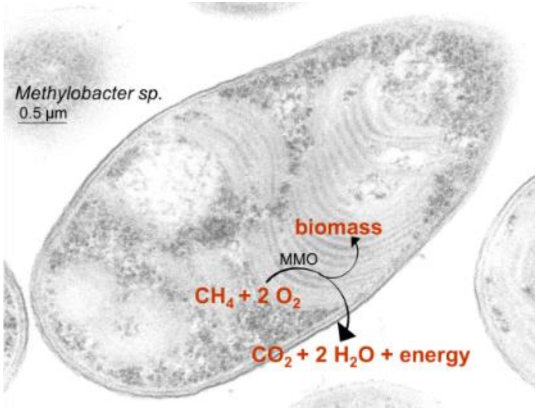
MCT Symposium 6 April 2023

**Success stories in environmental research**

# Optimizing microbial $CH_4$ oxidation for minimizing greenhouse gas emissions from landfills

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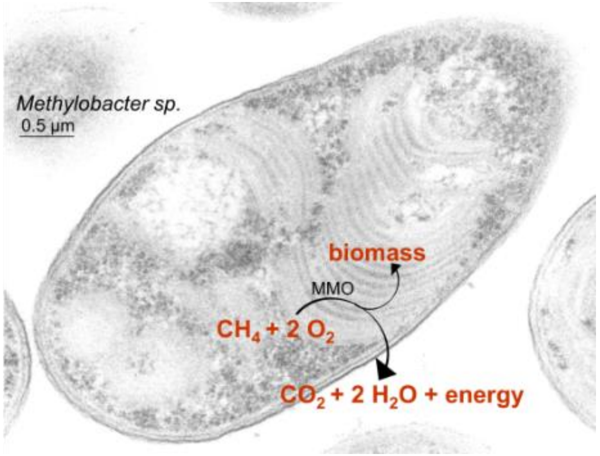
# Today

- Background & intro to $CH_4$ oxidation systems
- The $CH_4$ oxidation process & its driving factors
- Optimising $CH_4$ oxidation systems – design aspects
  - $O_2$ transport
  - Preferential flow paths
- Conclusions

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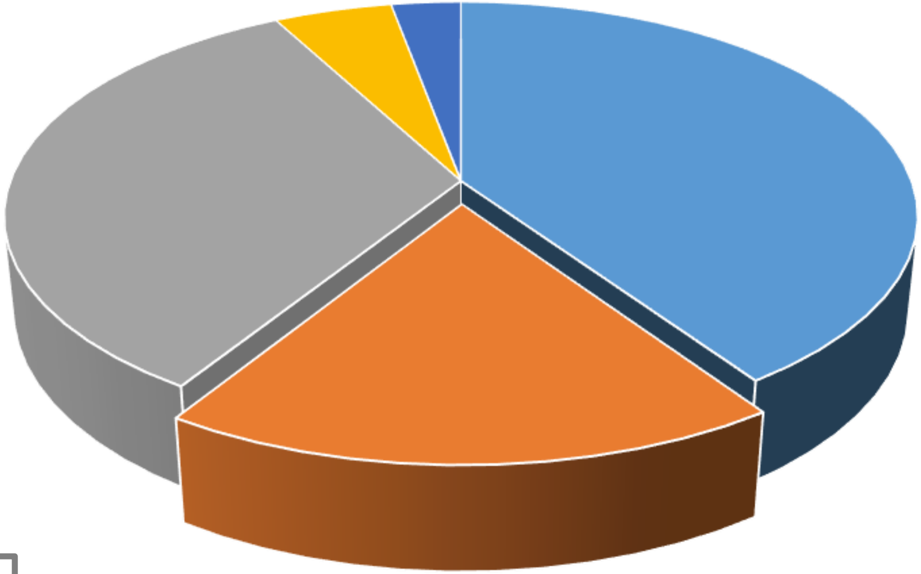
# Anthropogenic $CH_4$ emissions




Total anthropogenic sources = 356 Tg $CH_4$/a

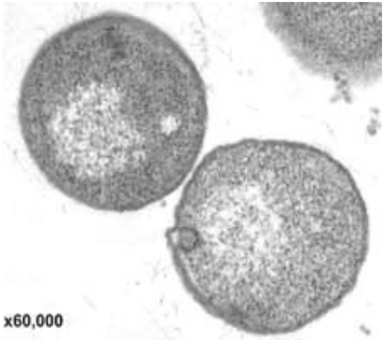
Data from: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change doi:10.1017/9781009157896

# Cause & problem

To reach short-term climate goals, reducing $CH_4$ emissions should be a top priority!

1. Climate forcing
   - Decay of waste organic matter under anaerobic conditions:
     **$(CH_2O)_n$ → $CH_4$ + $CO_2$** = 'Landfill gas' or 'Biogas'
   - Typical composition: 50-60% $CH_4$, 40-50% $CO_2$
   - **Global warming potential** of $CH_4$

| | | |
|---|---|---|
| $GWP_{100}$ | 100 years | **28-36** |
| $GWP_{20}$ | 20 years | **84-87** |




*Methanococcus* sp.

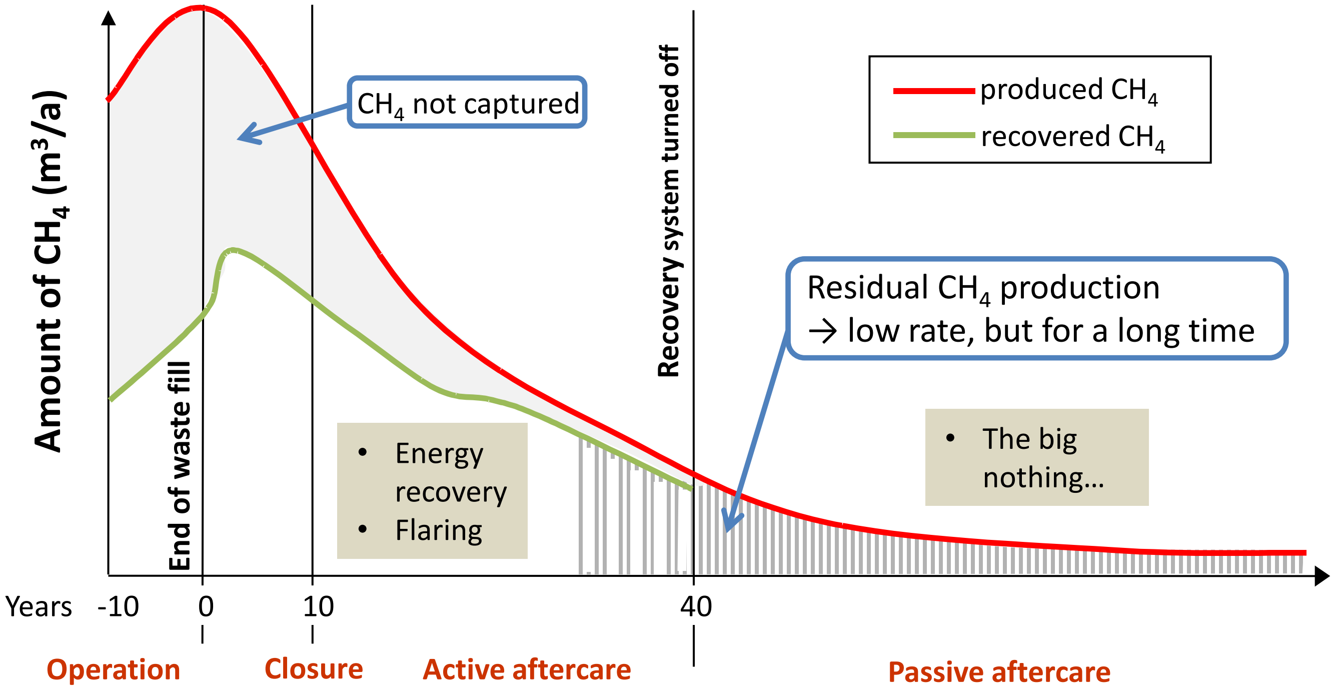
2. Safety

   $CH_4$ mixtures are explosive!

https://www.ridly.com.au/blog/how-to-separate-organic-and-inorganic-waste

# Fate of $CH_4$ in the lifetime of a landfill

- Typically, a significant part of landfill gas is not collected/recovered
- Microbial $CH_4$ oxidation as additional measure to mitigate the impact

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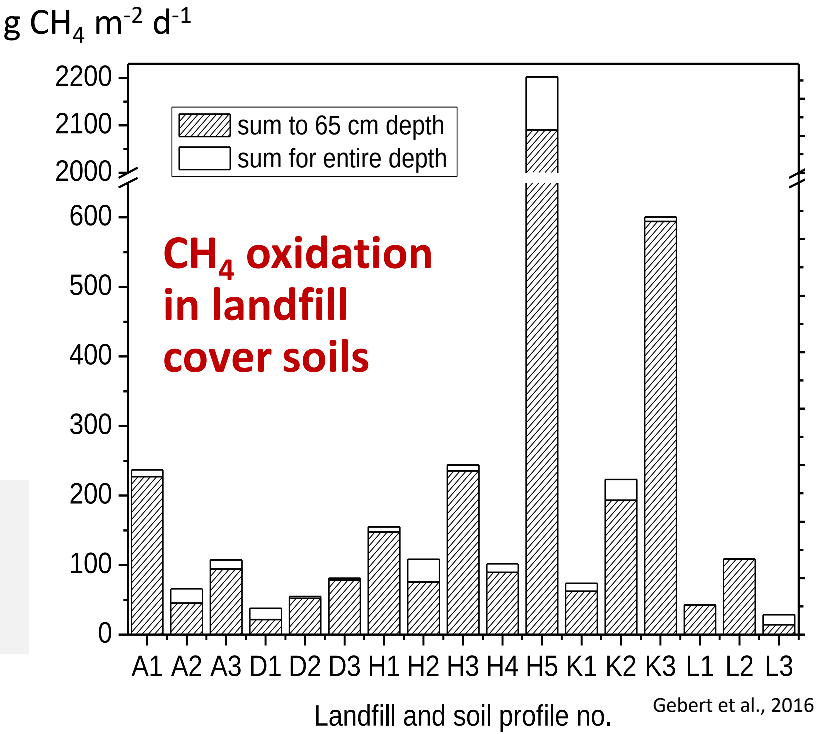
# Discovering the potential of microbial $CH_4$ oxidation

**Factor $10^3$ higher** than in natural $CH_4$ influenced habitats (rice paddies, peatlands…)




Gebert et al., 2016

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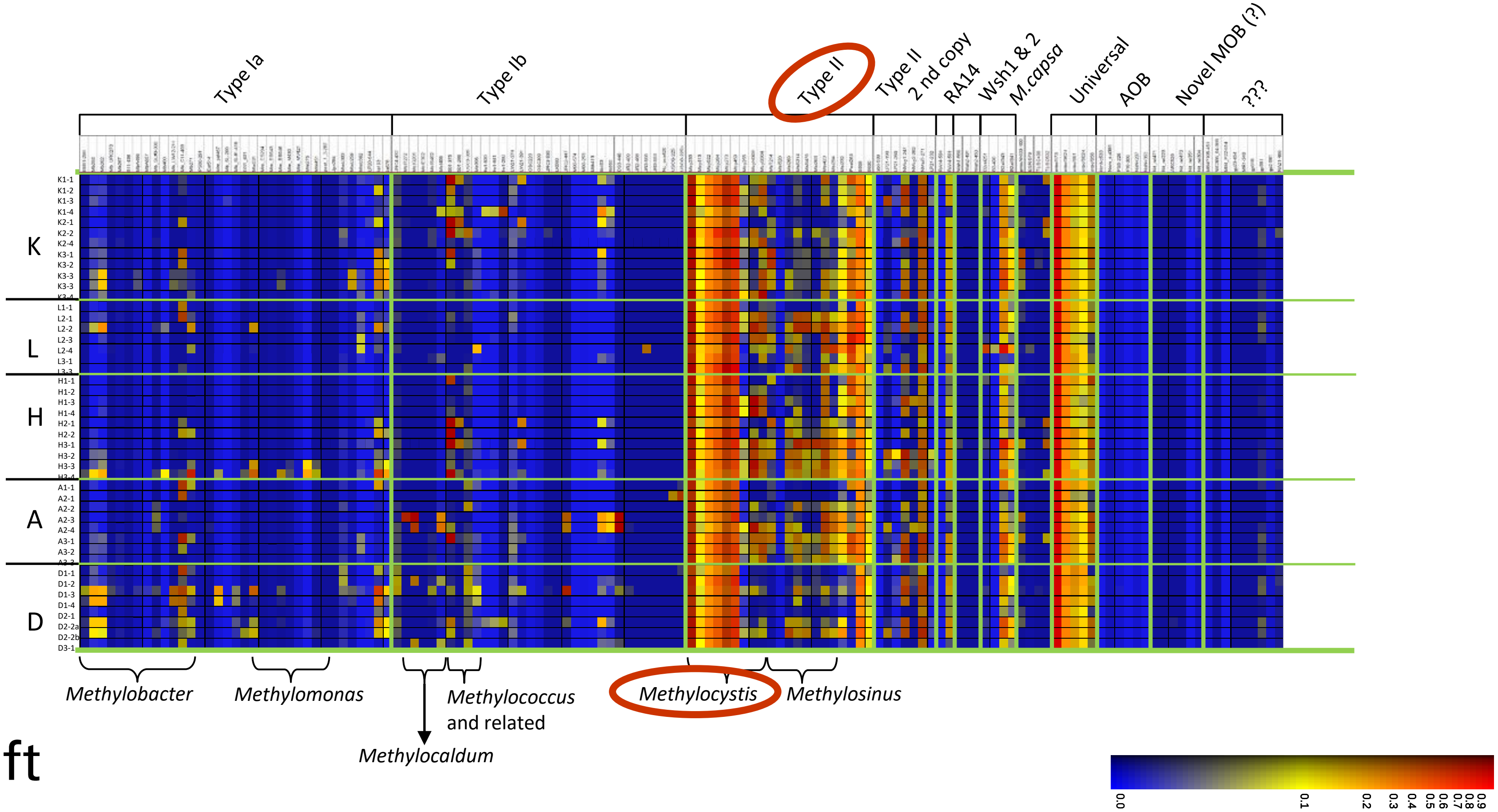
# We know who is there: Community composition

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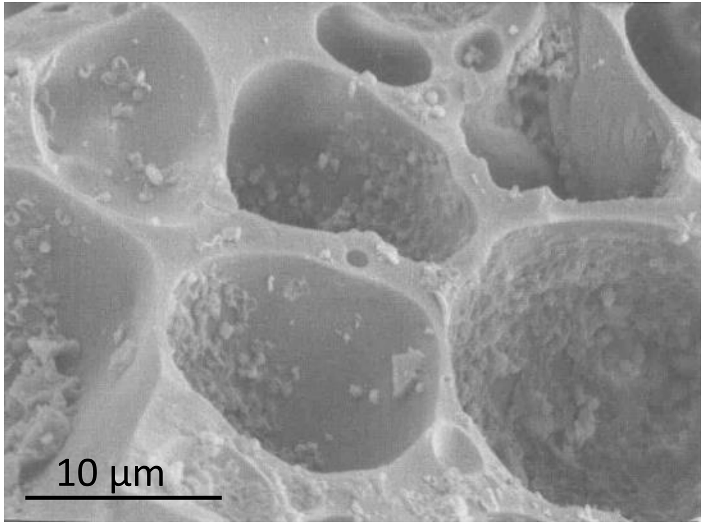
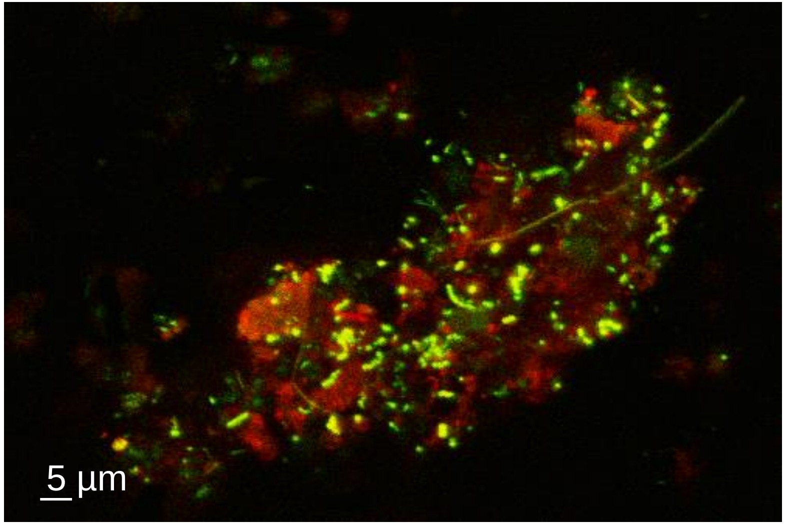
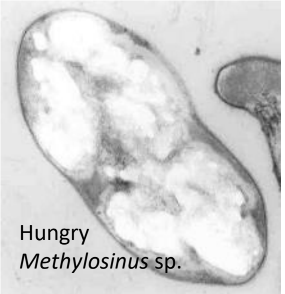
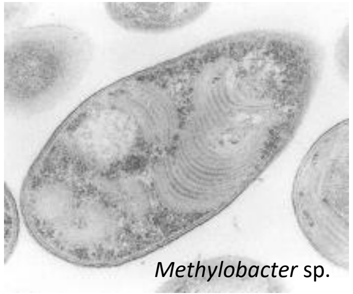
# We know where they are: Bacterial colonization of material




## … & how they look like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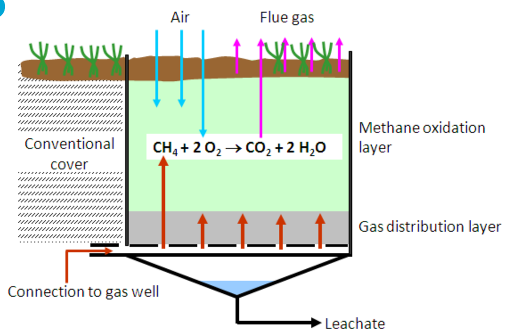
# $CH_4$ oxidation in ‘anthropogenic sinks’

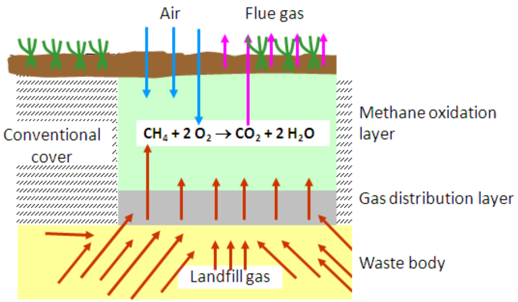
**Biofilter**

– Stable exhausts from animal husbandry (Melse & van der Werf, 2005; BiMoLa)
– Manure storage (Oonk & Koopmans, 2012)
– Coal mine ventilation (Du Plessis et al., 2003)
– Landfills with gas collection system (Streese & Stegmann, 2003; Gebert & Gröngröft, 2006)



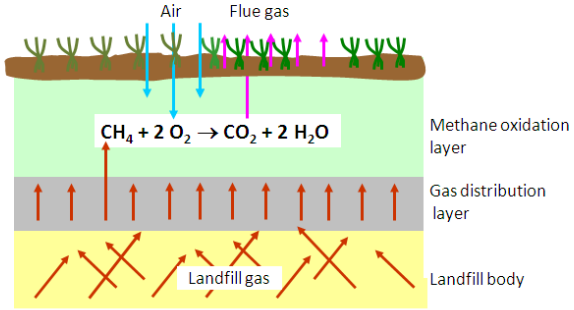

**Biowindow**

– Planned: Landfills without gas collection and surface lining (Pedersen et al., 2010)
– Remediation of emission hotspots on old non-sanitary landfills (Röwer et al., 2012)




**Biocover**

– Landfills with or without gas collection and surface lining (Huber-Humer et al., 2008; Geck et al., 2013)

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# Microbial $CH_4$ oxidation: Design goals

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

**Process controls**:

- Provide adequate physicochemical environment of high structural stability
- Optimise diffusive $O_2$ supply
- Maximise spatial evenness of $CH_4$ load
- Robust dimensioning, adapted to $CH_4$ load

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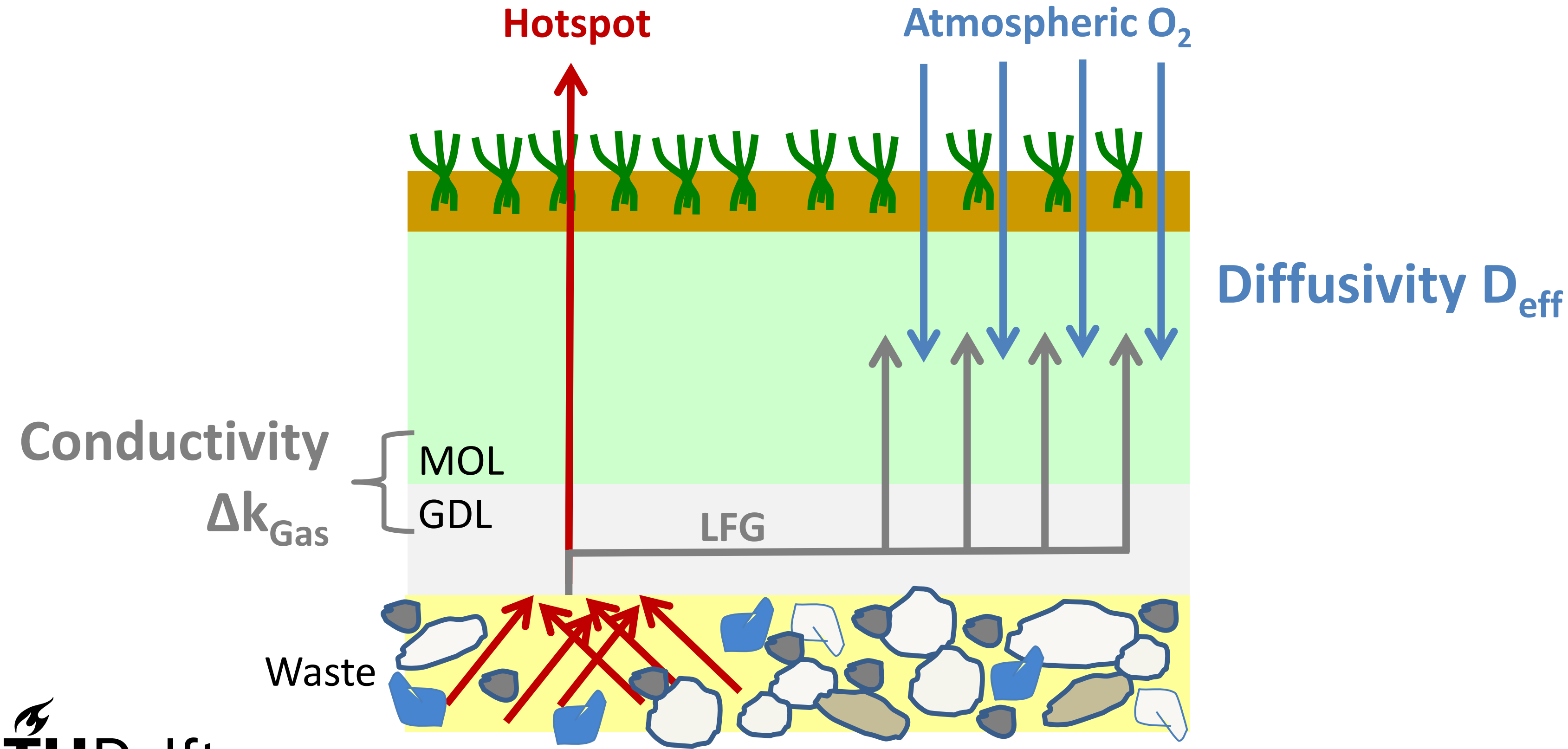
# Controls on spatial evenness & $O_2$ supply

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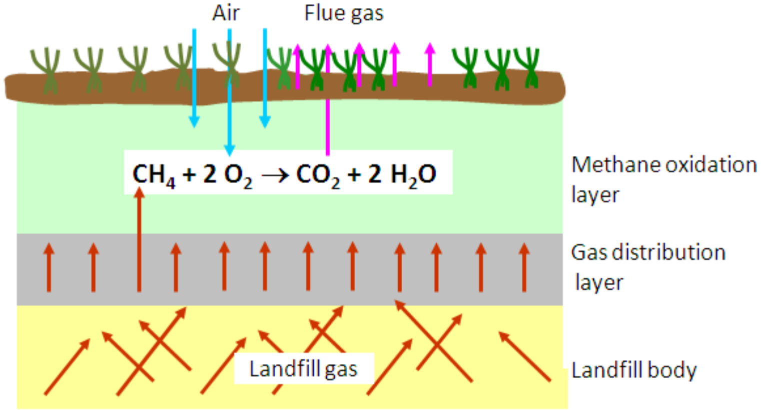
# Optimize diffusive ingress of oxygen




**Aim:**

Maximize depth of aeration to

– Create thick and “redundant” $CH_4$-oxidation layer

– Render oxidation process less susceptible to surface effects (frost, drought, heat, cold)

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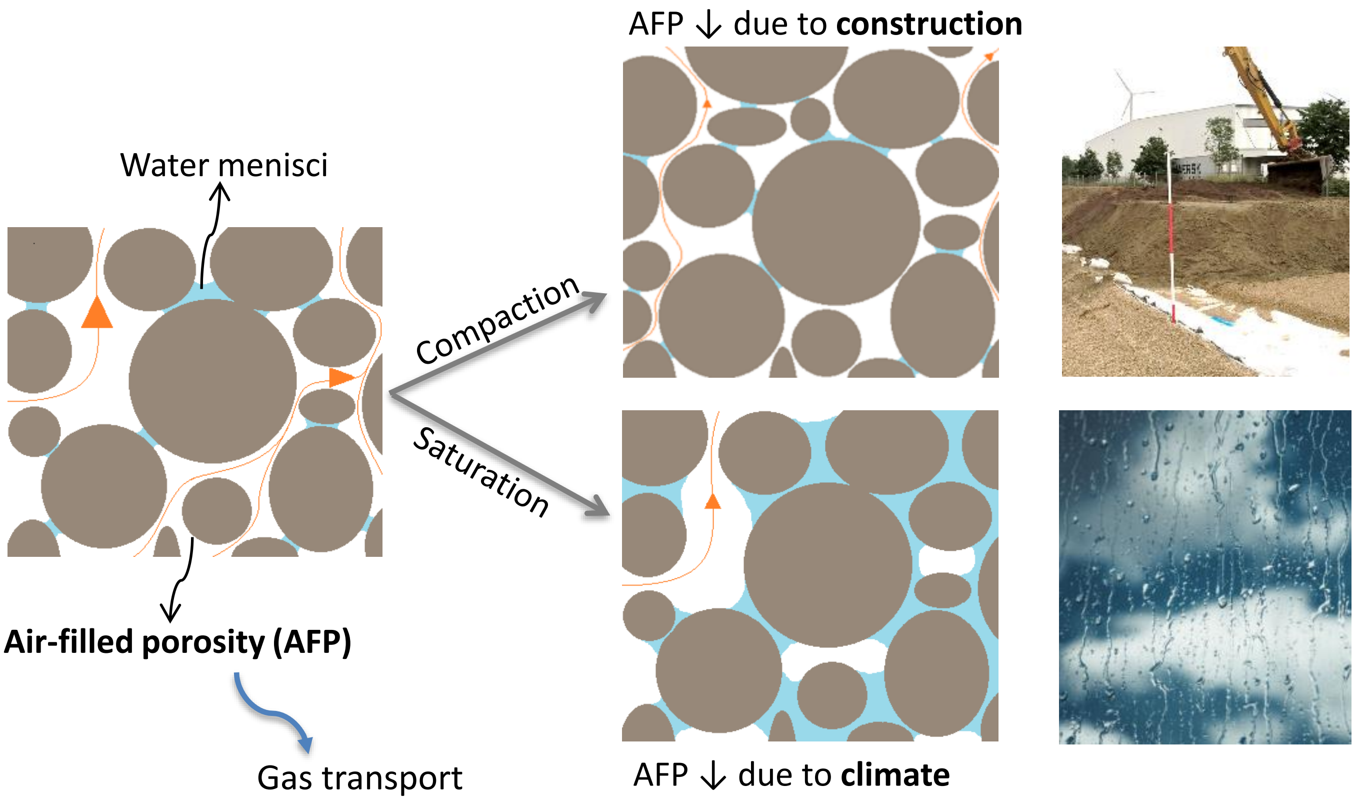
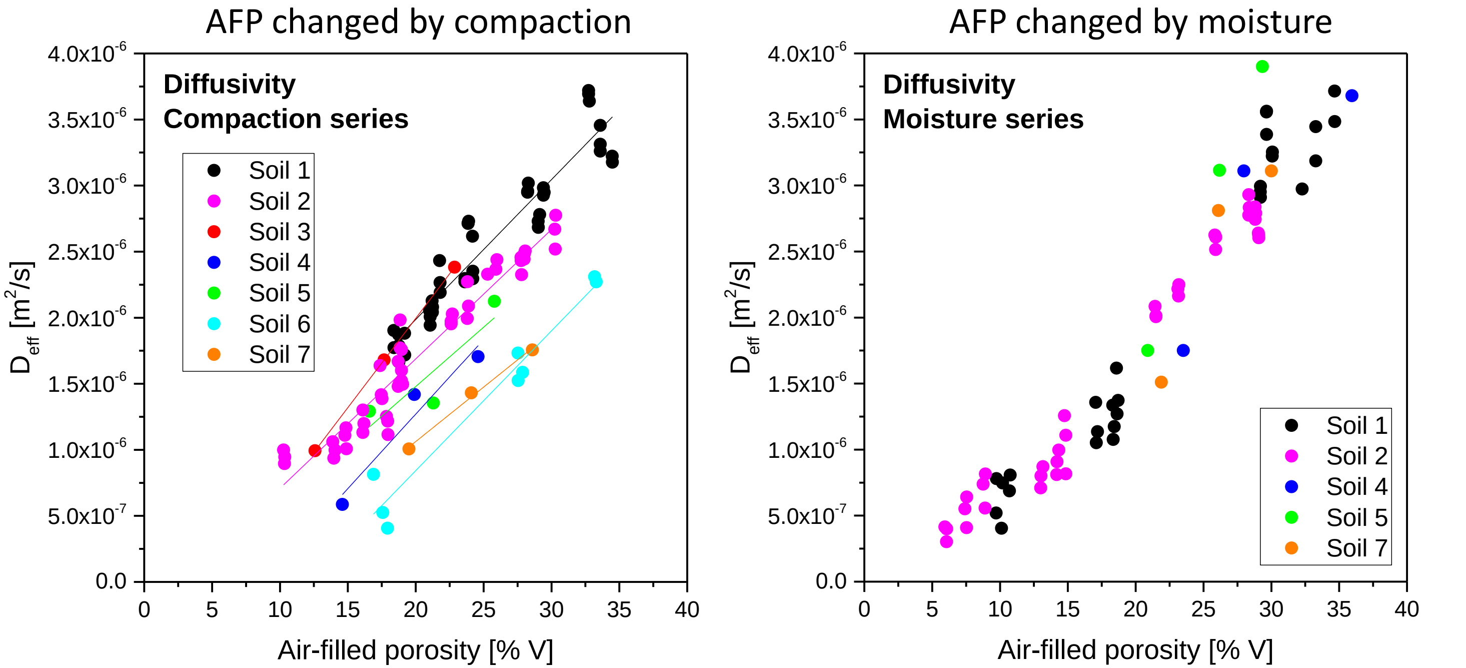
# Controls on $O_2$ transport



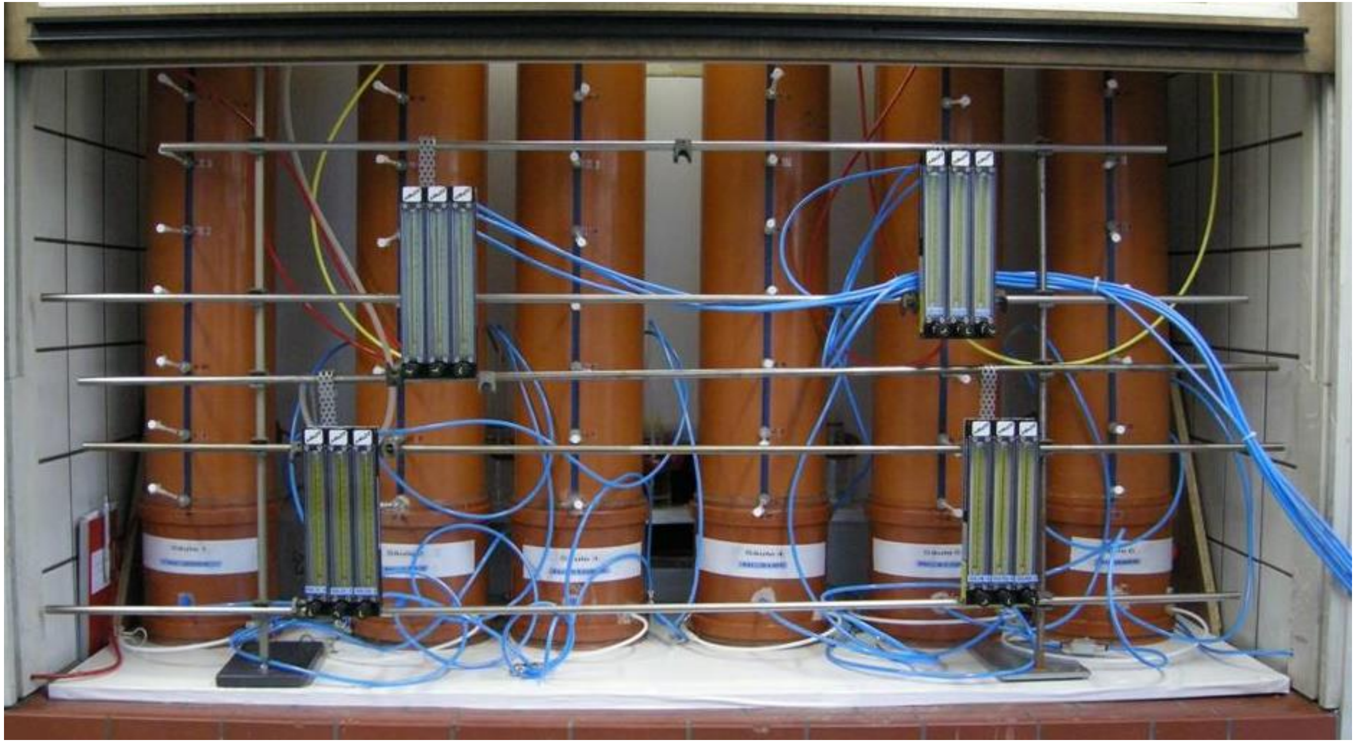
# Diffusivity depends on air-filled porosity




**Relationship is linear**
**± independent of soil type**

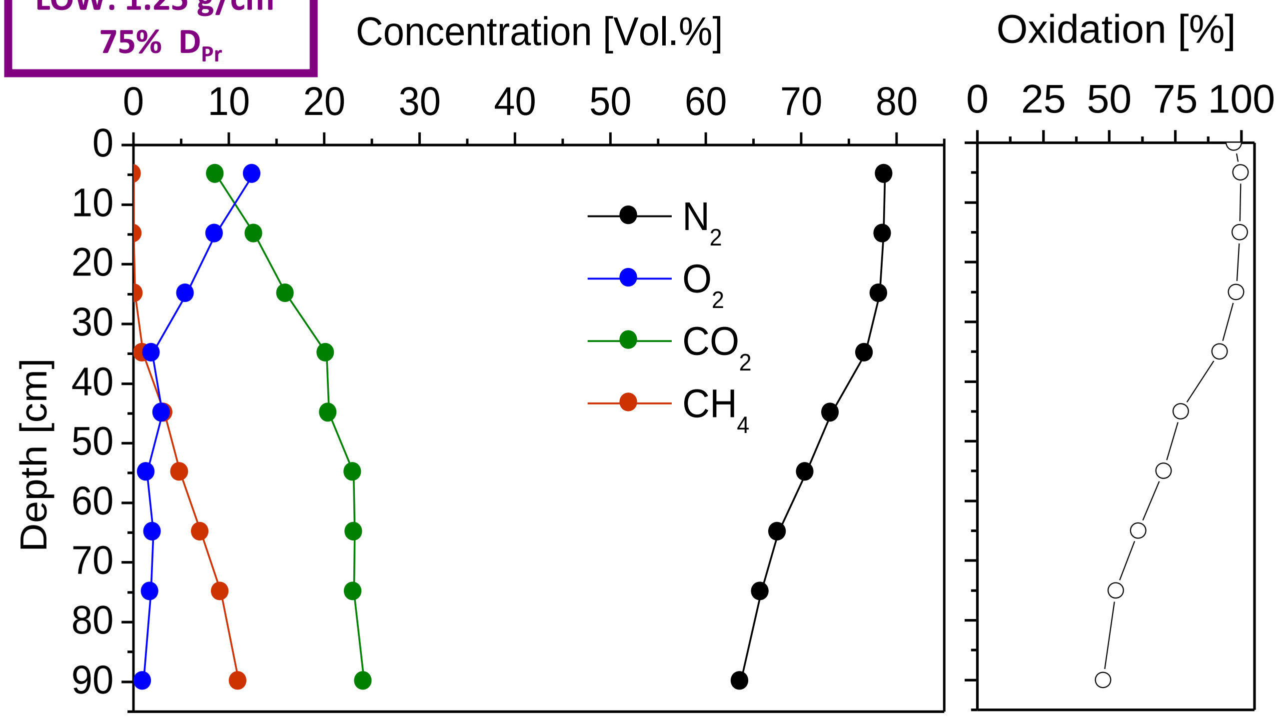
Gebert et al., 2019

# Column experiment



# Impact of soil compaction

LOW: 1.25 g/cm³
75% $D_{Pr}$




$CH_4$ load = 1.5 g $m^{-2}$ $h^{-1}$

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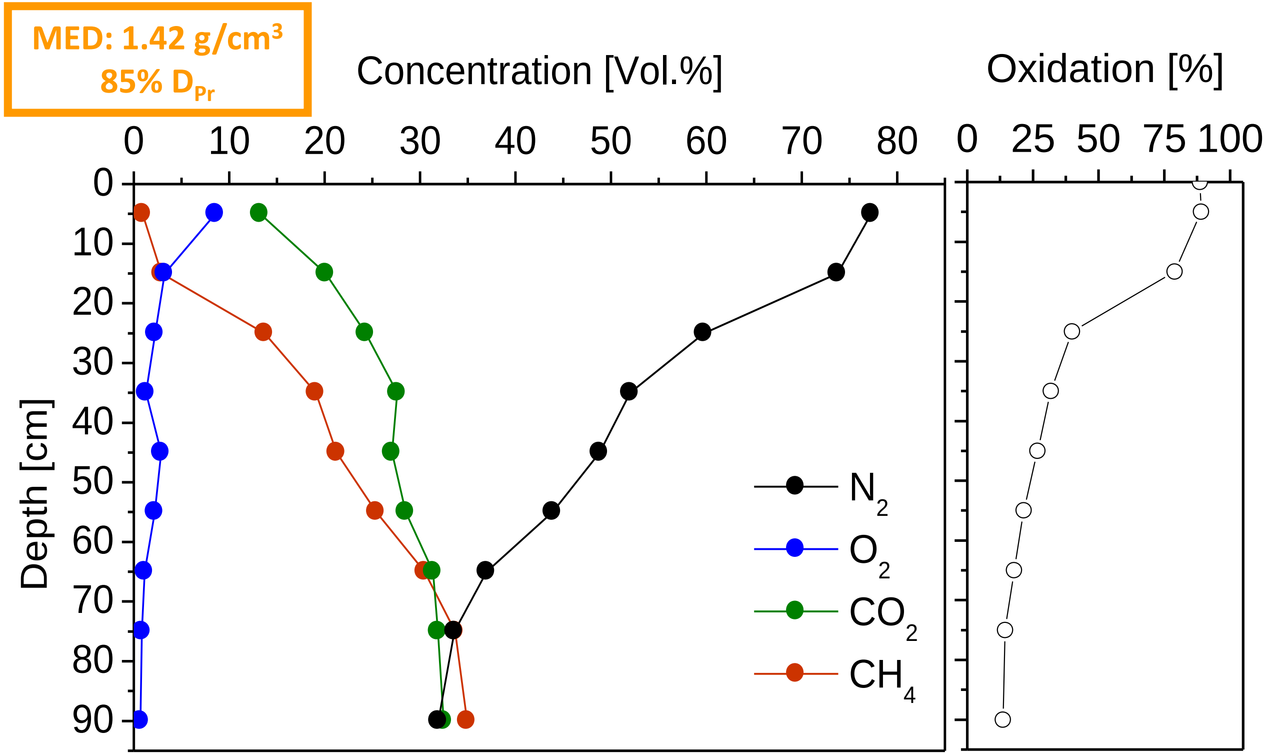
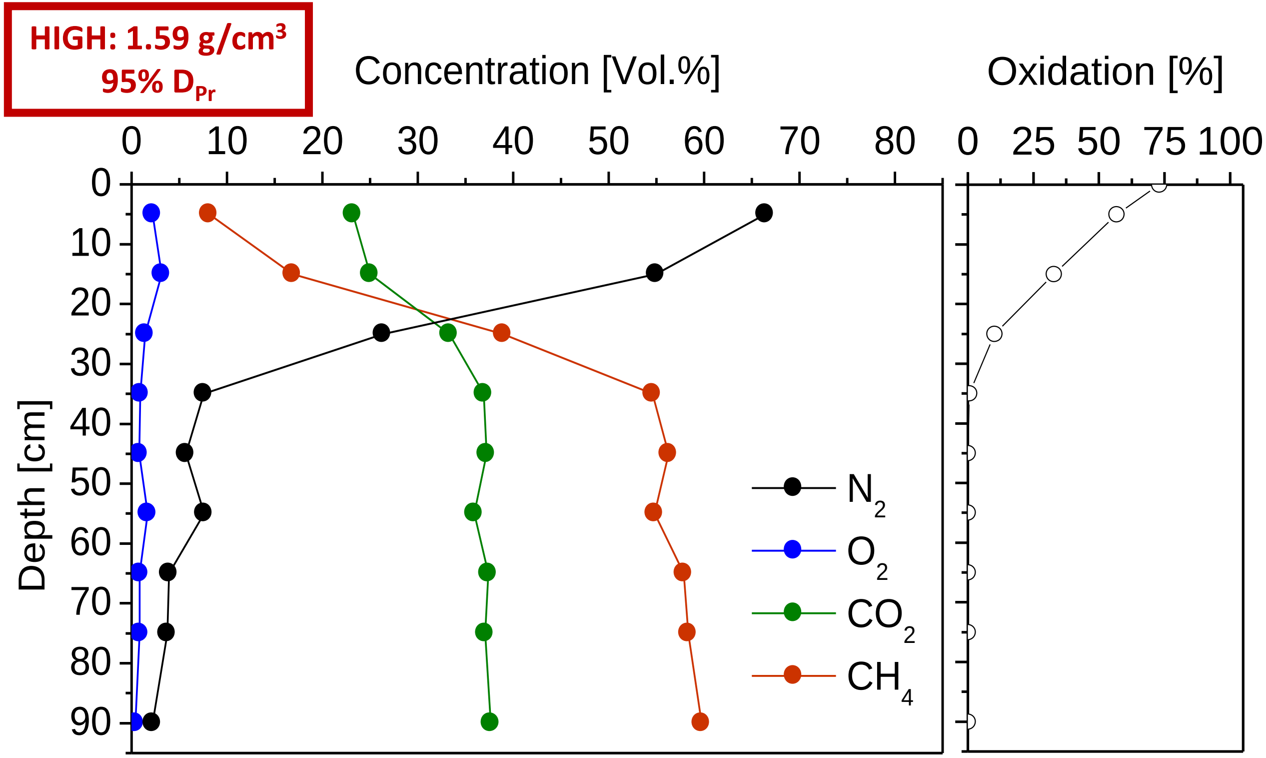
# Impact of soil compaction




$CH_4$ load = 1.5 g $m^{-2}$ $h^{-1}$

# Impact of soil compaction




$CH_4$ load = 1.5 g $m^{-2}$ $h^{-1}$

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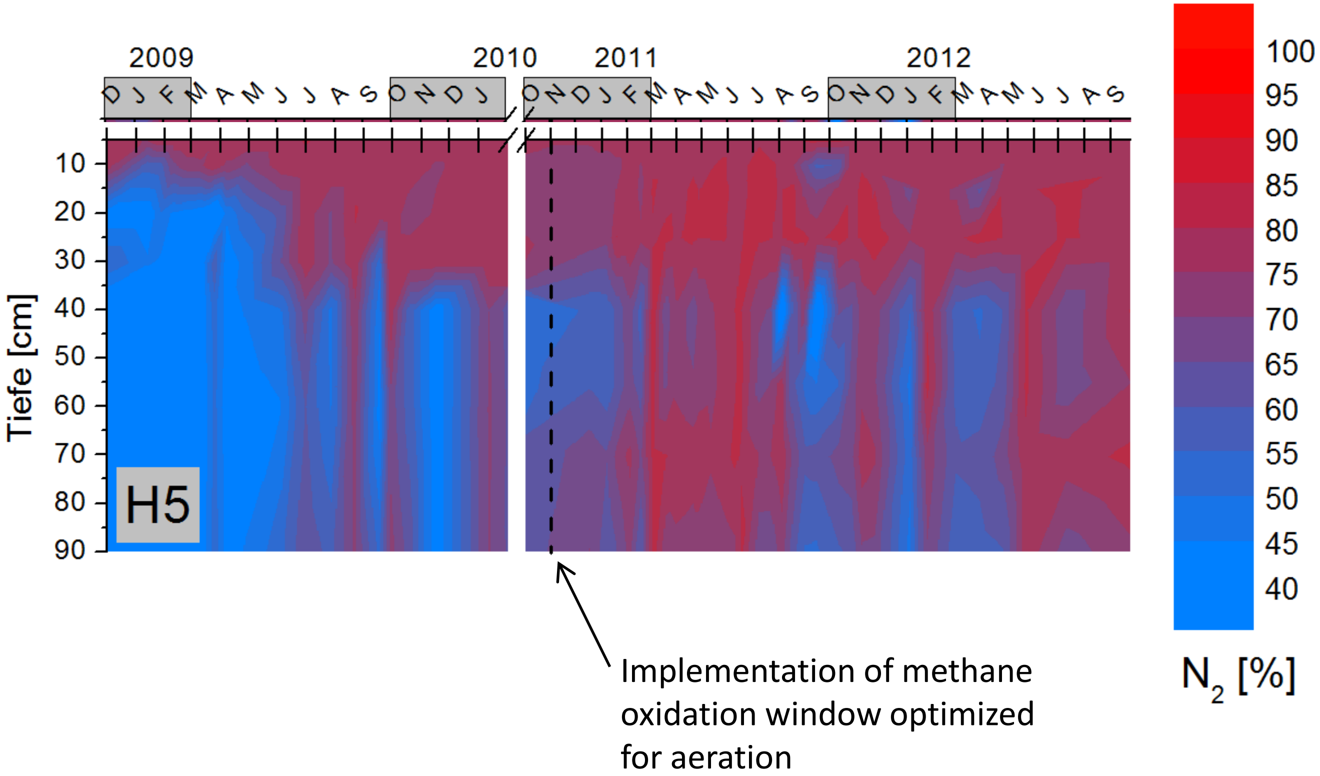
# Hotspot remediation by enhancing aeration

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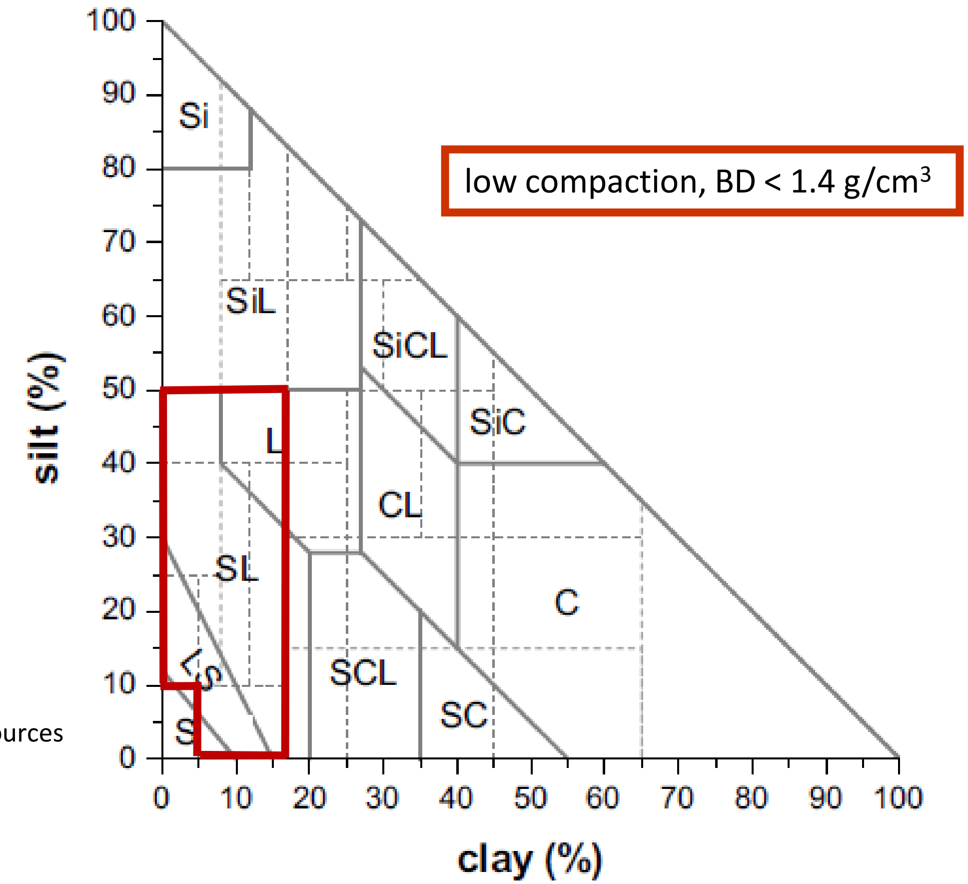
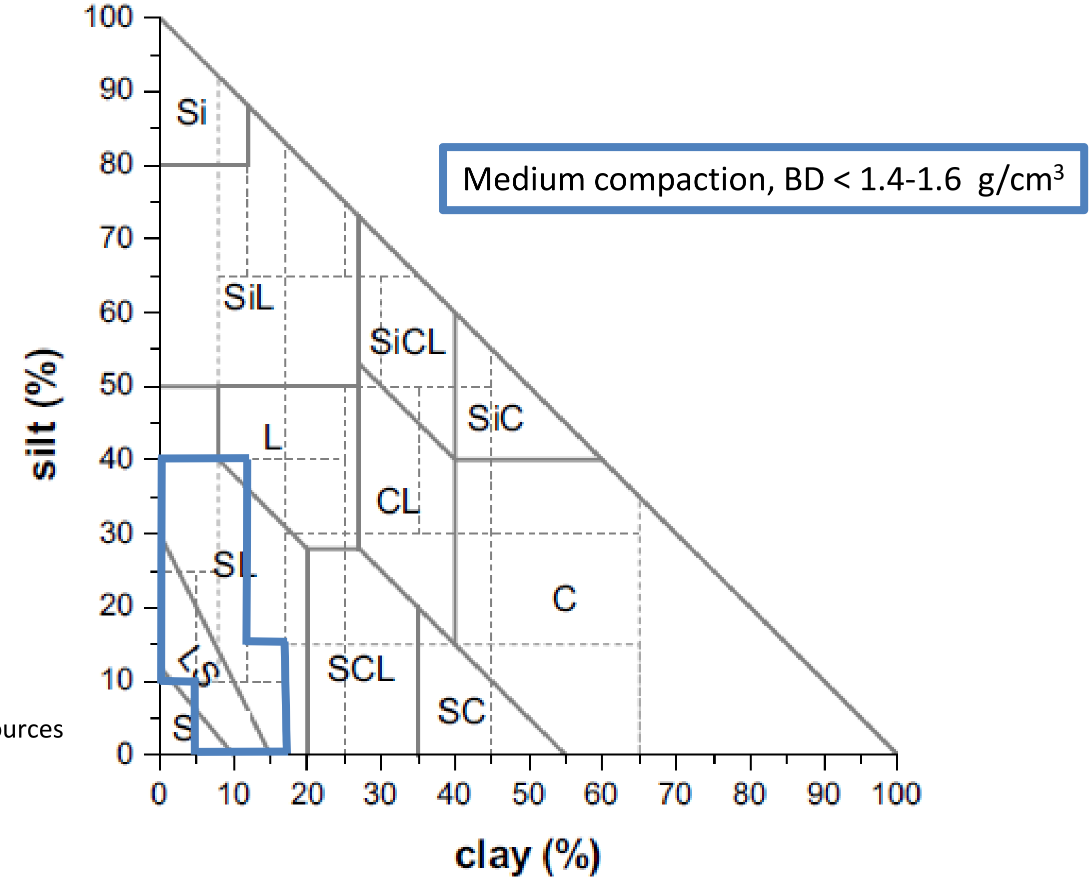
# Soil textures meeting a target of 14 vol.% AFP




FAO/ISS (2006): World reference base for soil resources

# Soil textures meeting  target of 14 vol.% AFP

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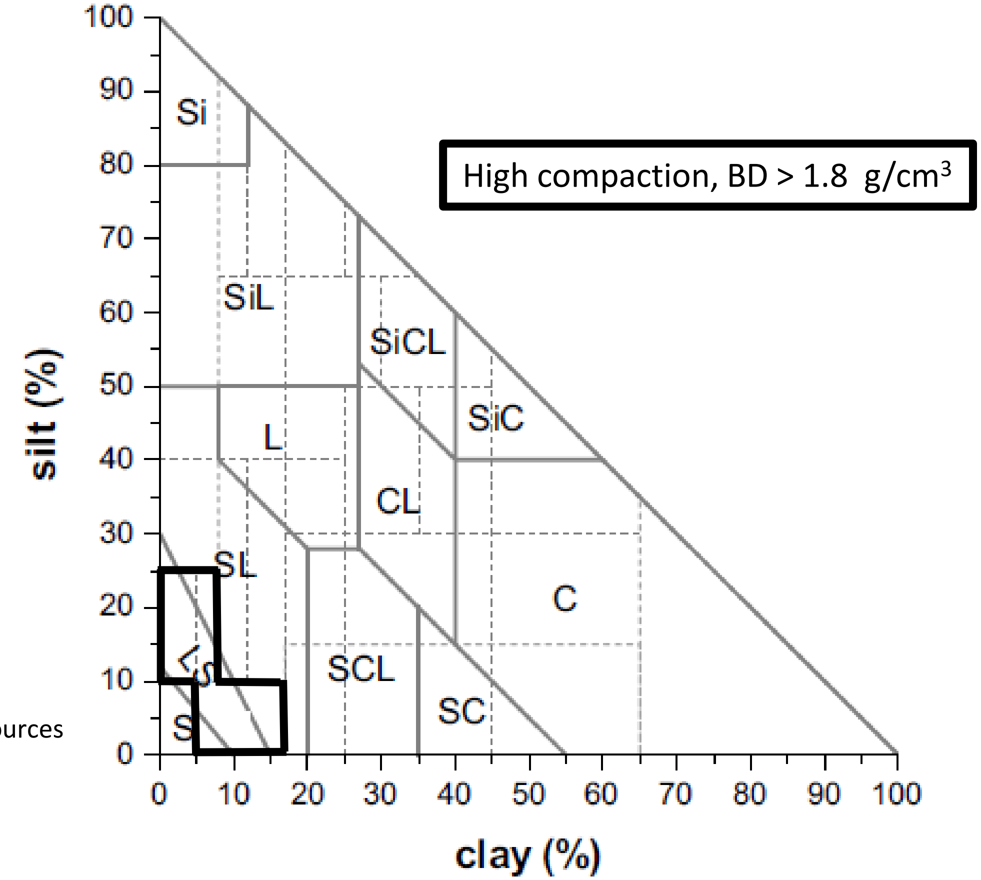


FAO/ISS (2006): World reference base for soil resources

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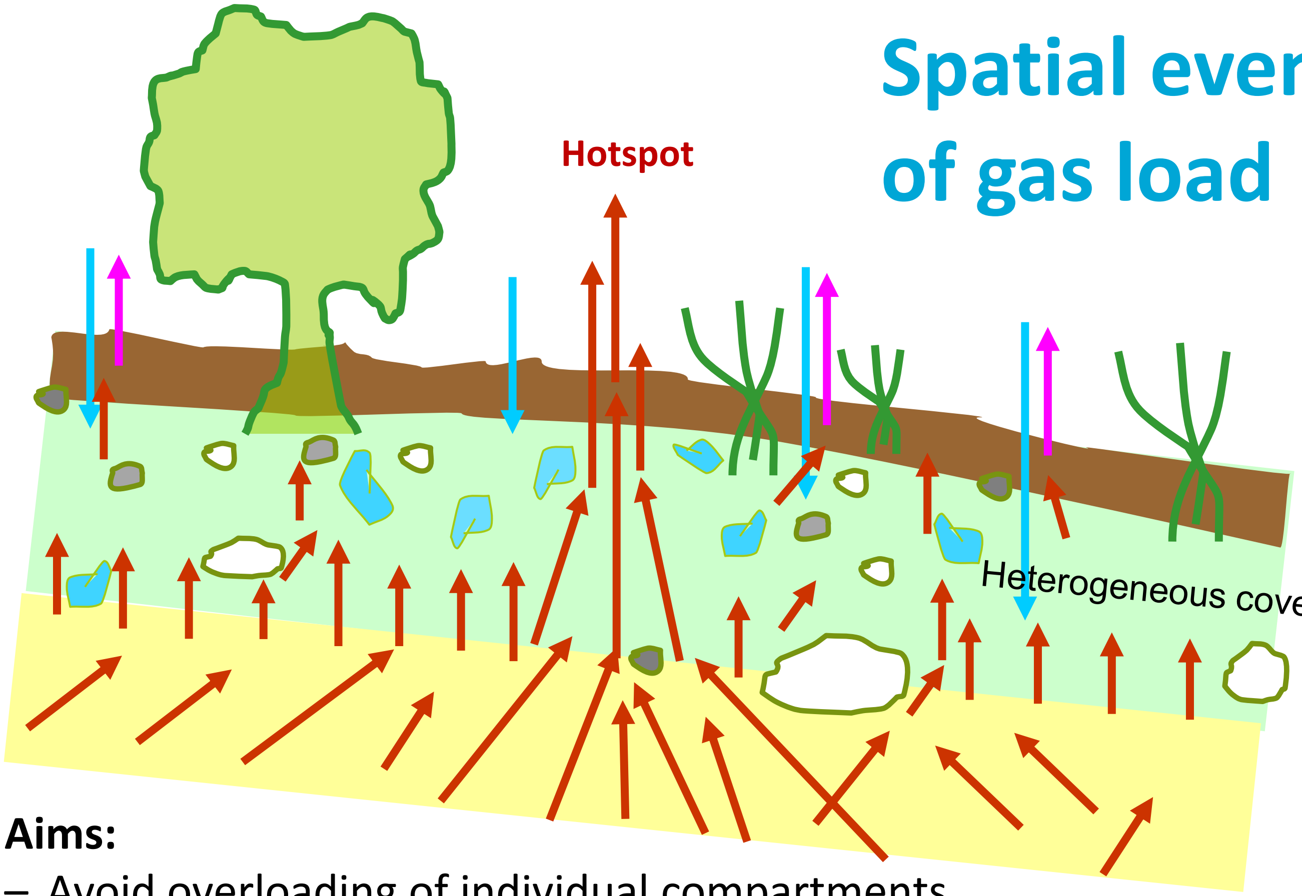
# Spatial evenness of gas load

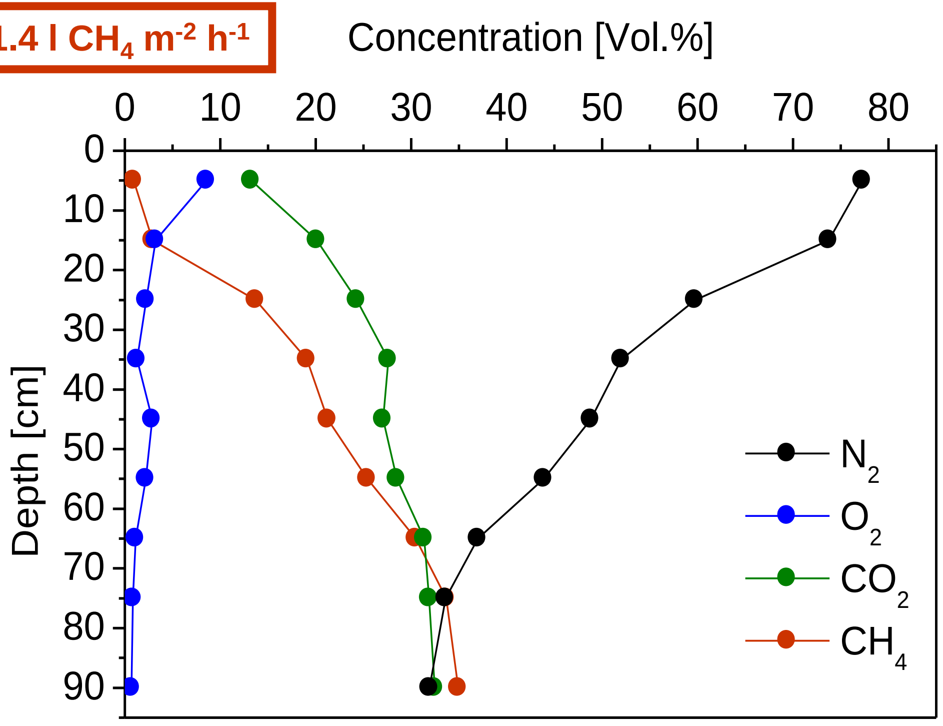



**Aims:**

- Avoid overloading of individual compartments
- Tap full system potential
- Avoid channelled advective transport

# Gas profiles with advection ↑

**1.4 l $CH_4$ $m^{-2}$ $h^{-1}$**




BD = 1.59 g/cm³, 85 % Proctor

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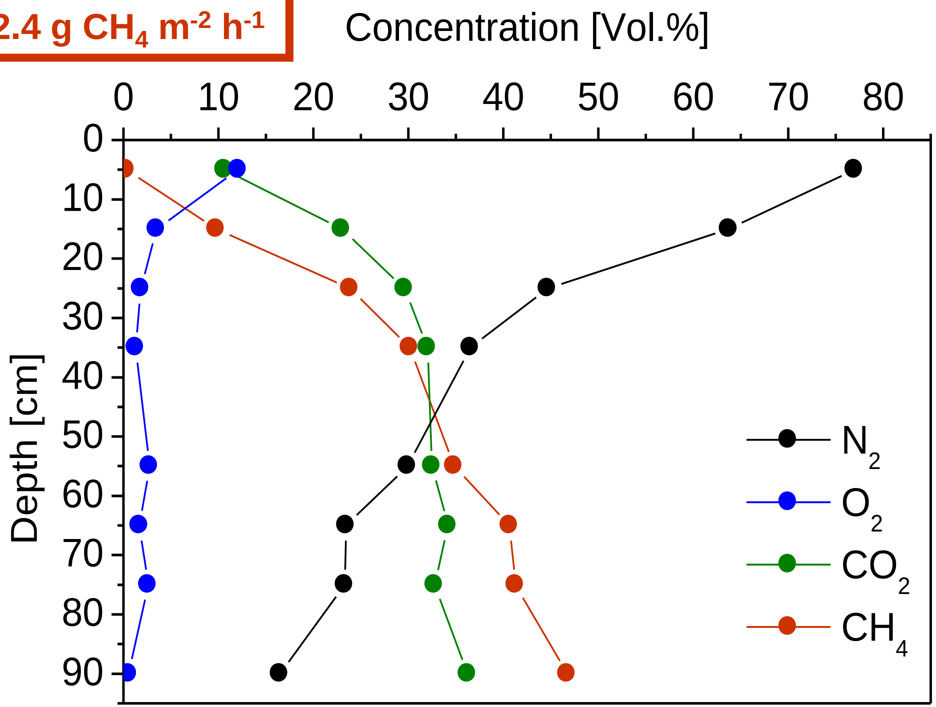
# Gas profiles with advection ↑

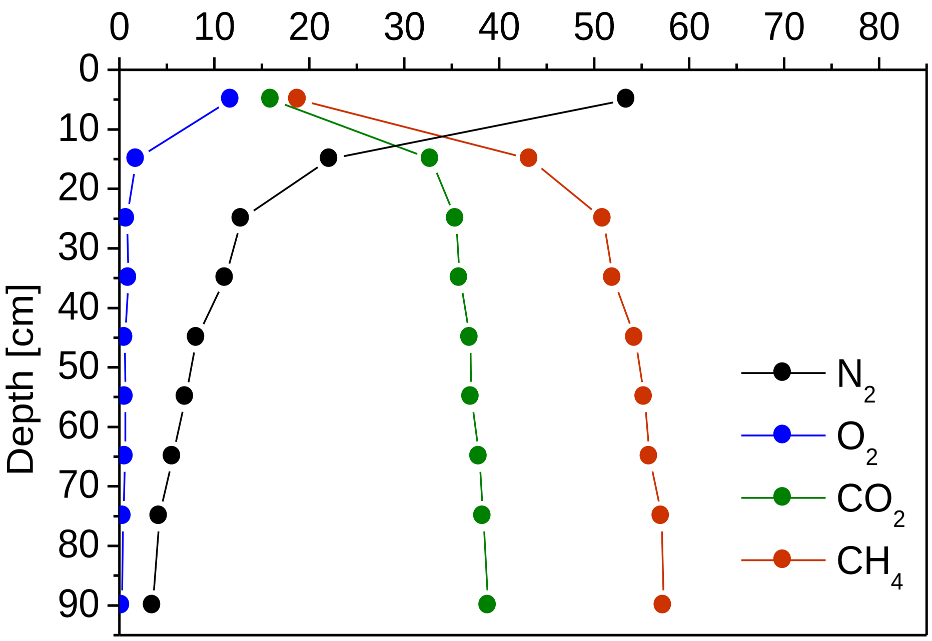
**2.4 g $CH_4$ $m^{-2}$ $h^{-1}$**




BD = 1.59 g/cm³, 85 % Proctor

# Gas profiles with advection ↑

**3.5 l $CH_4$ $m^{-2}$ $h^{-1}$**




BD = 1.59 g/cm³, 85 % Proctor

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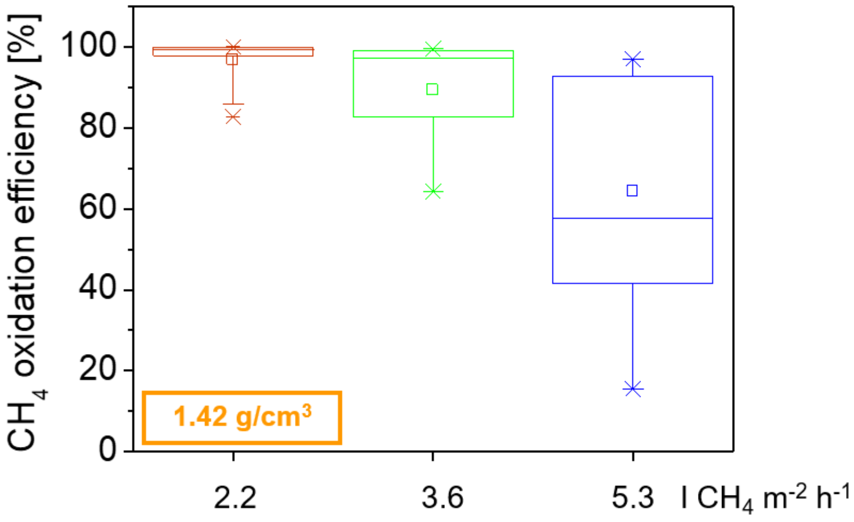
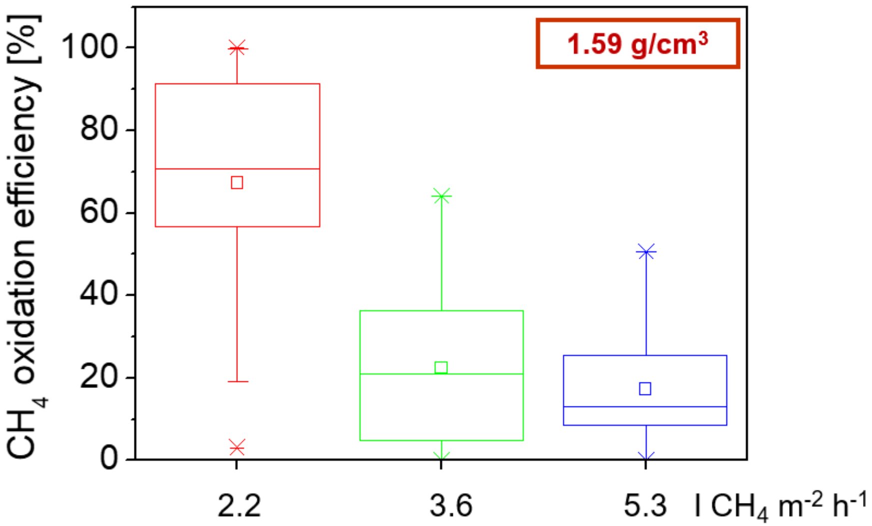
# Oxidation efficiency with advection




The higher the bulk density, the more susceptible the efficiency is to load

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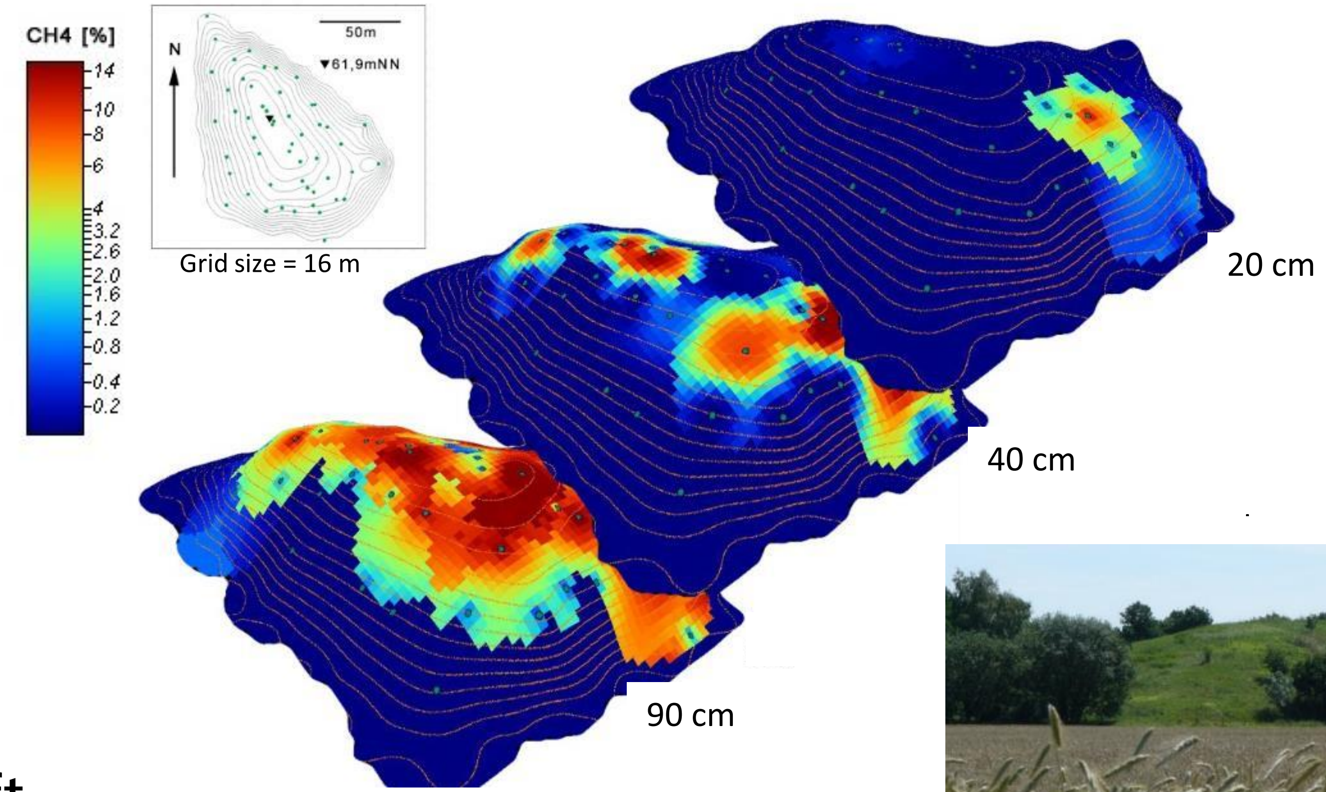
# Spatial variability of soil gas composition in a landfill cover soil

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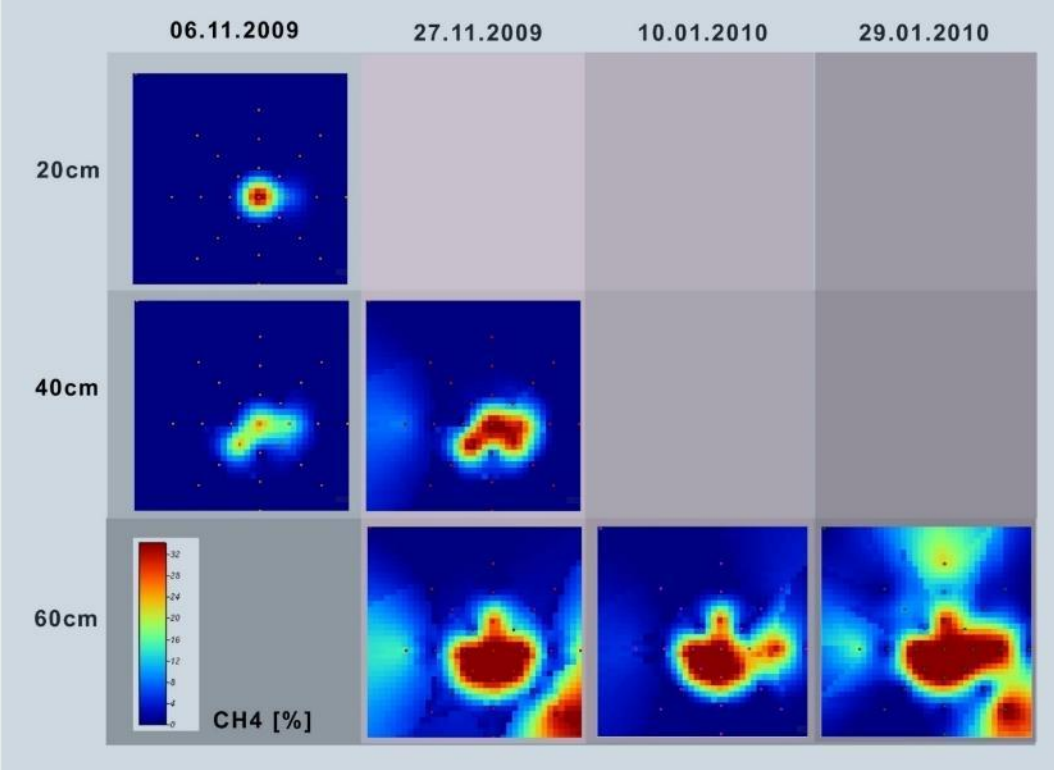
# Methane concentration at hotspot



# Morphology of hotspot soil profile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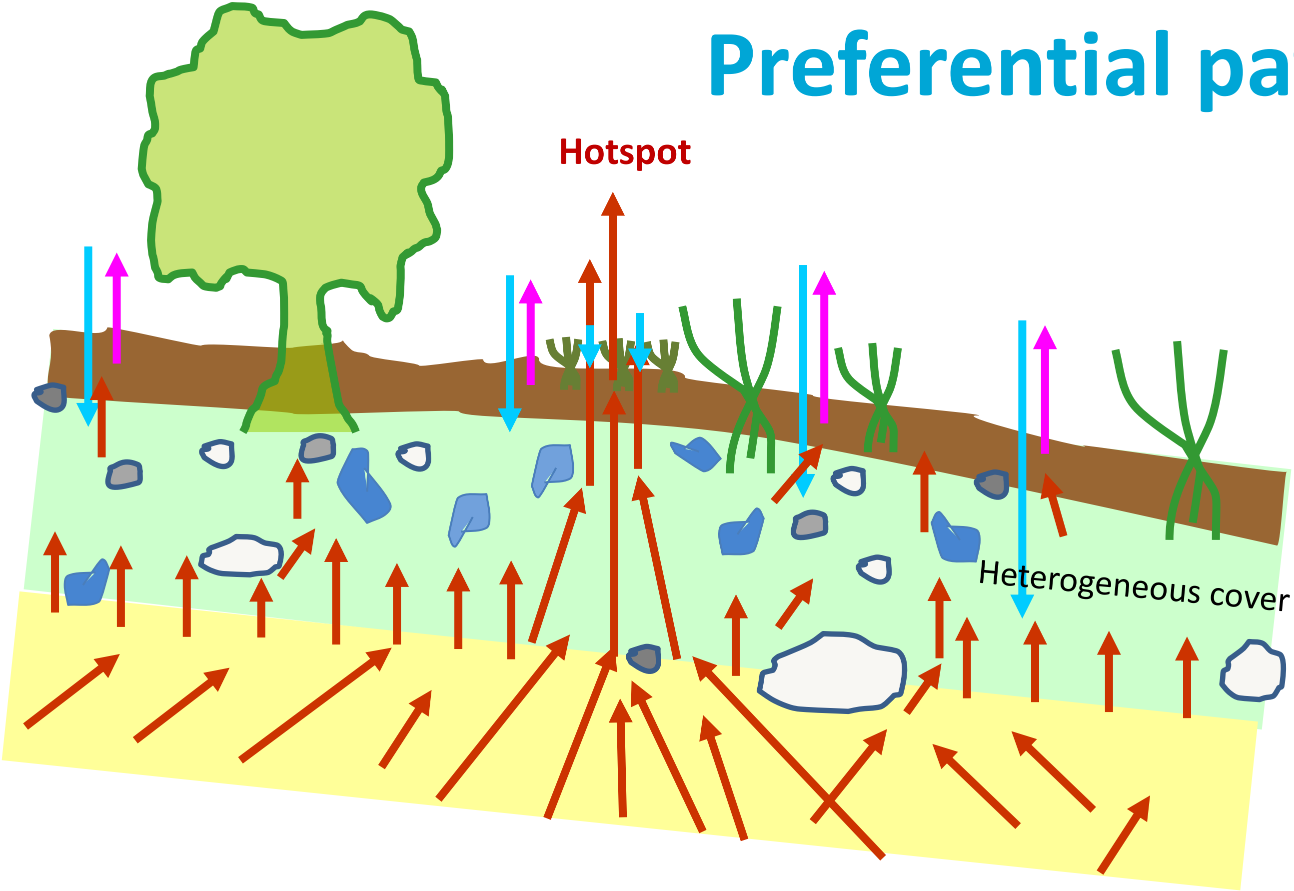
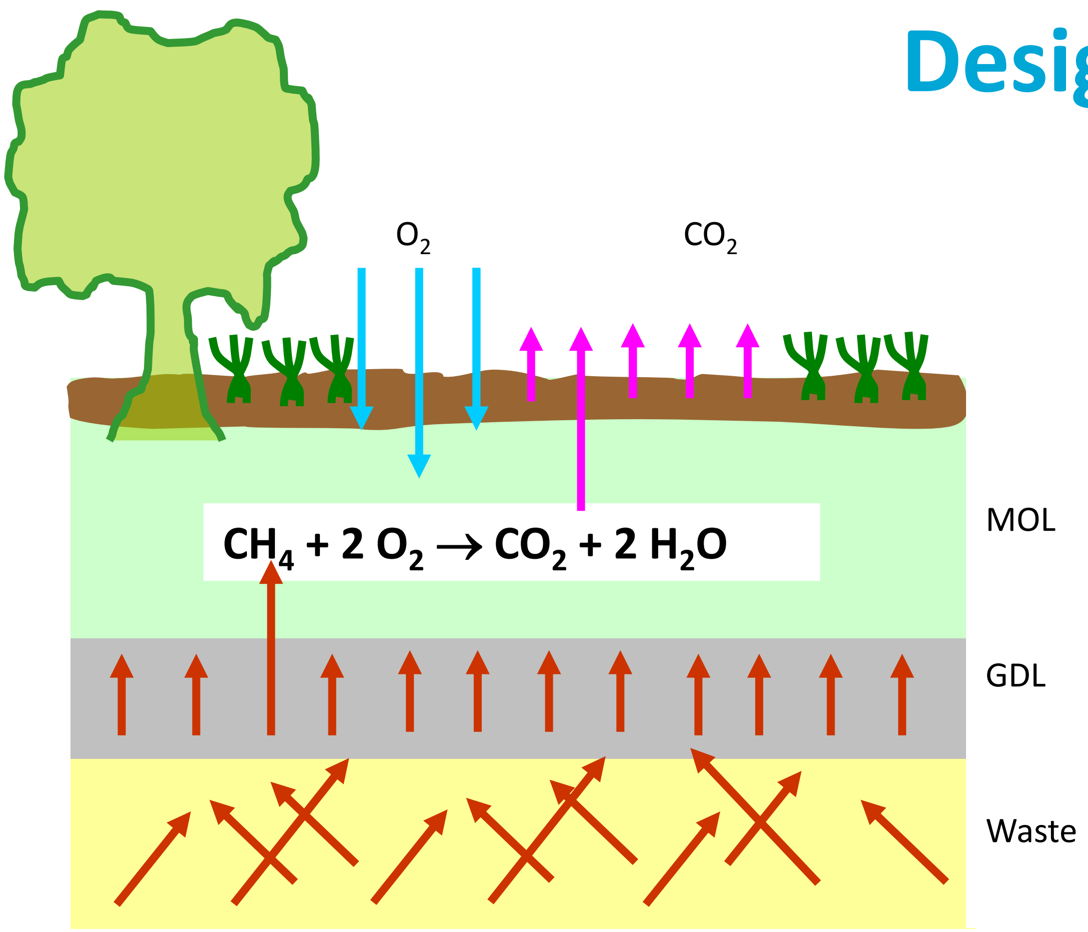
# Preferential pathways



# Designed cover

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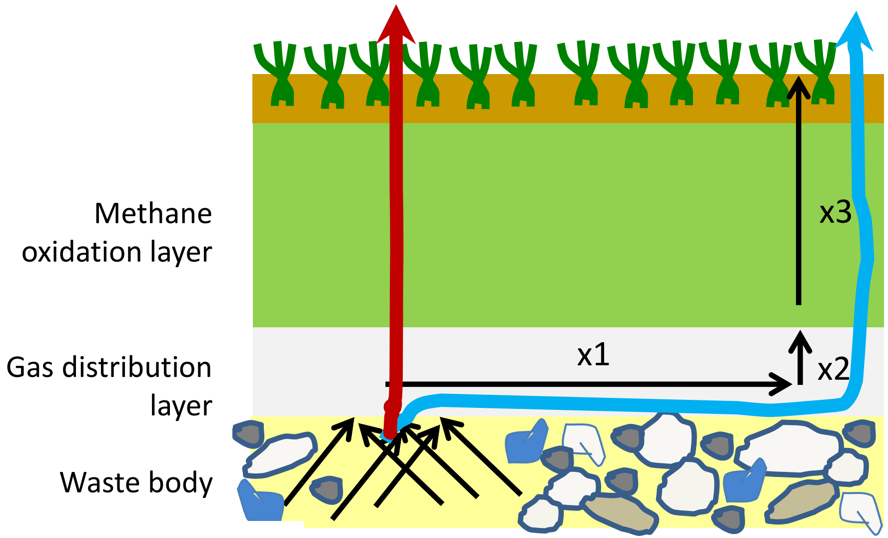
# Requirements on gas distribution layer

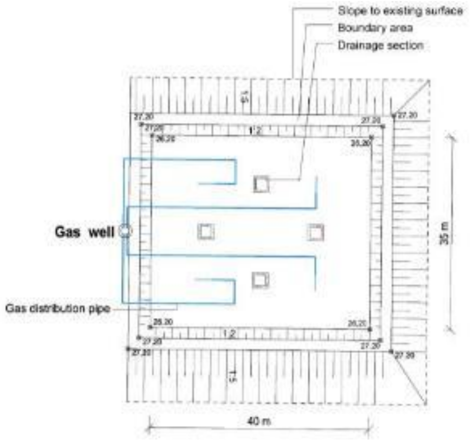
1. < 2% $CaCO_3$ → Avoid precipitation of $CO_2$
2. Purely mineral → High structural stability
3. High gas conductivity → $\mathbf{k_{Gas\_GDL}} \gg \mathbf{k_{Gas\_MOL}}$, so that




$\Sigma(R_{x1+x2+x3}) \gg \Sigma(R_{x1})$

→ Sum resistance homogenous over all path lengths
→ Horizontal gas transport favoured in GDL

With $R = 1/k_{Gas}$



# Conclusions

- Well designed methane oxidation systems are highly effective – removal rates of up to **300 g $CH_4$ $m^{-2}$ $d^{-1}$** have been measured!
- Gas transport properties of soil are key, are known and can be modelled
- Choice of suitable soil types and construction practice crucial
- Gas distribution layers are an essential element of design
- Technology is being implemented on full scale in several countries

$CH_4$ oxidation window on landfill Francop

# Guidance is available!

frontiers | Frontiers in Environmental Science

REVIEW
published: 01 September 2022
doi: 10.3389/fenvs.2022.907562

Check for updates

## Design of Microbial Methane Oxidation Systems for Landfills

*Julia Gebert*[1]*, *Marion Huber-Humer*[2] *and Alexandre R. Cabral*[3]

[1]*Department of Geoscience and Engineering, Faculty of CITG, Delft University of Technology, Delft, Netherlands,* [2]*Department of Water, Atmosphere and Environment, Institute of Waste Management, University of Natural Resources and Life Sciences Vienna, Vienna, Austria,* [3]*Department of Civil and Building Engineering, Faculty of Engineering, Université de Sherbrooke, Sherbrooke, QC, Canada*

Landfill methane currently represents the largest global source of greenhouse gas emissions from the solid waste sector. Emissions are expected to increase due to increasing waste generation, particularly in countries still landfilling biodegradable wastes. As a complementary measure to gas extraction with subsequent flaring or energy conversion, or for emissions reduction from old landfills or from landfills containing wastes with a low gas potential, microbial methane oxidation systems (MMOS) are considered a promising technology. Numerous studies relating to controlling factors and enhancement of microbial methane oxidation in biocovers, biowindows or biofilters, both in laboratory and in large scale field settings, have been published. The design of optimized MMOS requires thorough understanding of the involved processes, specifically the biological ones and of those related to the transport of gas and water in porous media, and of the impact of material properties and external environmental factors on these processes. Consequently, the selection of materials that are suitable from a biogeochemical and from a geotechnical point of view, meeting the required water and gas transport properties, are key aspects in the design process. This paper reviews the scientific background of the relevant concepts and processes dictating MMOS performance, and provides guidance on layout and design steps, including choice of materials and quality control. Further, a decision tree to support the choice of MMOS is proposed. This paper provides the scientific foundation for upcoming technical guidance documents.

**Keywords: Methane oxidation, biofilter, biowindow, biocover, design, consruction, monitoring**

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## INTRODUCTION

Anaerobic degradation of organic waste matter in landfills leads to the production of landfill gas, which contains mainly methane ($CH_4$; around 60%) and carbon dioxide ($CO_2$; around 40%). The global warming potential (GWP) of $CH_4$ is 28 over a 100 years observation period; however, within a period of 20 years, the GWP of $CH_4$ amounts to 84 (Aghdam et al., 2019). On a global perspective, $CH_4$ emissions from landfills represent the largest direct source of GHG emissions from the solid waste sector. According to the fifth IPCC assessment report, landfill contribution to greenhouse gases amounts to approximately 630 Mt $CO_2$eq (Fischedick et al., 2018) Global landfill emissions are expected to rise, since waste generation per capita is expected to increase, particularly in developing nations, who landfill large quantities of biodegradable organic matter (Heroux et al., 2010). Given the high short-term GWP, the nature of landfills as a point source and the magnitude of GHG emissions



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# Thank you!