruminants, rice agriculture and biomass burning (IPCC, 2001). Since landfills, in comparison, constitute "point sources" of emissions, it may be most efficient to focus on reducing landfill CH_4 compared to other sources of CH_4 emissions.

1.1 Methane oxidation in landfill covers

Naturally occurring microbial CH_4 oxidation in landfill top covers prevents a fraction of the CH_4 produced in deposited waste from being emitted to the atmosphere (Whalen et al., 1990; Jones & Nedwell, 1993; Bogner et al., 1995, Scheutz et al., 2009). Microbial CH_4 oxidation is attributed to a group of microorganisms called methanotrophs, which have been found in many different

ecosystems and climates (Keller et al., 1986; Born et al., 1990; Huber-Humer, 2004). CH_4 oxidation results in the following overall reaction (Scheutz et al., 2009):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat}$$

$$\Delta G° = -780 \text{ kJ mol}^{-1} CH_4$$

For CH_4 oxidation to occur, both CH_4 and oxygen (O_2) needs to be available. In landfill covers, CH_4 is emitted through the cover from the source, which is the landfilled waste mass. Oxygen is not present in LFG, but is supplied from the atmosphere via diffusion. As a result of this, the process occurs at a relatively confined horizontal "layer", where both CH_4 and O_2 are available. In Scheutz et al., 2009, the findings on laboratory and field studies on CH_4 oxidation in landfills performed so far are reviewed. Studies on laboratory simulated landfill soil covers show that the active zone regarding CH_4 oxidation is within the upper 30 to 40 cm of a landfill cover (Jones & Nedwell, 1993; Czepiel et al., 1996, Scheutz et al., 2004). The studies referred to in Scheutz et al., 2009 shows varying methane oxidation rates in cover soils determined in batch experiments ranging several orders of magnitude from 0.0024 µg CH_4 g^{-1} h^{-1} in a sandy clay loam found by Boeckx & Van Cleemput, 1996 to 173 µg CH_4 g^{-1} h^{-1} measured in a silty loam by Börjesson, 1997. In column studies simulating landfill covers, differences in CH_4 oxidation rates have been observed, ranging between 22 and 230 g CH_4 m^{-2} d^{-1} (Scheutz et al., 2009). Many factors may affect the CH_4 oxidation process. Both CH_4 and O_2 need to be available. In case of a high LFG flux, the process may be limited by the amount of O_2 available. Since the CH_4 oxidation process is a net consumer of gas, "self aeration" may occur within the CH_4 oxidative zone. Environmental factors such as temperature and soil moisture have also been found to be important. Although CH_4 oxidation has been observed under temperatures near 0 °C (Christophersen et al., 2000; Einola et al., 2007) the optimum temperature is 25 to 35 °C (Scheutz et al., 2009). Lack of moisture may reduce the process significantly. Analogue to the described "self aeration" caused by CH_4 oxidation, the process produces heat and moisture, which may mean that the process itself provides improved conditions depending on the rate of oxidation. Other factors such as nutrient availability and the physical properties

of the cover material, which affect the gas flow and thereby oxygen supply, also affect the rate of oxidation. Since large variations in oxidation rates are reported as a result of varying conditions, it may be feasible to engineer landfill covers to optimize CH_4 oxidation by creating improved conditions in order to reduce the global warming impact from these sites.

1.2 Optimization of methane oxidation in landfill covers

LFG extraction and utilization systems are now mandatory in many countries, but since LFG is produced in landfills over several decades (Christensen et al., 1996), CH_4 emissions occur uncontrolled from older landfills. Also, considerable LFG emissions occur before and after the operational period of LFG collection systems (Huber-Humer et al., 2008). Low cost passive technologies to mitigate greenhouse gas emissions from landfills are subject of present research (Scheutz et al., 2009). Biocovers, where the cover of the landfill is modified or constructed in a way to optimize conditions for biological CH_4 oxidation is a potential low cost technology to mitigate CH_4 emissions from landfills. Biocover technology is also relevant for newer landfills as supplement to LFG extraction, or as sole LFG remediation for landfills containing waste with low organic content, and thereby low CH_4 production per ton of waste. LFG extraction systems do not capture all LFG produced in landfills (Börjesson et al., 2009), and LFG mitigation systems such as biocovers can further reduce the environmental loads from landfills when used in conjunction with LFG extraction systems. Cost efficiency of biocover systems is potentially very high when implemented in connection with the final covering of a landfill, since biocovers can be part of the final covering and require minimal maintenance.

Recently, a few field trials in pilot scale biocovers and biofilters have taken place at several locations. Powelson et al., 2006, Gebert and Groengroeft, 2006 and Dever et al., 2007 describe pilot scale biofilter systems. Biofilters vary from biocovers in the sense that biofilters are constructed as separate units, to which landfill gas is led via pipes either passively or by pumping. In 1999, two biocover field trials in Austria were initiated on two different landfills (Huber-Humer, 2004; Huber-Humer et al., 2009). At one of the landfills, five 625 m^2 test cells of varying design including one control cell with no active material were constructed and monitored. At the second landfill, six 900 m^2 test cells were installed. At these trials, several designs were tested, where the active materials were composted municipal solid waste and sewage sludge compost. Soil gas probes, CH_4 surface screenings and flux measurements were used to evaluate the

performance of these biocover systems. These point measurements showed a reduction in CH_4 emissions of up to 98 to 100%, where emissions were measured throughout the year when using a 0.3 coarse gravel gas distribution layer and a compost CH_4 oxidative layer (Huber-Humer, 2004). Barlaz et al., 2004 describes performance testing of a large scale biocover system installed at a disposal unit in Outer Loop landfill in Kentucky, USA. The biocover consisted of a one meter thick yard waste compost layer placed on a 0.15 m layer of tire chips functioning as gas distribution layer which, in turn, was placed on a 15 cm clay layer. The soil cover surrounding the biocover areas was approximately one meter thick. Given orders of magnitude higher measured permeability of the compost material compared to the clay soil cover, more gas would be expected to flow through the biocover. CH_4 oxidation was evaluated through static chamber surface flux measurements and stable carbon isotope measurements. The CH_4 emission from the Outer Loop biocover was measured to be much lower than from the surrounding soil cover, and was in many cases negative, suggesting uptake of atmospheric CH_4. Also, static isotope measurements showed that CH_4 oxidation did occur in the biocover, and suggested that 55% of the CH_4 reaching the biocover was oxidized. The measurements did not show how much of the total CH_4 produced in the landfill cell that was oxidized in the biocover.

Einola et al., 2009 describes implementation of a landfill cover in full scale designed to facilitate biological CH_4 oxidation at Aikkala landfill, Finland. The 3.9 ha landfill was equipped with CH_4 oxidative layers integrated into a multilayer final cover, covering the entire site. LFG was passively fed to the biocover material through a system of gas wells and distribution pipes, which were installed prior to placing the biocover material. The biocover here consisted of two layers: A 50 cm compost/peat mixture layer on top of a layer of 50 cm mineral soil. CH_4 oxidation was quantified by use of a mass balance approach relying on point measurements of CH_4 and CO_2 flux from the biocover, measurements of LFG composition, as well as estimates of the significance of CO_2 production through respiration and uptake of carbon in soil. CH_4 oxidation efficiencies of 80-100% were measured at the majority of the measuring points through this approach (Einola et al., 2009).

Table 1.1 Overview of large or full scale biocover field trials

Reference	Location	Description of biocover	Evaluation approach	Reported CH_4 oxidation rate
Barlaz et al., 2004	Outer loop landfill, Kentucky, USA	Biocover zones established in the existing 1m clay soil top cover. Active material: composted yard waste	Static flux chamber measurements, stable isotope measurements	55 % oxidation when positive CH_4 flux was observed. Atmospheric CH_4 uptake was observed in 52% of tests.
Stern et al., 2007	Leon County Landfill, Florida, USA	Three 7.6*7.6 m biocover test cells placed on top of existing soil cover. Active material: : composted yard waste	Static flux chamber measurements, stable isotope measurements	41- 64 % oxidation three months after installation
Cabral et al., 2009	St-Nicéphore landfill, Quebec, Canada	Three 2.75*9.75 m experimental plots installed in a finally covered area of the landfill. Active material: compost/sand mixture	Stable isotope measurements, static flux chamber measurements	Up to 89%, depending on location
Huber-Humer, 2004 Huber-Humer et al., 2009	2 landfills, Austria	Landfill 1: Four 625 m^2 test cells and 1 control. Landfill 2: 6 900m^2 test cells. Active materials: Sevage sludge composted with wood chips, composted municipal solid waste	Soil gas probes, CH_4 screenings, Flux tunnel	68.1 to 99.7 % oxidation
Einola et al., 2009	Aikkala landfill, Finland	The entire landfill (area: 3.9 Ha) was covered with a CH_4 oxidative layer fed via a passive gas collection and distribution system. Active material: mixture of peat and sludge compost	Static flux chamber measurements	>46 % at one of four measurement campaigns

None of the full scale biocover studies performed so far have examined the total CH_4 mitigation efficiencies based on total emission measurements. Since these assessments were based on point measurements, undetected significant releases of LFG may have led to overestimation of CH_4 mitigation.

This thesis concerns a project, which was carried out from 2005 to 2008 at Fakse landfill in Denmark, where a biocover system was implemented in full scale. The main project objective was to reduce greenhouse gas emissions from Fakse landfill by use of a biocover system constructed of locally available materials and to measure the efficiency of the system relative to the total emission as accurately

as possible. The efficiency was to be determined primarily by comparing measurements of total CH_4 emission from the site before and after installation of the biocover system. This would be the first time such an assessment was done. More local studies on CH_4 oxidation were also performed, including performance evaluation through mass balance studies and stable isotope measurements. These measurements were done in parts of the biocover system using soil gas probes and flux chamber measurements.

1.3 Research objectives

The main objective of this study was to design, implement and evaluate a full scale biocover system at a modern landfill for the purpose of reducing the site's emission of CH_4, thereby reducing its global warming impact.

Several aspects were studied:

- Comparing the site's total emission of CH_4 prior to and after installation of a biocover system to determinate the net efficiency in reduction of emissions.
- Mapping emissions from the site to evaluate emission pathways at this type of landfill before and after installation of a biocover system.

2 Overview of methodology

The aim of this section is to present an overview of the methodology used for designing and implementing the biocover system at Fakse landfill, and subsequently for monitoring the biocover system's performance with regards to reducing the site's total CH_4 emissions. Some actions, which were important as a part of planning and monitoring the biocover system, were carried out by other project participants and are thus not described in further detail in this thesis. They are briefly presented here, since results of these related studies are referred to in this thesis, and in order to provide a more complete overview of the actions taken to realize the project.

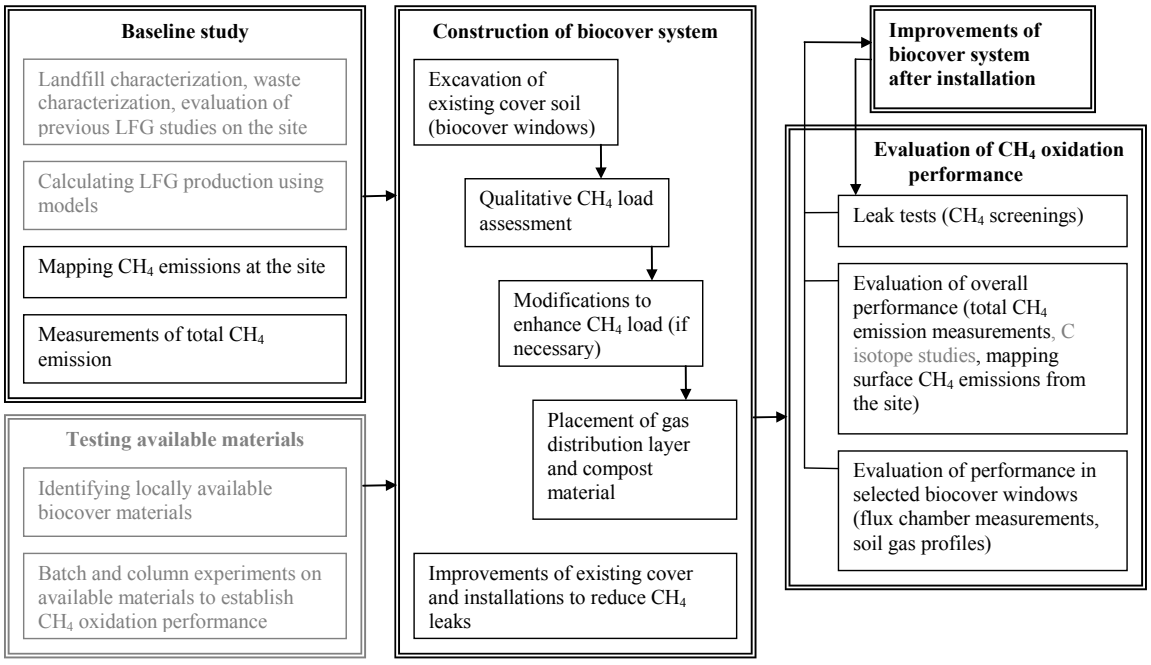

Fig. 2.1 Overview of methodology used for designing, implementing and monitoring the biocover system at Fakse landfill. Actions, which are outside the focus of the study presented in this thesis, are marked in grey in this figure. Methods and results regarding the baseline study are described in Fredenslund et al., III and Scheutz et al., II. Testing available materials are described in Pedersen et al., 2010. Methods and results of the remaining activities are presented in Fredenslund et al., IV

The first action taken with regards to the biocover project was a landfill characterization done as part of the baseline study (see Fig. 2.1), where data such as waste types, waste amounts and waste ages from different disposal units on

the site where collected in cooperation with the landfill operator. A characterization of the existing soil cover was done by soil sampling followed by grain size characterization laboratory measurements. Based on the available waste data, several LFG production models were used to assess the LFG production. The CH_4 emissions from the site were mapped using gas surface screenings, flux chamber measurements and tracer methods, which main purpose was to identify main LFG emission pathways. The site's total CH_4 emission was measured, the results of which had two important purposes. One was to establish a baseline value, to which post installation total emission measurements could be compared. By doing this, the overall efficiency of the biocover system could be determined. The second purpose of the total emission measurements was to determine the potential total load to the biocover system, which was used as basis for dimensioning the system.

From results of the baseline study, a design concept of the biocover system at Fakse landfill was developed. High permeable regions of the existing soil cover, so called "biocover windows", were to be established. These were filled with an active material in which CH_4 oxidation would reduce the landfills emission of CH_4. The choice of active material was done based on findings of the task referred to in Fig. 2.1 as "Testing biocover materials". Here, material availability was determined, and available materials were tested in batch and column experiments to assess CH_4 oxidation performance, which was a crucial parameter to examine to form basis for an appropriate dimensioning of the biocover windows.

Establishing the biocover windows was one of two main actions regarding the construction of the biocover system. The other main action was to improve the soil cover, where high CH_4 emissions were seen during the baseline study, as well as capping leachate wells which were found to be an important source of LFG emissions from the site. As shown in Fig. 2.1, constructing the windows consisted of four steps. First, the soil cover was removed from areas marked on the site where the windows were to be placed. Then a quantitative assessment of the CH_4 emission from the excavated area was done using a handheld CH_4 analyzer. If the emission was found to be low (concentrations measured did not exceed approximately 50 ppmv CH_4), initiatives were taken in an effort to increase LFG load to the biocover window. Lastly, the gas distribution layer and compost layer were placed in the excavated area.

The evaluation of the biocover systems performance consisted of three main parts. A simple, but important, part was leak testing, where a handheld CH_4 analyzer was used to qualitatively assess if and where significant emissions ("leaks") were occurring from areas outside of the biocover windows, or "hot spots" on the biocover windows. With regard to evaluation of the overall performance, total CH_4 emissions were measured, from which the results could be compared to previous similar measurements done before installation of the biocover. In this way, the actual total reduction in greenhouse gas emissions and the efficiency of the system could be evaluated. In connection to these measurements, stable isotope measurements were also performed to assess total CH_4 oxidation. As a part of the evaluation of the total performance, a measurement campaign was performed, where surface CH_4 emissions were mapped. This was performed to quantitatively evaluate where CH_4 was emitting from the site after installation of the biocover was complete, and which pathways of emissions (for example hot spots in the biocover windows) were significant compared to the measured total CH_4 emission. Finally, CH_4 oxidation in the biocover windows was studied at selected locations by use of soil gas profiles and flux measurements performed under different weather conditions. Initial performance testing showed the need for some improvements to be made. These improvements were done within the one year period of testing the installed biocover system.

3 Measuring landfill gas emissions

3.1 Nature of landfill gas emissions

To be able to make meaningful interpretations of results of LFG emission measurements, it is important to consider how LFG is typically emitting from landfills and which factors are affecting emissions. As described in the introduction, degradation of materials in landfilled waste causes a production of LFG consisting of mainly CH_4 and CO_2 and other organic compounds in lesser amounts (Scheutz et al., 2009). As a result of this, two types of mechanisms cause emissions of LFG from landfills to the atmosphere: diffusion and advection. Diffusive flow is induced by the difference in concentrations of different gas constituents between the landfill and the atmosphere. This means that, for example, CH_4 and CO_2 will emit from the landfill to the atmosphere by diffusion, whereas nitrogen (N_2) and oxygen (O_2) will tend to diffuse into the landfill. Advection will cause a net emission of LFG to the atmosphere, since the production of LFG causes a pressure buildup within the waste, and thereby a pressure difference leading to emission (Kjeldsen, 1996). However, since the barometric pressure is constantly changing, the conditions of advective flux are too. When the barometric pressure falls, the pressure difference increases, and an increased LFG emission is to be expected. A dramatic impact on LFG emission rates by changes in barometric pressure has been observed in many studies – including this study (Kjeldsen, P., 1996; Christophersen et al., 2001; Czepiel et al., 2003; Gebert & Groengroeft, 2006; Scheutz et al., 2009, Fredenslund et al., I). If a sharp increase in barometric pressure occurs, the direction of advective flux may be reversed, where the pressure in the atmosphere temporarily is higher than the gas pressure within the landfill. In Gebert & Groengroeft, 2006, where the performance of a passively fed biofilter system was studied, this phenomenon was observed on several occasions. Another factor which affects advective flow is wind, which may cause local differences in pressure conditions on a landfill surface.

LFG emissions are often found to occur with a high degree of spatial and temporal variation (Bogner et al., 1997; Lewis et al., 2003, Scheutz et al., 2003, Scheutz et al., 2008). Temporal variations may be caused by factors such as change in barometric pressure as described, whereas spatial variations can be attributed to local differences in conditions for gas transport through the soil cover or waste mass of a landfill. High emission areas are likely to be found at

high permeable features of the landfill surface such as slopes, where a thinner and less compacted soil cover is often seen (Börjesson et al., 2000; Fredenslund et al., III). Point releases from installations such as gas vents and leachate collection systems may also constitute significant pathways of LFG emissions (Fredenslund et al., I).

Also, the conditions may change over time due to factors such as change in soil gas transport properties caused by precipitation, which affects the emission pattern at a landfill. Therefore, in spite of the availability of precise gas measurement instruments and measurement methods, it remains a difficult task to perform assessments of LFG emissions.

3.2 Measurement techniques used in this study

This section provides an overview of the field methods used to quantify emissions and gas compositions at Fakse landfill, of which results are referred to in this thesis. Descriptions and specifications of the measurement equipment mentioned are not included here. This information, as well as more detailed method descriptions can be found in the appendices.

Landfill gas composition

Measuring LFG composition with regards to concentrations of CH_4, CO_2 and nitrogen (N_2) was done by using probes installed at the landfill for sampling of LFG and, subsequently, analyzing obtained samples using gas chromatography. The probes were 2.5 meter long, 4 mm internal diameter stainless steel tubes with six perforations at the tip. Installation of the probes was done by hand drilling through the top cover and hammering a steel pole further through the landfilled waste to create holes for installation of the probes. Approximately 20 cm of coarse sand was then added to the holes creating a filter from where LFG was to be sampled. After adding sand, the probes were installed, and a 30 cm layer of bentonite with water was added to the top of the coarse sand filter to prevent surface air from entering the filter. Lastly, clay soil was added.

Sampling was done by flushing the probes with LFG using a large syringe equipped with a stop valve and a septum, and afterward retrieving a 5 mL LFG sample using a 5 mL syringe through the septum. Samples were stored in evacuated glass vials. Fredenslund et al., I describe this method in more detail.

Flux measurements

Flux rates of CH_4 and CO_2 through the soil cover and biocover windows were measured using a portable static flux chamber coupled with either a handheld flame ionization detector (FID) for measurements of CH_4 flux only, or a photoacoustic gas monitor for simultaneous measurement of CH_4 and CO_2. Each flux measurement took approximately five minutes, where five to seven concentrations measurements were performed.

The portable stainless steel flux chamber was equipped with a manual fan, had a height of 20.5 cm and covered an area of 755 cm2; the volume was thereby 15.5 L. The chamber had fittings allowing gas sampling or attachment of other equipment such as pressure gauges while measurement of gas flux was performed. Fredenslund et al., I describes this method in more detail.

Tracer release measurements of local emissions

In connection with this study, a tracer release method was developed to measure LFG emissions from the leachate collection system (leachate wells and leachate pumping station). The principle of this method was to release carbon monoxide (CO) tracer at a constant rate of 2.7 L min^{-1} at the bottom of the leachate well, while continuously measuring downwind concentrations of LFG components CH_4 and CO_2 as well as CO tracer. To take background concentrations into account, which can cause error, LFG emissions were calculated using equation (1):

$$Q_{LFG} = Q_T \cdot \frac{C_{LFG} - C_{LFG,Background}}{C_T - C_{T,Background}} \qquad (1)$$

Q_{LFG} and Q_T are flow rates (L min^{-1}) of LFG component and tracer respectively, C_{LFG} and C_T are concentrations (ppmv) measured downwind and $C_{LFG,\ Background}$ and $C_{T,\ Background}$ are measured background concentrations (ppmv) of LFG component and tracer. Fredenslund et al., I describe this method in more detail.

Tracer release measurements of total emissions

The total CH_4 emission from Fakse landfill was measured using a tracer technique, where controlled nitrous oxide (N_2O) tracer gas release from the landfill was combined with time-resolved concentration measurements downwind from the landfill using FTIR (Fourier Transform Infrared) absorption

spectroscopy (Galle et al., 2001, Börjesson et al., 2009). The measurement principle is the same as the tracer release method used to quantify local emissions. Here, tracers were released at several locations on the landfill surface, which placements were determined by first screening surface concentrations of CH_4, since the placement of tracer release bottles should emulate the flow pattern of LFG from the site during measurement. Four or five tracer bottles were used for each measurement. Downwind measurements were performed several hundred meters from the site, which demanded a high precision measurement capable of measuring LFG and tracer concentrations in ppb range. The total CH_4 emission was calculated by applying equation (2) to measurements of downwind concentrations of CH_4 and tracer as well as tracer release rates:

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

Where Q_{tracer} is the known release rate of the tracer gas (L min^{-1}), C_{gas} and C_{tracer} denote the cross plume integrated concentrations above background (ppmv) (background measurements were performed prior to emission measurements) and x corresponds to distance cross the plume (between 200 and 1100 m for all cross plumes). Repeated plume integrations during a one to three hour period typically result in a robust estimate of average emission and variability for that time frame (including source variability and method uncertainties). Scheutz et al., III describes the method in more detail.

Submerged flux chambers to measure LFG load

A flux chamber method was developed and tested during this study for the purpose of measuring LFG load to the biocover windows. Flux chambers of approximately similar dimensions as the chambers used to measure surface flux were placed below the active compost material in the biocover windows. Two tubes running from the top of each chamber to the surface of the biocover were installed to enable flushing of the chambers. A manually operated fan was installed to mix the air within the chamber during measurements. Before each measurement atmospheric air was pumped into the 15 L chambers at a rate of

approximately 17 L min^{-1}, while air was pumped out of the chamber at the same rate using the second tube to flush the chamber. Each flux measurement was performed in the same manner as the surface flux measurements using the same photoacoustic gas monitor to measure CH_4 and CO_2 concentrations over time. Each measurement took five minutes.

In total, 72 measurements were performed on 12 locations using this method. At the same time, surface flux at the same locations was measured with the purpose of assessing CH_4 oxidation rates. However, the resulting flux values obtained by doing this led to the conclusion that the method applied as described here was not usable to measure the LFG load to the biocover windows. This was determined by comparing the measured load of CH_4 and CO_2 to the measured emissions at the same locations and times. In all cases, the moles of CH_4 and CO_2 exceeded the equivalent outflow by orders of magnitude. Though factors such as lateral gas transport, assimilation, and CO_2 dissolution in water may cause a difference in carbon input and output at a given time, the consistency of the high "load" measured led to the conclusion that the method was not working. The reasons for this conclusion were not definitively established, and thus the results of applying this method were not reported. An explanation could be that by flushing the submerged chamber with atmospheric air, a large concentration gradient was created leading to a high diffusion of LFG into the chamber, and thus a higher LFG flux than would occur if the chamber were not flushed.

4 Baseline study on emissions

A detailed study on landfill gas emissions at Fakse landfill was performed to provide part of the basis for design of the full scale biocover system. The field study was comprised of two parts: Total CH_4 emission measurements and local emission measurements to study the spatial variability in emissions.

4.1 Site description

Fakse landfill is located in South-eastern Zealand, Denmark. The landfill is divided into two sections. Section I, which is the oldest section, was mainly active from 1981 until 1997. After 1997 disposal at Fakse landfill has taken place at Section II, which is expected to be active until approximately 2040. At the time of this study, only a small part of the capacity of Section II had been used for waste disposal, and the location of deposited waste was at the far side of the landfill, several hundred meters from Section I. A total of approximately 660,000 tons of waste had been disposed of at Section I in the period 1981-2005. The dominating waste types are soil fill (26%), household refuse (23%) and mixed waste (21%). A natural layer of clay (15–20 meters in extent) functioning as a bottom liner is present beneath the landfill.

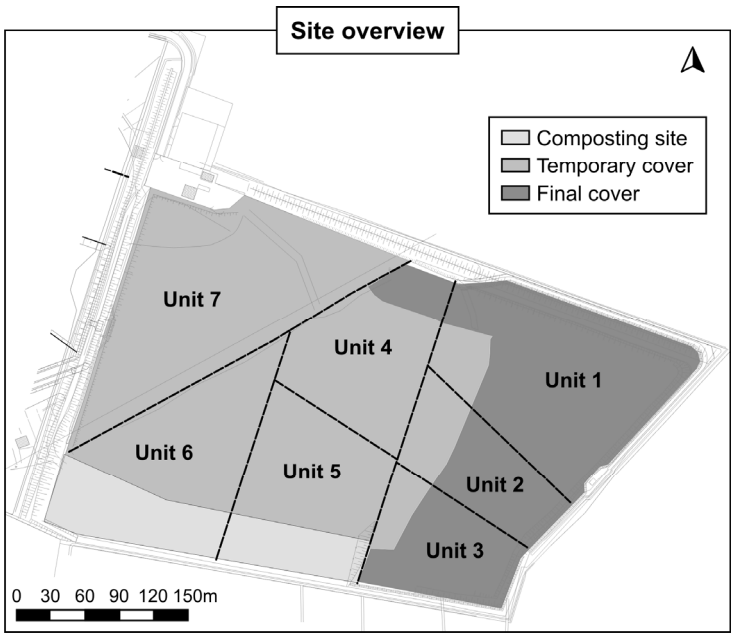

Fig. 4.1 Map of section I at Fakse landfill (Fredenslund et al., III). Section I is divided into 7 disposal units. At the time of the study, app. 1/3 of the landfill was finally covered

A draining layer consisting of 0.3 meters of gravel overlies the bottom liner. Leachate drainage pipes are placed in filter elements (coarse gravel) in trenches. The drainage pipes are made of PVC or PEH with diameters ranging from 95-130 mm and are placed 15-20 m apart. In each of the disposal units the drainage pipes are connected to an inspection well placed at the top of the unit and a collection well placed in the lowest point of the unit. From each collection well, leachate is led to a pumping station from where it is pumped to a municipal waste water treatment plant. No LFG extraction system was installed at Fakse landfill.

Fig. 4.1 shows a map of Section I at Fakse landfill, where the locations of the disposal units are given, as well as the extent of which final covering was in place during the project period. The disposal units in Section I were filled one at a time. Disposal began at unit 1 in 1981 and continued at unit 2 in 1984. The order of disposal corresponds to the names given to the disposal units, and the last unit in use was unit 7, which was active in the period 1993 to 1997. In all subunits, co-disposal of all received waste types was carried out. Some areas of Section I were finally covered – primarily disposal units 1, 2 and 3 (see Fig. 4.1). The remaining areas were temporarily covered. The final cover consisted of a 10 cm gravel layer topped by a 1 m layer of clayey soil, and an up to 50 cm layer of topsoil. Through particle size analysis, the soil type used for final cover was characterized as sandy clay loam (Fredenslund et al., III). The temporary cover was less homogenous than the final cover. The lowest clay content and highest content of larger particles (> 2mm) were found on the disposal units 6 and 7, which suggested that the gas permeability of the soil cover at this part of the landfill was higher than the remaining parts (Fredenslund et al., III).

4.2 Spatial variability in emissions

Surface methane emission

Initial CH_4 surface screenings suggested that the LFG surface emission was occurring very inhomogenously at Fakse landfill, and that a large part of the LFG emission occurred through “hot spots”, which were located mainly on slopes at the temporarily covered part of the site. The purpose of the surface CH_4 emission measurements was to evaluate the significance of these hot spots on both the final and temporary covered parts of the soil cover by measuring the emission through these hot spots and to compare the results to measurements of total CH_4 emission from the site. Four measurement campaigns were performed, where CH_4 concentrations near the surface were measured on a grid consisting of 155

marked locations at the site. At these campaigns, flux measurements were performed on located hot spots at the site.

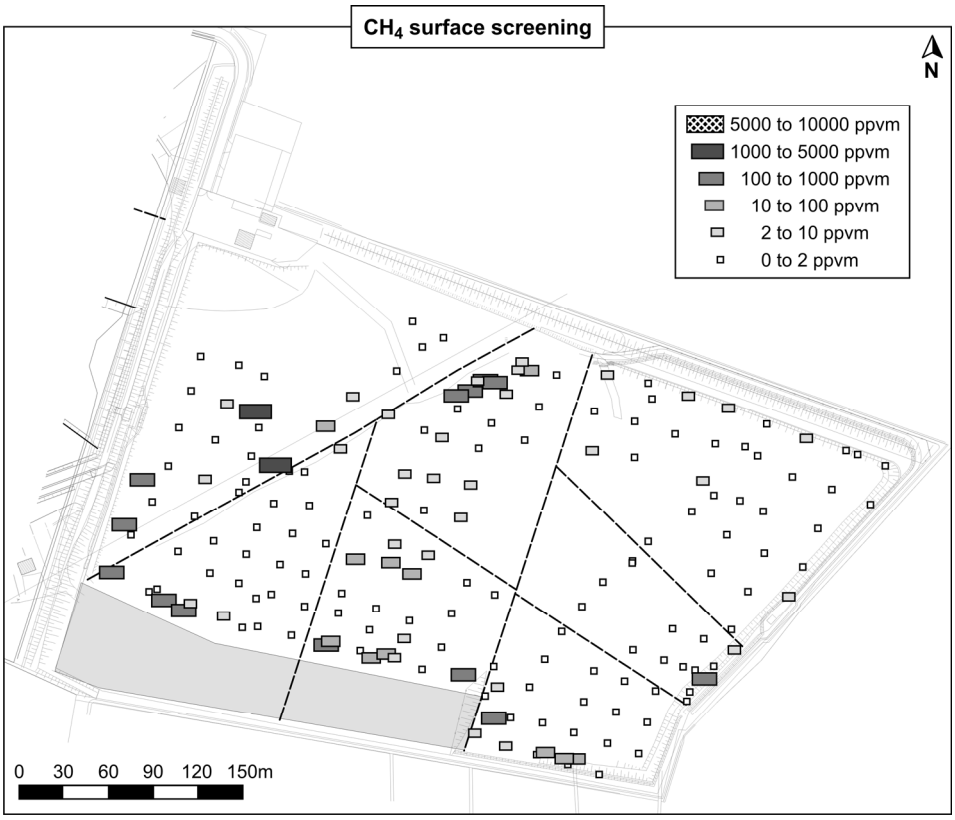

Fig 4.2 Measured CH_4 concentrations at grid points and hot spots at a screening (Fredenslund et al., III). Locations were recording using a high precision GPS. Varying size and color of the marked locations indicate concentration range

Fig. 4.2 shows near surface CH_4 concentrations measured during one of the four campaigns. At most of the 155 grid points, concentrations were near background level (approximately 2 ppmv). At 36 of the grid points, concentrations were above background level and at only 6 of these, the concentration exceeded 10 ppmv. The CH_4 concentrations measured at hot spots were much higher. The CH_4 concentrations at these locations were measured up to 10,000 ppmv. In general, the highest concentrations were found on the newer, temporarily covered disposal units (units 4, 5, 6 and 7). This was the case in all four campaigns. The results of the CH_4 concentration screenings confirmed the notion that LFG was emitting very inhomogenously from Fakse landfill. The results of the concentration screenings also suggested that the highest surface LFG emissions occurred through the temporary cover rather than through the finally covered part

of the landfill. This was confirmed from flux measurements, where much higher flux rates were measured on hot spots on the temporary cover. Average fluxes measured at the hot spots varied between approximately 5 to 4000 g CH_4 m^{-2} d^{-1}. Emission rates measured at the located hot spots and areas of the hot spots are listed in Table 4.1. The rates of CH_4 emission were determined by multiplying the average flux rate measured at the different measurement locations within the hot spot area with the measured area of the hot spot. Areas of the hot spots were established by using the FID and funnel to screen for CH_4 concentrations above ground level. First, the boundaries of the areas were screened (CH_4 concentration above 10 ppmv). Four marking poles were placed at the approximate locations of the corners of this border. This was followed by screening inside the boundary to check if elevated CH_4 concentrations were seen over the entire area. The boundary was screened again, and the four marking poles were adjusted to form a rectangle which corresponded to the approximate area of the hot spot. The combined area of the identified hot spots was 376 m^2 corresponding to approximately 0.4% of the total area of Section I.

Table 4.1 CH_4 emissions from hot spots at Fakse landfill during four measurement campaigns

Location	**Area of hot spot (m^2)**	**Number of measure-ment locations**	**CH_4 emission (kg CH_4 d^{-1})**					
			1st camp.	2nd camp.	3rd camp.	4th camp.	Avg.	St. dev.
Unit 1, near small slope	1	1	0.06	0.00	0.00	0.05	0.03	0.03
unit 2, near leachate pumping station	10	4	0.35	0.00	0.11	0.09	0.14	0.1
Slope on unit 3	35	3	0.44	0.65	0.27	0.49	0.46	0.1
Slope on unit 3	4	1	0.01	1.86	1.07	2.22	1.29	0.9
Slope on unit 5	56	6	1.43	1.80	4.53	8.08	3.96	2.7
Slope on unit 6	53	5	6.91	0.71	3.30	4.03	3.74	2.2
Slope on unit 7	90	2	22.54	88.67	56.58	31.52	49.83	25.7
Slope on unit 4	99	6	19.83	24.21	12.66	14.41	17.78	4.6
Slope on unit 7	25	1	19.49	6.97	104.13	262.82	98.35	102.1
Near electrical pole on unit 7	5	1	2.14	6.40	5.13	12.61	6.57	3.8
		Sum	73.2	131.3	187.8	336.3	182.2	97.8
Tendency in atmospheric pressure			↑	↓	-	↓		
Pressure gradient during measurement (hPa h^{-1})			0.15	-0.46	-0.02	-0.22		

Emission through leachate collection system

Initial CH_4 concentration screenings suggested that significant point emissions of LFG was occurring though the leachate collection system at Fakse landfill through so-called leachate wells which are horizontal, 1 m in diameter, concrete pipes that allow inspection of the leachate drainage pipes from the surface. One measurement campaign was performed at the site, where emission rates of each of these wells were measured using a tracer method described in Fredenslund et al, I. The measurements were done under relative stable weather conditions, since it was found that rise or fall in barometric pressure has a very high impact on emission rates and thereby would induce error (Fredenslund et al., I). Emission rates from each of the individual wells ranged from 1 kg CH_4 d^{-1} to 76 kg CH_4 d^{-1}. At two out of the 16 wells the rate of CH_4 emission was not measurable, since the concentration of CH_4 downwind from these wells was equal to the background concentration, which indicated zero emission. The sum of CH_4 emitting through the wells was 351 kg CH_4 d^{-1}, which was almost twice the average measured rate of emission through hot spots on the soil cover. In contrast to the surface emissions, a significant emission of CH_4 through leachate wells at the finally covered part of the landfill was observed. Fig. 4.3 shows measured emission rates from the leachate wells as well as average surface emissions from each disposal unit. Here, the difference in emissions through hot spots between the finally and temporarily covered disposal units is evident. From the finally covered disposal unit 7, CH_4 emission was mainly occurring through soil cover on slopes (155 kg CH_4 d^{-1}) rather than leachate wells (73 kg CH_4 d^{-1}); emissions from units 1, 2 and 3 were occurring mainly through the leachate wells (2 kg CH_4 d^{-1}), and only a small amount was emitting through the soil cover (2 kg CH_4 d^{-1}).

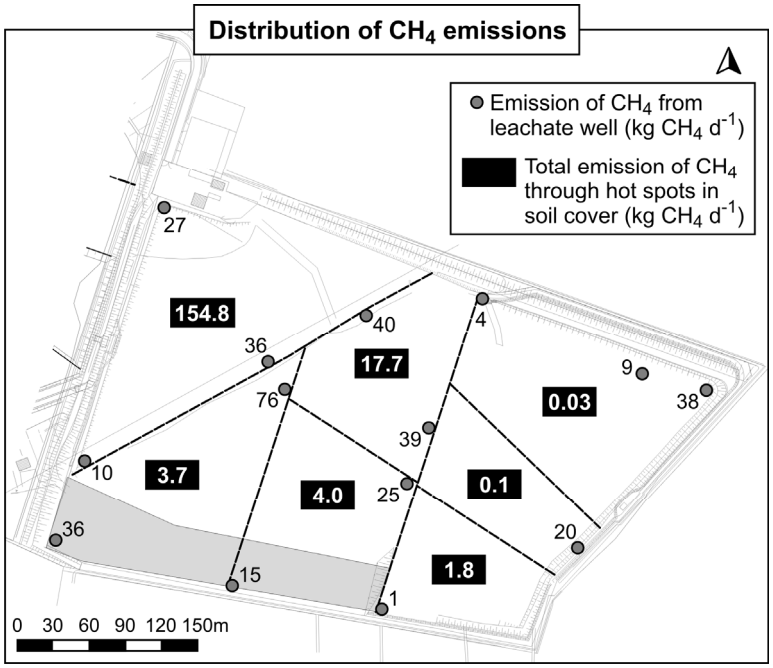

Fig 4.3 Distribution of CH_4 emissions obtained from flux measurements assessing surface emissions and tracer measurements to assess emissions through the leachate collection system at the site (Fredenslund et al., III)

Landfill gas composition

Soil gas probes installed at the site enabled sampling of LFG from the deposited waste material at ten locations at the site (Fredenslund et al., III). The composition of LFG sampled from gas probes at the landfill showed that the gas consisted mainly of CH_4 (average: 54 % v/v) and CO_2 (average: 35 % v/v) which was expected. At many of the locations, sampled LFG contained significant concentrations of N_2, which suggests influx of atmospheric air, since N_2 is not produced from degradation of the waste. No significant difference in compositions between LFG from finally covered units (1-3) compared to temporarily covered units (4-7) was observed. The CH_4 / CO_2 ratio varied between 1.2 and 1.9.

4.3 Total methane emission

Two campaigns were completed before installation of the biocover system (October 11, 2006 and February 19, 2007), where the total emission of CH_4 from Fakse landfill was measured using a tracer technique (Scheutz et al., II). In both cases, an initial leak search was done to determine the locations of tracer release bottles for the measurements. Fig. 4.4 displays the result of a leak search

performed at Fakse landfill. The overall leak search showed that the CH_4 emission from the old landfill part was localized to the leachate collection wells and some slope areas, verifying the results found during earlier surface screenings (Fredenslund et al., III). In addition to emissions from Section I, a "new" CH_4 source was identified near the western border of the landfill on Section II (See Fig. 4.4).

Fig. 4.4 CH_4 leak survey with FTIR across the Fakse landfill and composting area on of October 11, 2006. Color scale and dot size indicate concentration of CH_4 in ppb, sampled 2 m above ground. The scale is linear

During the first field campaign, four nitrous oxide (N_2O) tracer release points were established at Section I, and one CO tracer release point was established on the western part of Section II, where CH_4 screenings showed elevated CH_4 concentrations. This dual tracer approach was used in order to be able to differentiate emissions from Section I, where the biocover system was to be installed, and Section II (Scheutz et al., II). The downwind plume was traversed 26 times at a distance of about 840 m downwind from Section I during release of the tracers. During the experiment the wind velocity was on average 4.4 m s^{-1} coming from the east. The weather was cloudy, and the air temperature was 16 ˚C. During the 6 hour measurement, the barometric pressure dropped linearly at a rate of 0.3 hPa per hour, going from 1015.7 hPa to 1013.7 hPa.

The second field campaign was conducted February 19, 2007 during a period with the wind coming from the west-south-west (WSW). This made it possible to measure CH_4 emissions from the two sections separately, without the use of two different tracers. During the second field campaign a tracer experiment with N_2O-release from four point sources on Section I and one source from Section II. A total N_2O tracer release rate of 11.6 kg N_2O h^{-1} was used. In addition to this, a CO tracer was centered on the source at section II. The CO tracer release rate was 2.7 kg CO h^{-1}. During the experiment the wind velocity was on average 1.9 m s^{-1}. The weather was cloudy, the air temperature was 1.9 ˚C, and the barometric pressure was dropping with 0.2 mbar per hour, going from 1008.1 hPa to 1007.0 hPa during the 5 hour experiment. Plume measurements were conducted approximately 1100 m downwind from Section I.

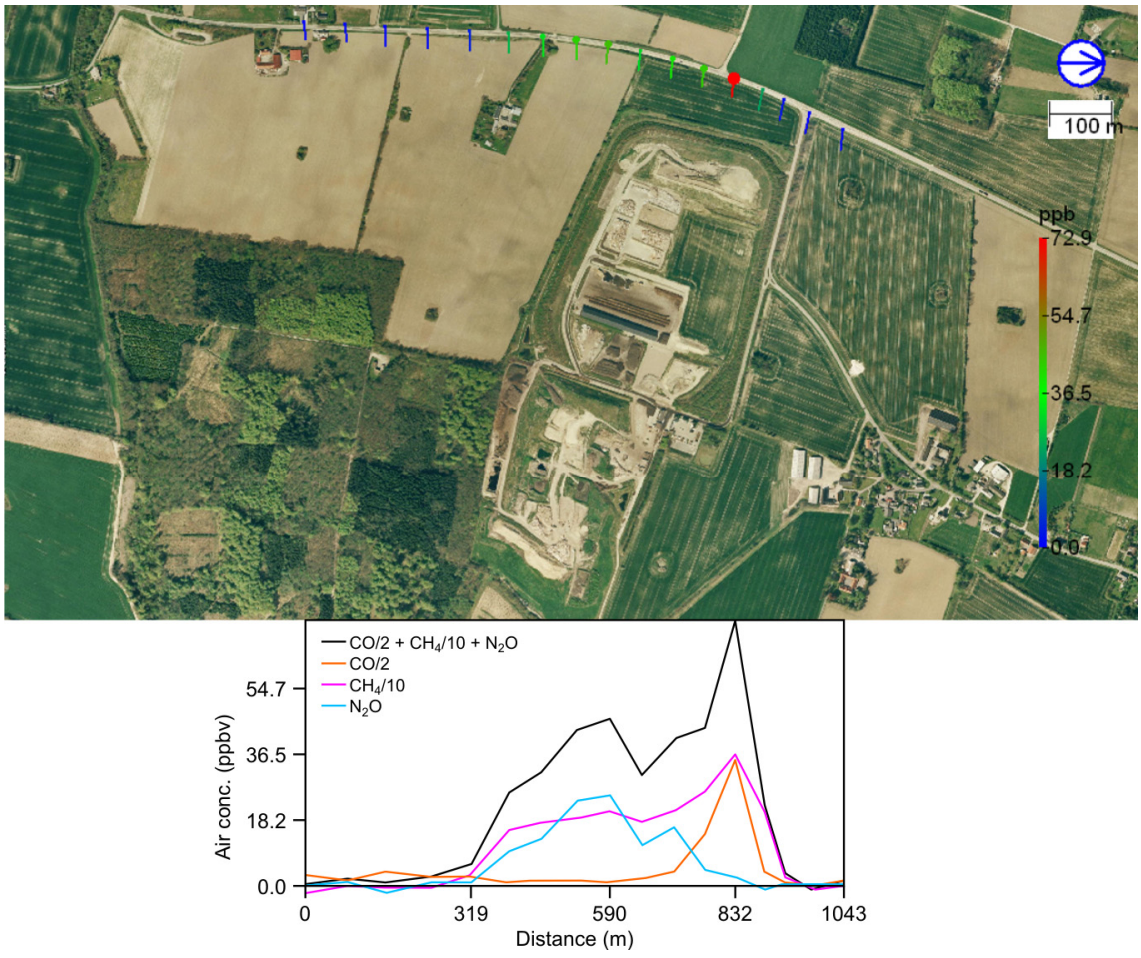

Fig. 4.5 Measured downwind concentrations of CH_4 as well as N_2O and CO tracers during the October 11, 2006 campaign. The lines from the measurements points shown on the map are directed towards the wind (Scheutz et al., II)

Fig. 4.5 shows the concentration measurements downwind the landfill site during the first field campaign. The tracer (N_2O) plume matches the CH_4 plume from section I, whereas the emission from section II, which was taking place near the western border of the landfill led to the highest measured concentrations of CH_4 due to the relative short distance between the source of emission and locations of measurements.

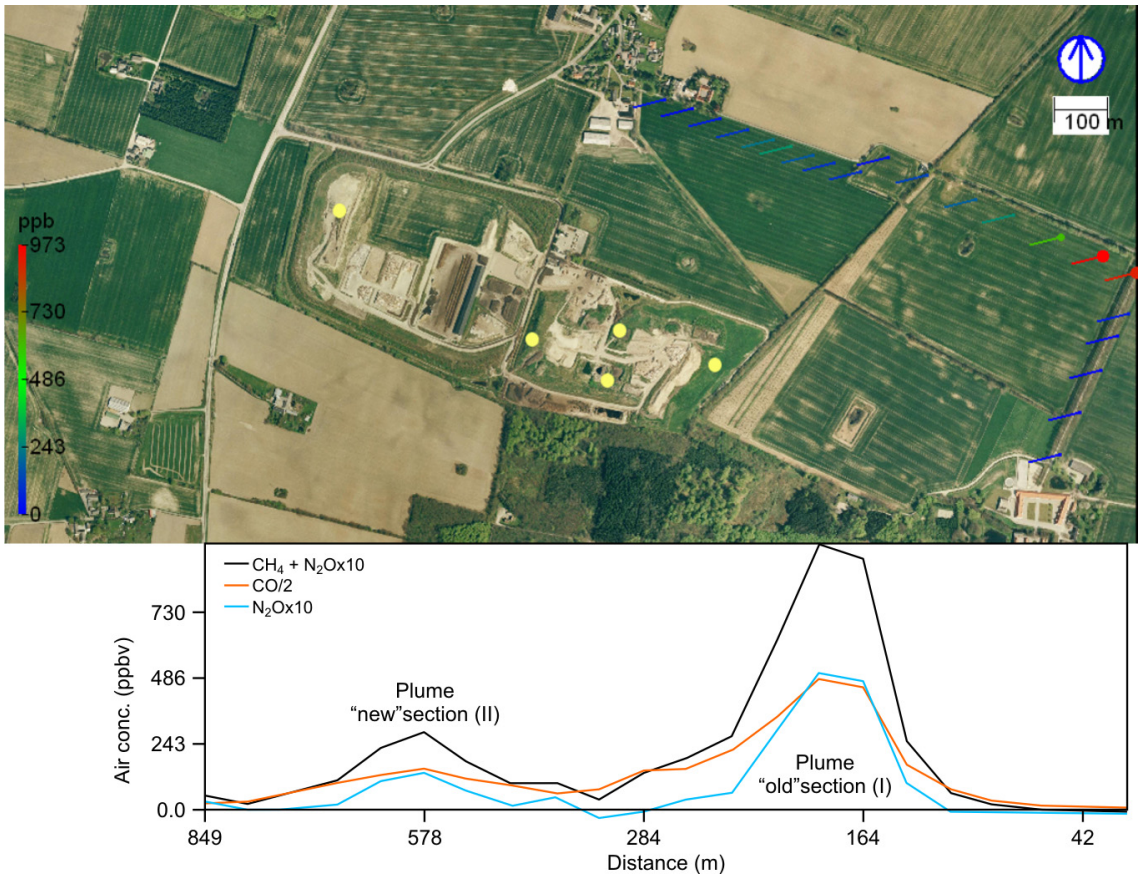

Fig. 4.6 Measured downwind concentrations of CH_4 as well as N_2O and CO tracers during the February 19, 2007 campaign. The lines from the measurements points shown on the map are directed towards the wind. The locations of tracer release bottles are shown as yellow circles (Scheutz et al., II)

The second measuring campaign performed February 19, 2007 was performed during more favorable wind conditions, since the plumes from Section I and Section II could be measured separately without the need to use two tracers (see Fig. 4.6). This led to an arguably higher accuracy when assessing the emissions from Section I during the second campaign. The measured emissions from Section I were found to be similar for the two campaigns: 748 kg CH_4 d^{-1} (first

campaign) and 732 kg CH_4 d^{-1} (second campaign) (Scheutz et al., II). With respect to the weather conditions during the two campaigns, both were performed during a relatively moderate decrease in barometric pressure (0.3 and 0.2 hPa h^{-1} for campaigns 1 and 2), both during light winds (4.4 and 1.9 m s^{-1}). The temperature was considerably higher during the first campaign (16 °C) than during the second campaign (2 °C).

4.4 Conclusions

Near surface CH_4 concentration screenings showed that emissions through the soil cover occurred mainly through relatively small "hot spots" located on slopes of a temporary soil cover. Flux rates measured at these hot spots varied between approximately 5 to 4000 g CH_4 m^{-2} d^{-1}. The CH_4 emission through these hot spots was estimated to be 182 kg CH_4 d^{-1} by using results of flux measurements (average of four campaigns), but large temporal variations in emissions were seen. CH_4 emission through the leachate collection system was measured to be 351 kg CH_4 d^{-1}, meaning that the leachate collection system was a very important route of CH_4 emission at Fakse landfill, since it constituted almost half of the total CH_4 emission measured from Section I. Based on the results of the baseline studies on emissions described in this section, a conceptual model of emissions, shown in Fig. 4.7, was set up:

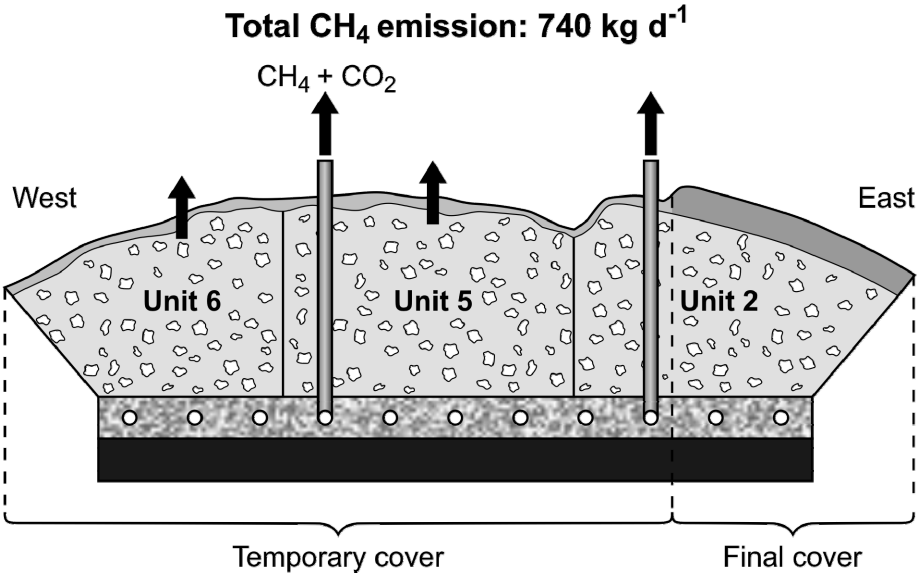

Fig. 4.7 Conceptual model of emissions derived from observations made during the baseline study on emissions at Fakse landfill (Fredenslund et al., III). Black arrows indicate pathways of LFG emissions

The total emission measurements provided the most reliable information on the potential total load to the biocover system, since large spatial variability in emissions caused uncertainty when assessing the total emission by adding up measured local emissions. The two main pathways of emissions were the leachate collection wells and hot spots in the temporary soil cover, where sometimes very large flux rates were seen. Surface CH_4 concentration screenings also suggested that more diffuse emissions occurred through the temporary cover, but surface emissions through the final cover were insignificant.

5 Description of the biocover system

The biocover system was designed to reduce CH_4 emissions by optimizing conditions for biological oxidation of CH_4 in high permeable compost filled regions of the cover of the landfill, which were passively fed with LFG (Fredenslund et al., III). The windows consisted of a gravel layer to distribute gas to the overlying compost layer where CH_4 oxidation was to occur. The thicknesses of the layers were approximately 100 cm (compost), and 15 cm (gravel layer).

The total CH_4 load was assumed to be equal to the average total emission measured before installation: 740 kg CH_4 d^{-1} (Scheutz et al., II). Production modeling done for each of the 7 disposal units on the site was used to determine the distribution of CH_4 load, and thereby the distribution of "biocover area" to the different parts of the landfill (Fredenslund et al., III). Column tests of available biocover materials were used to establish CH_4 oxidation capacity. CH_4 oxidation was observed in all tested materials. The material chosen for the biocover windows was composted garden waste (3-4 years old), since this material was available in large amount at Fakse landfill, and the CH_4 oxidation capacity was relatively high (average: 108 g CH_4 m^{-2} d^{-1}, maximum: 147 g CH_4 m^{-2} d^{-1}) (Pedersen et al., 2010). Based on the potential CH_4 load to the biocover system as well as the measured CH_4 capacity of the material, the total area of the biocover windows was decided to be 5000 m^2.

Since more than half of the CH_4 emitting from the site was found to occur through the leachate collection system (Fredenslund et al., I), gas barriers were made to prevent gas from emitting through leachate collection wells. The gas barriers were removable PVC caps covering the top of each leachate well. The edges of the caps were sealed using neoprene rubber seals between the concrete sides of the wells and the caps, and tightening the caps was done by use of stainless steel bands. All wells, where significant emissions were measured during the baseline study, were fitted with caps – 13 in all. The baseline study of CH_4 emissions from Fakse landfill showed significant emissions from the sides of a few of the slopes of the soil cover (Fredenslund et al., III). To reduce these emissions, a 10 – 20 cm layer of clay was added to two slopes on disposal units 4 and 7. Construction of the biocover system at Fakse landfill was started May 2007 and completed August 2007. As seen in Fig. 5.1, the largest windows were placed on the newer part of the site, since LFG production models predicted a

higher CH_4 production at these parts per area unit. The locations of the biocover windows were chosen considering both the emission pattern measured during the baseline study on emissions from the site and practical considerations, since some areas at the site were used for temporary storage of combustible waste and other uses.

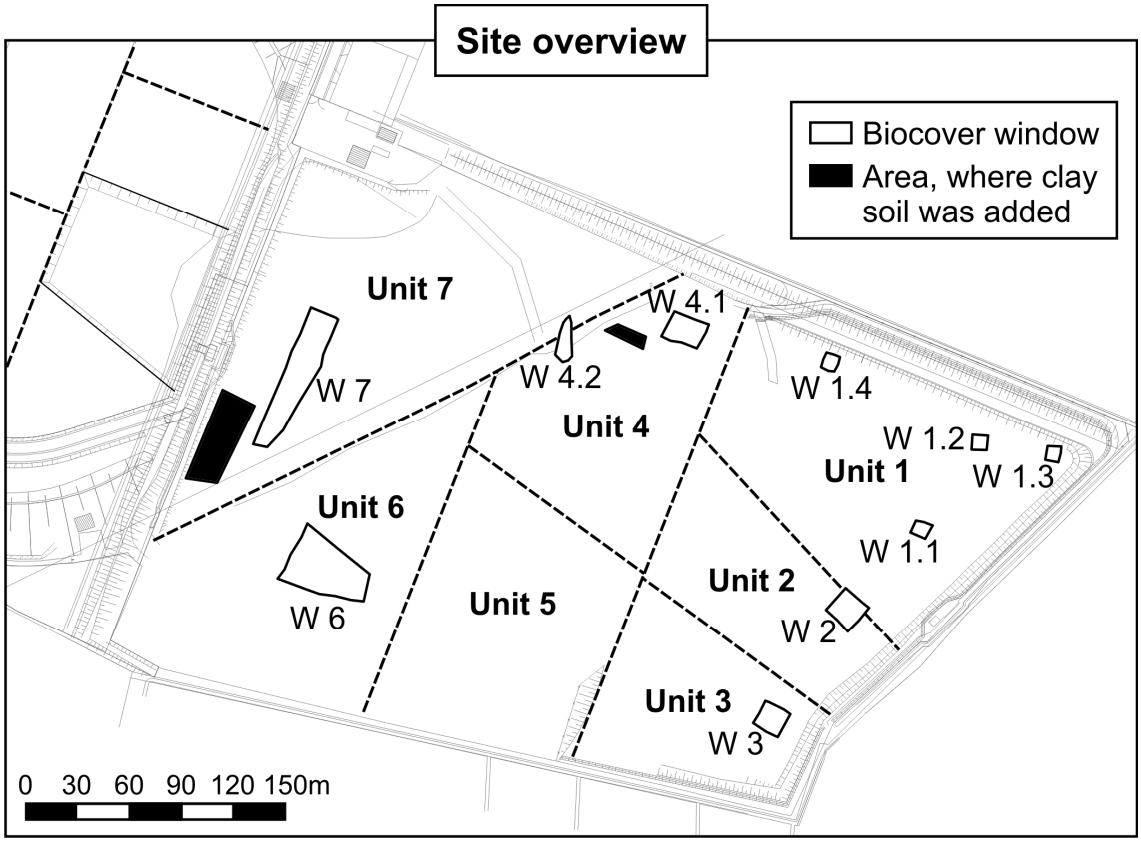

Fig. 5.1 Locations of biocover windows (white areas) and cover improvements (black areas) measured using a gps (accuracy ≈ 1cm) (Fredenslund et al., IV). Throughout this thesis the windows are distinguished by their numbers shown here

During construction, concerns about the permeability of the deposited waste beneath windows 2, 6 and 7 caused some further measures to be taken to increase gas transport to the windows. Beneath window 2 an approximately 4 meter thick layer of deposited clay soil was found. To increase the likelihood of LFG reaching the window itself, a grid of 16 10 cm diameter holes were drilled through the clayey soil layer, and filled with gravel. FID measurements showed that LFG was emitting through these holes. At windows 6 and 7, the waste beneath the excavated cover soil was found to be mixed with clay. To improve condition for LFG to flow to these biocover windows, 4 meter deep trenches at

the edge of the windows closest to the slopes were dug in the waste and filled with large tree roots, thereby creating “corridors” for gas to pass through. Three trenches were dug in both windows 6 and 7.

Initial performance testing of the installed biocover system (CH_4 concentration screenings and measurement of whole site CH_4 emission) suggested that a large part of the CH_4 emissions measured during the baseline study was still emitting from the site. Several improvements to the system were implemented to increase the CH_4 oxidation performance. These improvements were implemented in February and March 2008 and included the following actions:

- Sealing of the soil surface around capped leachate wells with bentonite
- Installing water locks at leachate inlet pipes to the leachate pumping station
- Establishing trenches beneath biocover windows 1.1, 1.2, 1.3 and 1.4 by use of the same procedure as for windows 6 and 7, when constructing the biocover system
- Covering two unused leachate recirculation wells with 1 m clay

6 Evaluation of biocover performance

6.1 Timeline of evaluation activities

The biocover system described in section 5 was realized at Fakse landfill in the period May 2007 through August 2007, starting with one of the smaller 100 m^2 biocover windows (window 1.1 – see Fig. 5.1). At this test window, flux measurements performed in the excavated area before placement of cover soil confirmed the validity of the window design concept, since a high CH_4 flux was observed (unpublished results). The order of constructing the remaining windows followed to some extent the number given to the windows, so that the windows 6 and 7 were the last completed. The performance of the system was monitored more than a year afterwards, to observe impacts of changing weather conditions (if any), and to see if lag in CH_4 oxidation efficiency was occurring, due to time needed to obtain a sufficient population of methanotrophs in the active material. Table 6.1 lists field activities, which comprise the evaluation of the biocover system, and shows when the improvements which seemed to have a positive impact on the system's performance were made.

Table 6.1 Timeline of field activities performed after installation of biocover at Fakse landfill (Modified from Fredenslund et al., IV)

	Oct-07	Nov-07	Dec-07	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08	Aug-08	Sep-08	Oct-08	Nov-08	Dec-08
Improvements of biocover system					×	×									
Leak tests	×						×								
Evaluation of performance in selected biocover windows	×	×	×	×			×			×			×		
Mapping spatial distribution in emissions													×		
Measurement of total CH_4 emission	×						×				×				×

The improvements of the biocover system were implemented since the first measurement of total CH_4 emission showed that the CH_4 mitigation was low, and

since leak tests confirmed that LFG was emitting from the site through other pathways than the biocover windows. After completing the improvements, the evaluation of performance in selected windows was done less intensely, since it was found more useful to perform a more rigorous study on the spatial distribution in emissions from the entire site, which was not planned for originally. The sections 6.2 and 6.3 describe main results of the performance testing of the system, which is also reported in Fredenslund et al., IV. Results from "leak tests" and "evaluation of performance in selected biocover windows (see Table 6.1) are described in section 6.2, whereas results from "mapping spatial distribution in emissions" and "Measurement of total CH_4 emission" are described in section 6.3.

6.2 Local measurements

Leak tests

As described in section 2, a simple but important part of the study was "leak testing", where surface CH_4 concentrations were monitored using a handheld FID. A measurement grid, such as the one used in the baseline study on emissions, was not used, but measurements were performed more ad hoc to perform qualitative assessment of the effects on emission patterns of installing the biocover windows, soil cover improvements and leachate well caps, and subsequently studying the effects of performing the improvements to the biocover system.

Both leak tests performed after installation of the biocover system and after the improvements made to the system suggested that CH_4 was emitting from the landfill from the biocover windows themselves as well as through hot spots in the soil cover and through the leachate collection system (Fredenslund et al., IV). Capping the leachate wells seemed to cause a significant emission through a leachate pumping station observed at the October 2007 leak test, which was not seen during the baseline study. As a result of this, water locks were installed at the leachate drainage inlets to the pumping station. The soil surface around the capped leachate wells was found to be a source of CH_4 emissions, and large quantities of bentonite were deposited around these wells in an effort to reduce the emissions by creating a low permeable sealing layer. Also, two unused leachate recirculation wells seemed to be the source of significant LFG emissions which were covered with approximately 1 meter of clay. More areas of elevated CH_4 concentrations were found on the biocover windows at the April 2008

screening (after improving the biocover system) compared to the first one, which might be due to a higher LFG load caused by the improvements to the biocover system. The total area of elevated CH_4 concentrations on the biocover windows was found to be approximately 550 m^2 corresponding to 11% of the total area of the biocover windows.

Soil gas profiles from test biocover windows

As part of the activity "Evaluation of performance in selected biocover windows" (see Table 6.1) soil gas probes were installed at four locations on each of the biocover windows 1.1, 1.4 and 7. Sampling from these probes was done in each of the measurement campaigns of which seven were performed from October 2007 to October 2008. The design of the probes enabled gas sampling from multiple depths; the samples were then analyzed for concentrations of CH_4, CO_2, O_2 and N_2 using a gas chromatograph. The results of these measurements were used to qualitatively study CH_4 oxidation at local level.

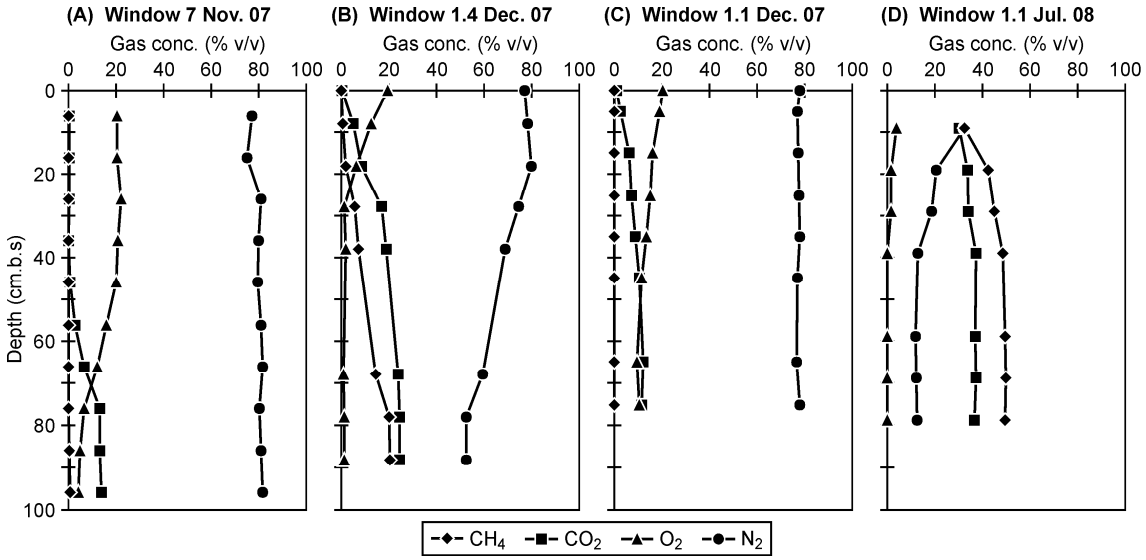

Fig. 6.1 Soil gas concentration profiles from biocover windows at four different locations (Fredenslund et al., IV)

Fig. 6.1 shows four selected gas profiles (CH_4, CO_2, N_2 and O_2) from the three test biocover windows. Fig. 6.1A, 6.1B and 6.1C are profiles sampled from the permanently installed nests of probes and locations of flux measurements, whereas 6.1D is a gas profile sampled from a hot spot, where a high surface emission of CH_4 was detected when screening surface concentrations using a

handheld FID. In Fig. 6.1A and 6.1B, gas profiles show that CH_4 is not present in significant concentrations, whereas CO_2 concentrations are approximately 15 % v/v. near the bottom of the profiles. Oxygen is present in all depths in all four profiles in Fig. 6.1A, which means that oxygen in these cases was present in the gas distribution layer and possibly in the top part of the waste material below. In Fig. 6.1B CH_4 is present at the bottom of the profile. The CH_4/CO_2 ratio is decreasing from 80cm b.s.l. and upwards, which indicate CH_4 oxidation. O_2 decreases from 20 % v/v near the surface to 1 % v/v at 30 cm b.s.l. Since N_2 does not decrease in concentration to the same extent, this suggests that O_2 is consumed which also suggests CH_4 oxidation. The profile shown in Fig. 6.1D taken from an emission hot spot contained CH_4 in high concentrations (> 33 % v/v) in all depths. The CH_4/CO_2 ratio decreases from 1.4 at 80 cm b.s.l. to 1.1 at 10 cm b.s.l., which indicates oxidation of CH_4 to some extent. Of the 65 profiles analyzed from the 12 measurement locations, the CH_4/CO_2 ratio in the lowest sampling port exceeded 1.0 in only two cases – both in biocover window 1.4. In only 26% of the profiles, the concentration of CH_4 exceeded 1 % v/v in the lowest port. The average oxygen concentration in the lowest sampling port was 9.5 % v/v, and the lowest concentration measured was 0.9 % v/v, which meant that oxygen was available over the entire depth of all profiles.

Flux measurements at test biocover windows

Flux measurements of CH_4 and CO_2 on the three test biocover windows were performed at seven campaigns over a one year period after installation of the biocover system at Fakse landfill. Flux measurements were performed once at each of the four measurement locations on each biocover window. In Table 6.2, average flux rates are listed from each campaign as well as a total average. CH_4 flux rates were very low, and in many cases negative flux rates were seen, indicating uptake of atmospheric CH_4. The average CH_4 emission measured at the October 2008 campaign was significantly higher than the remaining campaigns. This was mainly due to one measurement on biocover window 1.1, where CH_4 and CO_2 flux rates were measured to be 412 g CH_4 m^{-2} d^{-1} and 769 g CO_2 m^{-2} d^{-1} respectively, which meant that the biocover window was overloaded at that location during this specific measurement.

Table 6.2 Results of LFG flux measurement campaigns and calculated CH_4 oxidation rates (Fredenslund et al., IV)

	Points measured	Measured CH_4 flux g CH_4 m^{-2} d^{-1}			Measured CO_2 flux g CO_2 m^{-2} d^{-1}			Mean CH_4 oxidation[a]
		Mean	Median	Std. dev.	Mean	Median	Std. dev.	%
Oct-07	1.1A, 1.1B, 1.1C, 1.1D	-0.1	-0.1	0.1	166.6	127.6	107.9	100.0
Nov-07	1.1A, 1.1B, 1.1C, 1.1D, 1.4 A 1.4B, 1.4C, 1.4D, 7A, 7B, 7C, 7D	0.2	0.0	0.6	30.2	17.5	37.7	98.5
Dec-07	1.1A, 1.1B, 1.1C, 1.1D, 1.4 A 1.4B, 1.4C, 1.4D, 7A, 7B, 7C, 7D	0.1	0.0	0.5	33.9	12.5	52.3	99.1
Jan-08	1.1A, 1.1B, 1.1C, 1.1D, 1.4 A 1.4B, 1.4C, 1.4D, 7A, 7B, 7C, 7D	0.0	0.0	0.2	17.4	0.0	48.0	100.0
Apr-08	1.1A, 1.1B, 1.1C, 1.1D, 1.4 A 1.4B, 1.4C, 1.4D, 7A, 7B, 7C, 7D	-0.1	-0.1	0.1	29.6	17.2	33.5	100.0
Jul-08	1.1A, 1.1B, 1.1C, 1.1D, 1.4 A 1.4B, 1.4C, 1.4D, 7A, 7B, 7C, 7D	-0.1	0.0	0.1	295.1	217.0	276.5	99.9
Oct-08	1.1A, 1.1B, 1.1C, 1.1D, 7A, 7B, 7C, 7D	66.4	0.3	133.0	194.7	104.6	244.4	70.2

[a] Methane oxidation is calculated without subtracting CO_2 flux caused by respiration in the compost material

The results of the two final campaigns performed after improvements to the biocover system were done suggest that much more CO_2 was emitting from the test windows compared to previous measurements. Since most of the CH_4 flux rates measured were near zero, the calculated CH_4 oxidation rates expressed as % CH_4 oxidized were higher than 98% in all but one campaign. CH_4 oxidation rates calculated using the mass balance method varied between 0 and 227 g CH_4 m^{-2} d^{-1}, and the total average oxidation rate was 20.4 g CH_4 m^{-2} d^{-1} without considering CO_2 emission caused by respiration. If a CO_2 emission caused by respiration is set to 30 g CO_2 m^{-2} d^{-1}, the calculated total average oxidation rate was 15.0 g CH_4 m^{-2} d^{-1}. Since the average CO_2 flux rates were approximately 30 g CO_2 m^{-2} d^{-1} or

below in four of the seven campaigns, the CO_2 emission caused by respiration in the compost was probably around 30 g CO_2 m^{-2} d^{-1} or lower.

The flux measurements showed that the CH_4 load to the biocovers at the 12 measurement locations in general was much lower than the predicted average load (150 g CH_4 m^{-2} d^{-1}), since the CO_2 emission in this case would have been 680 g CO_2 m^{-2} d^{-1}, considering 100% CH_4 oxidation but not considering CO_2 emission caused by respiration and assuming steady state (zero assimilation)

Spatial variability in emissions

As a part of the "Mapping spatial distribution in emissions" study (see Table 6.1) the soil cover was screened by measuring CH_4 concentration near the surface of the soil cover and surface of the biocover windows using a portable FID. The purpose of this study was to assess where CH_4 was emitting from the site, since total CH_4 measurements (described in the following section) showed that much of the CH_4 emissions observed in the baseline study were still occurring after the biocover system and improvements were finalized. The results of screening at the soil surface and surfaces of biocover windows were somewhat similar to the results from the April 2008 leak test. The highest surface CH_4 concentrations where found on four biocover windows, where CH_4 concentrations exceeded 3000 ppmv as well as at a slope on disposal unit 7, where soil had been added to lower gas permeability as a part of the improvements to the biocover system. Elevated CH_4 concentrations were observed near 10 of the 16 leachate wells at the site. The highest CH_4 concentration seen near the wells varied between approximately 200 and 3000 ppmv. The elevated concentrations were seen near the soil surface near the wells, but in some cases LFG emission seemed to occur from leaks in the caps installed to reduce emissions from the wells, caused by damage.

The areas of each hot spot were determined. This was done to be able to calculate emission rates from flux measurements, which results are shown in the section below. Flux measurements were performed on hot spots found on the soil cover and the biocover windows, as well as areas around leachate wells, where CH_4 screenings suggested emissions occurred. Flux measurements were performed on all areas of the soil cover and biocover windows where elevated CH_4 concentrations were seen. At three of the ten leachate wells where high CH_4 concentrations were found, it was not possible to measure emissions using flux chambers, meaning that emissions from these locations were not quantified.

Also, emissions occurring through leaks in the caps installed on the leachate wells were not measured. In Fig. 6.2, CH_4 measured emissions during the campaign are shown on a map of the site. Emissions from surface surrounding leachate wells, as well as the emissions through biocover windows and soil cover is shown. Most CH_4 was found to be emitting near leachate wells or through biowindows, with the exception of the steep slope of the soil cover near window 7. In all 75 kg CH_4 per day was estimated to emit through hot spots on the soil cover and biocover windows, and 40 kg CH_4 per day was estimated to emit through the soil surface near leachate wells. Since it was not possible to measure emissions from all of the leachate wells or emissions through the caps on the wells, the actual emission from the leachate wells was arguably considerably higher.

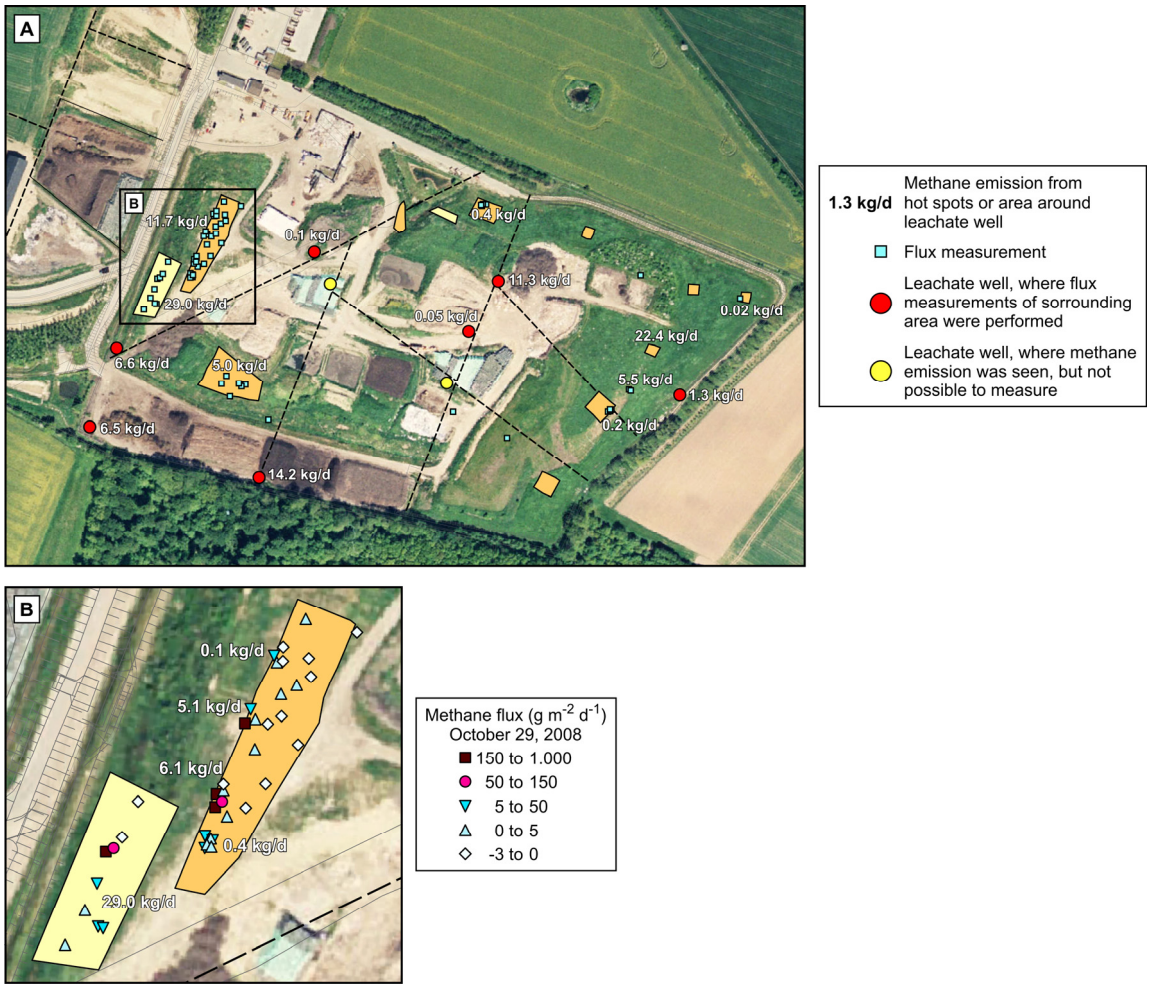

Fig 6.2 Overview of measured CH_4 emissions from surface of biocovers and soil cover including areas near leachate wells during October, 2008 campaign to map emissions (Fredenslund et al., IV)

6.3 Total methane emission

After installation of the biocover system, four measuring campaigns were carried out, where the total CH_4 emissions were quantified. These field campaigns were generally planned so measurements were carried out under stable weather conditions, where the measured emission is believed to be representative for the whole landfill emission rate at the particular season. Table 6.3 provides an overview of the weather conditions during the field campaigns, and lists emissions measured. Table 6.3 also includes measurements conducted as part of the baseline study done before installation of the biocover for comparison.

Table 6.3 Weather conditions and measured total CH_4 emissions from section I at Fakse landfill (Fredenslund et al, IV)

Date and time of measurement	Tendency in atmospheric pressure during measurement [a]	Average change in barometric pressure during measurement	Average temperature during campaign	CH_4 emissions
		hPa h^{-1}	°C	kg CH_4 d^{-1}
Oct. 11th 2006 12:00 – 16:30	↓	-0.3	15.1	749
Feb. 19th 2007 18:30 – 23:15	↓	-0.2	3.1	732
Biocover implemented				
Oct. 17th 2007 16:30 – 18:10	-	-0.1	10.6	864
System improvements finalized				
Apr. 1st 2008 17:45 – 19:00	↓	-1.6	10.4	881
Aug. 8th 2008 8:00 – 9:10	↑	0.3	18.0	658
Dec. 4th 2008 9:50 – 11:50	↓	-1.2	2.4	533

[a] Tendency in atmospheric pressure during measurement is described here as increasing: "↑ ", no trend: "–" or decreasing: "↓" (Fredenslund et al., IV)

The average CH_4 emission from the site before installation of the biocover system, which was done Oct. 11th 2006 and Feb. 19th 2007, was 740 kg CH_4 d^{-1} (Fredenslund et al., III). At the two following campaigns performed immediately after installation of the biocover system and after completions of the improvements to the system were completed, quite similar emissions were measured. At decreasing atmospheric pressure, a higher than average LFG

emission is expected, while increasing atmospheric pressure leads to lower than average emissions. This has been observed to be the case for both LFG emissions through soil covers (Czepiel et al., 1996, Christophersen et al., 2001) and leachate collection wells (Fredenslund et al., I). At the two baseline campaigns the atmospheric pressure was moderately decreasing, whereas during the October 2007 campaign the pressure was neither increasing nor decreasing, and during the April 2008 campaign, the pressure was decreasing by 1.6 hPa h^{-1}, which likely caused an increased LFG emission at the time of measurement. The last two campaigns conducted in October, 2008 and December, 2008 both showed significantly smaller CH_4 emissions in comparison to the baseline study, even though a pressure decrease, which was more pronounced than the decrease during the baseline measurements, was observed during the last campaign. The emission from the site was measured to be 533 kg CH_4 d^{-1} indicating an overall reduction of 9 kg d^{-1} corresponding to 29% in comparison to the baseline study.

6.4 Conclusions

Performing emission measurements during a 1 year period after installation of the biocover system at Fakse landfill was used to evaluate the system's efficiency with regards to CH_4 oxidation, and thereby reduction of greenhouse gas emissions from the site. Flux chamber measurements repeated during the monitoring period on 12 locations of the biocover windows indicated high oxidation efficiencies at these locations (Fredenslund et al., IV). Also, soil gas profiles indicated CH_4 oxidation within the biowindows. However, from measurements on total CH_4 emissions from the site it was concluded that most of the emissions measured before implementation of the biocover were still occurring after installing and improving the system. The overall efficiency seemed to be increasing over time, and the lowest emission was measured during the last performed measurement campaign. Mapping emissions at the site showed that significant emissions were occurring through leachate collection system, in spite of several measures taken to seal off this pathway. High CH_4 emissions were observed at hot spots on the biocover windows, indicating that the load was unevenly distributed to the biocover area leading to overload in parts of the system and thereby reduced efficiency.

7 Conclusions and perspectives

A biocover system to reduce greenhouse gas emissions was constructed at Fakse landfill in full scale. The efficiency of the system was evaluated on local and total LFG emission measurements, of which the total CH_4 emission measurements suggested, that the CH_4 emission from the site was reduced by approximately 30% at the end of the one year period of performance evaluation.

Previous evaluations of biocovers based on point measurements made by others (described in section 1.2) suggested very high CH_4 oxidation efficiencies. Flux measurements performed on the biocover windows in this study also suggested high efficiency (~100 %), but since large emissions occurred through hot spots in the biocover windows, soil cover and through the leachate collection system, the overall efficiency was reduced. At the site, low permeable clayey soil was used daily covering of the waste. This led to a complicated flow pattern of the landfill gas from the waste to the atmosphere. When installing the biowindows, clayey soil was often seen to be mixed with the waste beneath the soil cover, which can explain difficulties of obtaining a high enough and evenly distributed load to the windows without important leaks such as the leachate drainage system. After installing caps to prevent leaks through wells at the site, gas was measured to emit from the leachate pumping station instead. After installing water locks at the pumping station to counter this leak, gas was seen to emit through the soil surface immediately near the leachate wells.

A much higher overall CH_4 mitigation efficiency at Fakse landfill would have been obtained by combining the biocover system with an active LFG extraction system using the leachate collection system such as described in Townsend & Miller, 2007. Such a system is now planned to be realized at the landfill. The findings of this study suggest that a combined system would be preferable at landfills where a leachate collection system is in place. Another factor which was shown to be important was an uneven spatial distribution of CH_4 load to the biocover windows. These were, for example, seen where trenches were dug to increase the load to window 7. The 0.15 m gravel gas distribution layer used in this study to even the load to the biocover was not sufficient. In Huber-Humer et al., 2009 a thicker (0.3 m) gas distribution layer was used and in Einola et al., 2009 a passively vented gas distribution system including canals with high permeability material and distribution pipes was used. Based on experiences from Fakse landfill made in this study, two new Danish biocover projects have

been initiated, where improved gas distribution systems are to be used. From this study it is concluded that a well functioning distribution of LFG load to a biocover system is essential to obtain a well functioning system. Since CH_4 was observed to emit at quite high rates through hot spots in the biocover windows, it can be concluded that parts of the biocover system were overloaded. The study of gas transport and oxidation of window 7 did show an inhomogeneous flow of landfill gas to the windows with areas of little or no load, as well as other areas of loads higher than the CH_4 oxidation capacity of the compost previously measured as a part of this project. Significant CH_4 oxidation, and thereby reduction of greenhouse gas emission was, however, observed at Fakse landfill. Several types of measurements performed point to this conclusion:

- Measurements of total CH_4 emission from the site did show lower CH_4 emissions after the improvements of the system were done.
- Mapping surface CH_4 emissions showed that significant amounts of landfill gas was passing through the biocover windows
- Gas concentration profiles from biocover windows 1.1, 1.4 and 7 showed that CH_4 oxidation was taking place in the biocover material
- Carbon balance calculations on surface flux measurements of CH_4 and CO_2 performed on biocover windows 1.1, 1.4 and 7 suggests CH_4 oxidation in the biocover windows

Since previous biocover field trials had shown such promising results, the obtained CH_4 mitigation efficiency of the Fakse biocover system (percentage of total emission reduced) was unexpectedly low. A conclusion of this study is that point measurements are not sufficient to determine a biocover system's total efficiency.

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9 Appendices

I Fredenslund, A.M., Scheutz, C., Kjeldsen, P., 2010. Tracer method to measure landfill gas emissions from leachate collection systems. Waste Management. DOI: 10.1016/j.wasman.2010.03.013

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III Fredenslund, A.M., Lemming, G., Scheutz, C., Kjeldsen, P., 2010. Mitigation of methane from Fakse landfill using a biocover system 1: Baseline study. Manuscript

IV Fredenslund, A.M., Pedersen, G.B., Scheutz, C., Kjeldsen, P., 2010. Mitigation of methane from Fakse landfill using a biocover system 3: Design and Performance. Manuscript

The papers are not included in this www-version but can be obtained from the library at DTU Environment. Contact info: Library, Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, DK-2800 Kgs. Lyngby, Denmark or library@env.dtu.dk.

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DTU Environment
Department of Environmental Engineering
Technical University of Denmark

Miljoevej, building 113
DK-2800 Kgs. Lyngby
Denmark

Phone: +45 4525 1600
Fax: +45 4593 2850
e-mail: reception@env.dtu.dk
www.env.dtu.dk

ISBN 978-87-91855-92-4