THE EFFECT OF VEGETATION ON MICROBIAL METHANE OXIDATION

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SUMMARY: Basically, the activity of the methane oxidizing bacteria is limited by the availability of oxygen in the landfill cover soil. Enforced by the use of fine-grained soils like silt, the surface tends to crust due to vertical erosion, blocking pores required for gas exchange. A column study was carried out to examine the impact of vegetation on improving the aeration of critical soil material and supporting the oxidation process. Oxidation potential was strongly diminished in the bare control column filled with clayey silt even at low CH₄-loads. In contrast, the planted clayey silt showed a high oxidation potential of 91 % at a CH₄-load of 5.6 l CH₄ m⁻² h⁻¹. It was shown, that spreading root system forms secondary macro-pores, and hence amplifies the air diffusivity and sustains the oxygen supply to the bacteria. Water produced during methane oxidation was reduced by evapotranspiration, and more water-free pores are available for gas diffusion. Leguminous plants support the enrichment of soil with nitrogen compounds, which benefit the oxidation process. In conclusion, vegetation is relevant to the increase of oxygen diffusion into soil and subsequently enhances effective methane oxidation in landfill cover soils.

1. INTRODUCTION

Worldwide, methane emissions from the waste sector account for 18 % of the total methane emission dominated by emission from landfills (Bogner et al., 2007). Even when state-of-the-art techniques for active or passive gas recovery are employed, substantial amounts of methane still escape into the atmosphere and contribute to global warming. The microbial oxidation of methane in landfill cover soils bears great potential for an inexpensive and sustainable mitigation of methane emission from landfills. The main factors influencing the efficiency of methane oxidating bacteria (MOB) are temperature, soil moisture, special nutrients like nitrogen (N) compounds, type and texture of soil (Berger, 2008; Bodelier & Laanbroek, 2004; Huber-Humer, 2004; for a review see Scheutz et al., 2009). In addition to the listed parameters, there are only few information about the influence of vegetation growing on the landfill top cover on the microbial oxidation process.

In general, vegetation has some positive effects on the top cover including agglomeration, isolation against high temperature variability, mechanical stabilisation, but first and foremost protection from erosion. Some types of soil, such as clay or silt, are rich in fine-grained material
(<2 µm) and the surface tends to be sealed when it wets.

The splash-effect of rain drops lead to choke the interstices of larger particles in the surface layers by the washing of fine particles into the pores (Blaikie, 1985). This “puddle erosion” is a physical breakdown of soil, by consequence the blocked pores restrain the air diffusivity into soil and diminish activity of MOB by limited oxygen concentration (King, 1994). A well developed vegetation zone should counteract this kind of vertical erosion and stabilize the particles. Further, it is considered that plant roots enhance the aeration of soil by building up of secondary macro pores. This improves the diffusion of oxygen into soil as well as the supply of methane to bacteria. As a result, the methane oxidation potential is expected to increase.

2. METHODS

2.1 Column study

Four column tests in lab-scale were carried out in a laboratory climate chamber (temperature at 20 °C, air humidity of around 60%). The set-up of the column experiment is shown in Figure 1. Each column was filled with 0.9 m of soil material (Table 1) above a 0.2 m gas distribution layer of coarse gravel (grain size 0.4–0.8 cm). Two different soil samples were compared: greencut compost, rich in organic matter, generally shows a high air capacity even at high moisture contents (Huber-Humer, 2004). These are favourable conditions for methane oxidation. However, the long term stability of compost is questionable due to possible biological degradation of its organic constituents. The second soil was a mixture of clayey silt, critical in a high content of fine-grained material mixed up with 25 vol-% greencut compost.

Column I, II and III were planted according to Table 1, while column IV stayed bare (reference column). It is worth to mention the plant group of leguminous plants, which lives in symbiosis with a specific kind of bacteria, called Rhizobium, which settles in with the plant roots (nodulation). Rhizobium can fix atmospheric nitrogen, build up nitrogen compounds, and release them into the surroundings. The supply of nitrogen compounds is essential for plants and furthermore beneficial for microbial methane oxidation (Gebert et al., 2009, Krüger & Frenzel, 2003, Nikiema et al., 2005).

The column study was conducted over a total of 267 days. During the experimental time all columns were charged with artificial landfill gas (50 vol% CH₄ and 50 vol% CO₂).

<table>
<thead>
<tr>
<th>column No.</th>
<th>type of soil</th>
<th>type of vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.3 m mature compost 0.6 m clayey silt</td>
<td>mixture of Poaceae (grass) (vegetation not well developed until day 200)</td>
</tr>
<tr>
<td>II</td>
<td>0.9 m mixture of clayey silt + 25 vol-% greencut compost</td>
<td>Canada goldenrod (Solidago canadensis)</td>
</tr>
<tr>
<td>III</td>
<td>0.9 m mixture of clayey silt + 25 vol-% greencut compost</td>
<td>Mix of leguminous plants (pea, clover, lentil, etc.)</td>
</tr>
<tr>
<td>IV</td>
<td>0.9 m mixture of clayey silt + 25 vol-% greencut compost</td>
<td>reference without vegetation</td>
</tr>
</tbody>
</table>
Regular measurements during the experimental time:
- Gas profiles (\(\text{CH}_4, \text{O}_2, \text{CO}_2, \text{N}_2\)) measured by GC / FID
- Methane surface emissions were detected by chamber measurements and FID
- Profiles of temperature and soil humidity
- Soil specific parameters (pH, organic matter, TOC, \(\text{PO}_4\)-P, \(\text{SO}_4\)-S)
- Changes in \(\text{NO}_3\)-N by (1) plant uptake and (2) by nitrogen-fixing bacteria living in symbiosis with leguminous plants (column III)
- Column drainage was drained and quantified periodically

The methane oxidation efficiency was calculated by mass balance based on the difference between methane influx and efflux.

After the experiment was terminated, five 100 cm\(^3\) undisturbed soil cores were retrieved from the top layer of each of the four columns for measurement of soil diffusivity. The water content of soil samples were adjusted to field capacity by first watering them on a sand bath, followed by de-watering using a pressure head of 6 kPa in a pressure-plate apparatus. The residual air filled pore volume (air capacity) was determined by pycnometry. The soil cores were placed in a diffusion chamber purged with \(\text{N}_2\). Diffusive re-entry of atmospheric \(\text{O}_2\) into the chamber via the soil core was monitored by GC-TCD analysis (Agilent JAS 2). The method is explained in detail in Gebert et al., 2010.
3. RESULTS

3.1 Oxidation potential

During experimental period synthetic landfill gas was continuously charged at the bottom of each column with an increasing input flux of 1.4, 2.8 and 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$ in phase one, and 1.4, 2.8 and 5.6, plus additionally 8.4 l CH$_4$ m$^{-2}$ h$^{-1}$ in phase two. Figure 2 shows the methane oxidation potential [l CH$_4$ m$^{-2}$ h$^{-1}$] of the four columns depending on the different CH$_4$-levels.

During the period of an input of 1.4 l CH$_4$ m$^{-2}$ h$^{-1}$ in the first 82 days, no significant difference was observed between the four columns. The volume of CH$_4$-input was completely oxidized in all columns. Then gas input was doubled to 2.8 l CH$_4$ m$^{-2}$ h$^{-1}$. While columns I, II and III still oxidized the whole CH$_4$-input, the methane oxidation rate started to decrease in column IV (reference without vegetation) around day 120. A significant effect was observable when a CH$_4$-flux of 5.6 l m$^{-2}$ h$^{-1}$ was tested. Column II on average mitigated 3.9 ± 1.0 l CH$_4$ m$^{-2}$ h$^{-1}$ (70% of CH$_4$-input), whereas a slightly lower CH$_4$-oxidation rate of 2.3 ± 1.5 l CH$_4$ m$^{-2}$ h$^{-1}$ (41% of CH$_4$-input) was achieved in column III. The control column IV showed no methane oxidation at a CH$_4$-input of 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$. Instead of negative oxidation rates were observed in this column, i.e. methane production by anaerobic digestion of organic soil material or temporal methane storage because of the clogged surface.

After a break of 45 days, allowing the plants to grow and to develop their root system, the investigation was restarted. The CH$_4$-inputs were similar to the first phase of the investigation (1.4, 2.8 and 5.8 l CH$_4$ m$^{-2}$ h$^{-1}$). The inputs of 1.4 and 2.8 l CH$_4$ m$^{-2}$ h$^{-1}$ showed similar results to phase one: even the small decrease in methane oxidation rate in column IV was reproduced. The input of 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$ resulted in a similar outcome for column I and IV in first and second phase. However, improved methane oxidation potentials of 4.9 and 5.1 l CH$_4$ m$^{-2}$ h$^{-1}$ (87.5 and 91 % oxidation rate, respectively) were observed in columns II and III respectively, whereas the potentials determined in the first phase were at 3.9 l CH$_4$ m$^{-2}$ h$^{-1}$ and 2.3 l CH$_4$ m$^{-2}$ h$^{-1}$, respectively. The increased oxidation potential can be explained on the one hand by a subsequent heightened water uptake increasing the water-free pore volume. On the other hand, the rooting increased the air capacity and diffusive oxygen supply. Furthermore, proliferation and adaptation of the MOB as a result of exposition to higher methane fluxes during the experiment could increase the methane oxidation potential.

To identify the limit of the oxidation potential of the soil material, the CH$_4$-input was increased to 8.4 l CH$_4$ m$^{-2}$ h$^{-1}$. However, higher influx of landfill gas into the root zone may harm the vegetation irreversibly (Jäger & Jager, 1983). It causes a lack of oxygen in the root zone and the plant chokes.

![Figure 2. Methane oxidation potential [l CH$_4$ m$^{-2}$ h$^{-1}$]](image-url)
3.2 Gas profiles

To analyse the extent of soil aeration, the N$_2$-profile can be used as an indicator for the depth of air penetration. In contrast to oxygen, which is consumed during the methane oxidation process, N$_2$ is inert and does not take part in biological or chemical processes. In all Figure 3a–d it can be seen that an increase of advective bottom-up gas flux clearly diminished the diffusive top-down air penetration into the soil. Columns I, II and III showed similar ranges of aeration at the two CH$_4$-levels in a depth of 0.5 m (50 and 58 vol% N$_2$ at 1.4 l CH$_4$ m$^{-2}$ h$^{-1}$; 31 and 34 vol% N$_2$ at 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$). The crusted surface in column IV resulted in reduced N$_2$-concentration in a depth of 0.5 m (48 vol% at 1.4 l CH$_4$ m$^{-2}$ h$^{-1}$; 10 vol% at 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$).

Figure 3. Gas profiles of the four columns. Profiles are given for the lowest (1.4 l CH$_4$ m$^{-2}$ h$^{-1}$) and highest (5.6 l CH$_4$ m$^{-2}$ h$^{-1}$) CH$_4$-input. Indicated are the average values of each CH$_4$-input level

3.3 Influence of soil diffusivity on the methane oxidation potential

In Figure 4 the correlation of the soil specific D$_{eff}$ and the concentration of N$_2$ [vol%] at three CH$_4$-levels (1.4, 2.8, 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$) is shown. The D$_{eff}$ determines the air penetration, apparent in the concentration of N$_2$ in a depth of 0.4 m, which is the deepest layer of methane oxidation activity in the column study. At the lowest CH$_4$-load, the N$_2$-concentration was 55 vol% at a diffusion value of 1.4 x 10$^{-6}$ m s$^{-1}$, and 59 vol% at 7.2 x 10$^{-6}$ m s$^{-1}$. Obviously, the N$_2$-penetration is barely restricted by the D$_{eff}$ at low gas load. At a high CH$_4$-load of 5.6 l CH$_4$ m$^{-2}$ h$^{-1}$, the air penetration is strongly reduced by the soil specific D$_{eff}$ (16 vol% N$_2$ at 1.4 x 10$^{-6}$ m s$^{-1}$, and 39 vol% N$_2$ at 7.2 x 10$^{-6}$ m s$^{-1}$, respectively).
The effective diffusive ingress of atmospheric air is controlled by the pore size distribution as determined by particle size distribution and compaction. Pore size distribution determines water retention characteristics, affecting the amount of water-filled pores and pores available for gaseous transport (Gebert et al., 2010).

### 3.4 Nitrogen fixing bacteria and the methane oxidation potential

When the experiment was terminated, some plants were excavated from column III planted with leguminous plants and scanned for visual nodes built by symbiotic bacteria called *Rhizobium* of the family of *Rhizobiacea*. Due to the weak plant development, some nodes were visible, but only slightly developed (Ø 0.3 cm). The NO$_3$–N values at the beginning and the end of the experiment are shown in Table 2. In the column I, II and IV, NO$_3$–N contents decreased during the experiment, maybe due to the uptake by the plants and consumption by the bacteria. Only in column III, the NO$_3$–N contents increased, which could be an indicator for the N-enrichment by N-fixing bacteria.

Since a lack of nitrogen compounds can limit the metabolism of methanotrophic bacteria, the additional nitrogen supply introduced by leguminous plants is expected to benefit the microbial oxidation of methane.

Table 2. NO$_3$-N content in the four columns at the beginning and at the end of the experiment

<table>
<thead>
<tr>
<th>NO$_3$-N [ppm]</th>
<th>column I compost Poaceae</th>
<th>column II clayey silt <em>S. canadensis</em></th>
<th>column III clayey silt mix of leguminous plants</th>
<th>column IV clayey silt without vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>521.7</td>
<td>3.5</td>
<td>13.9</td>
<td>10.0</td>
</tr>
<tr>
<td>End</td>
<td>107.9</td>
<td>1.1</td>
<td>20.1</td>
<td>1.11</td>
</tr>
</tbody>
</table>

### 4. CONCLUSIONS

For economical and practical reasons, landfill covers are often built of less qualified material. Mineral substrates, mostly clay or fine-grained material like silt are used to construct dense top...
covers. Weather conditions (e.g. rainfall) can significantly modify the surface structure. Vertical erosion (suffusion) can block the pores and thereby limit the gas permeability. O2 required by MOB then becomes a limiting factor and methane oxidation is impeded.

Lab-scale column studies with different types of soil and vegetation were carried out to investigate the influence of vegetation on physical soil properties, and hence the influence of vegetation on the methane oxidation process. The results show that without vegetation (column IV), air influx into the soil is limited by a decreased share in pores available for gas transport. Especially the surface of fine grained material crusted when it gets wet by watering. The study shows that vegetation improves soil diffusivity, the extent of oxygen penetration, the leachate reduction and, by the use of leguminous plants, the improvement of N supply, and thus the methane oxidation potential.

However, vegetation growing on the top cover can improve the air capacity of less permeable soil materials through soil aggregation, formation of secondary macro-pores by spreading roots and transpiration of pore water within the limit of the available field capacity. Therefore, a soil with an inherently poor methane oxidation potential can be improved considerably by the soil structuring processes of vegetation.

The results demonstrate that for the development of optimized methane oxidising landfill cover system, the choice of vegetation, in addition to the soil properties, plays an important role. For optimal development and low-maintenance, the selection of plants should be site-specific and adapted to the local climatic conditions.

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REFERENCES


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