Predicting CH$_4$ Emissions Under Climate Change: Model Structures, Uncertainties, and Needs

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Overview

• Of the big three (CO₂, CH₄, N₂O), CH₄ emissions are the most difficult to predict

• Models need to represent:
  – Production, oxidation, transport, aerenchyma, ebullition, aqueous chemistry, inundation
  – Temperature, pH, redox dependence of processes
  – Propagation of uncertainty, sensitivity analyses

• Observations to constrain and test model performance

• Synthesis of model predictions
  – Current CH₄ emissions
  – Expected changes over this century

• Poorly constrained processes and parameterizations – i.e., what’s needed for the next generation of CH₄ BGC models and predictions?
Hierarchy of Model Structures

1. Regression models of net CH$_4$ fluxes
   - [Bellisario et al., 1999; Frolking and Crill, 1994; Moore and Roulet, 1993]

2. Predict monthly net CH$_4$ fluxes dependent on water chemistry, temperature, and belowground C fluxes
   - [Potter, 1997]

3. Predict hourly CH$_4$ production, oxidation, transport, aerenchyma, ebullition, inundation, aqueous chemistry, and temperature-, pH-, and redox-dependences
   - [Cao et al., 1996; Walter et al., 2001; Wania et al., 2010; Zhang et al., 2002; Zhuang et al., 2004; Riley et al. 2010]

4. Added dynamics of several microbial populations and their interactions with substrates, pH, and redox potential
   - [Grant, 1998; 1999; Segers and Kengen, 1998; Segers et al., 2001].
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This class of models developed from that of Walter et al. (1996, 2000, 2001)
Details Vary Across Models

• Substrate for CH\(_4\) production function of:
  – NPP, decomposition, decomposition+NPP, decomposition (+NPP) (W&H, TEM, LPJ, CLM)

• \(Q_{10}\) for CH\(_4\) production (beyond substrate production):
  – 6, 3.5-4.5, None, 2

• pH, redox:
  – None, complex, none, optional

• Oxidation in rhizosphere:
  – 50%, 40%, 75%, prognostic

• Fractional inundation:
CLM/CESM CH$_4$ Model

- 25-y simulation
CLM/CESM CH$_4$ Model

- Comparison to atmospheric inverse estimates

![Net CH$_4$ Flux (TgCH$_4$ year$^{-1}$)](chart)

2004; $Q_{10} = 2.3$
CLM Comparison to Site Observations

- In general, insufficient observations to thoroughly test model
Current High-Latitude CH$_4$ Emissions

• Bottom-up (Tg CH$_4$ y$^{-1}$)
  – 31-106 (synthesis by Zhuang et al., 2004)
  – 60 (Walter et al., 2001)
  – 36 (Zhuang et al., 2006)
  – 41-74 (Wania et al., 2010)
  – 55 (Riley et al. 2010)

• Top-Down inversions (Tg CH$_4$ y$^{-1}$)
  – 35 (Bergamaschi et al. 2009)
  – 55 (Bloom et al. 2010)
  – 29 (Bousquet et al. 2006)
Predicted 21st Century High-Latitude CH$_4$ Emissions

- Zhuang et al. [2006] and Gedney [2004] predict about a doubling
  - Applied Q$_{10}$ for CH$_4$ production of ~3-7
  - However, some studies suggest that Arctic methanogens are primarily substrate-limited
- Bohn et al. [2007] estimate that CH$_4$ emissions would double over a 100 × 100 km region in Western Siberia
- Shindell et al. [2004] concluded that northern latitude wetland emissions would triple during Northern summer
- Volodin [2008] predicted a positive high-latitude feedback that added 300 ppb of CH$_4$
- Koven et al. (2010), using a vertically-resolved model, predicted up to a tripling of current high-latitude CH$_4$ emissions
CLM4 Emission Predictions Sensitivity

![Chart showing high-latitude CH₄ emissions (Tg CH₄ y⁻¹) for different Q10 values: Q10 = 1.5, Q10 = 3, and Q10 = 4. The baseline parameters are indicated by a horizontal line.](chart.png)
Emission Predictions Sensitivity

Baseline Parameters

High-Latitude CH₄ Emissions (Tg CH₄ y⁻¹)

Low Vmax

High Vmax
Two Classes of Studies Could Benefit CH$_4$ Biogeochemical Modeling

1. Those to better constrain model structure and parameterization of processes
2. Those to improve the spatial representation of relevant surface properties

- Experiments should be designed with model structures in mind, and inform mechanisms represented in the models, rather than correlations with environment conditions
1. Structure and Parameterization

- **Should inform mechanistic representations in models**
  - E.g., if there is a transient increase in methane emissions with warming (under constant hydrology), is that from changes in:
    - Rate of SOM input
    - C decomposition rate
    - Methane production rate
    - Fraction of methane oxidized
    - Others ...

  - How are the transient and equilibrium responses different?

- **Experiments needed to better describe impacts of**
  - Methane production:
    - Temperature, substrate availability, pH, redox \( \text{CH}_4 : \text{CO}_2 \)
  - Rhizosphere competition for \( \text{CH}_4 \) and \( \text{O}_2 \)
  - Aerenchyma transport and oxidation
  - Exudation
  - Vertically resolved anoxic SOM and root dynamics
  - N cycling interactions in thawing permafrost
Microbial Process Characterization

• Common need across models and model processes:
  – Characterize microbial functional group responses and equilibrium behavior to environmental conditions
Questions for Experimentation

• How do microbial functional groups evolve?
  – Temperature, moisture, and N sensitivity; population and activity dynamics

• Do methane-producing and non-methane producing decomposition pathways respond differently to warming?
  – Observe CO$_2$:CH$_4$ ratio under different alternative electron acceptor levels

• Does warming differently affect CH$_4$ production and oxidation?

• Characterize substrate and rate limitations for methanogenesis

• Characterize turnover properties of thawing permafrost
  – Multiple pools in recently thawed organic matter? Microbial activity changes?

• How does N cycle impact CH$_4$ dynamics under warming?

• Vegetation dynamics:
  – E.g., sedge encroachment as raised sphagnum bog transitions to a fen
2. Spatial Representation of Properties

• Fractional inundation
• Vegetation characteristics and dynamics
• Soil characteristics
  – Excess ice (vertical versus horizontal)
  – Concentration and quality of OM as f(depth)
• pH and redox potential in wetland systems
  – Requires specifying the relevant inputs (e.g., N and S inputs, alkalinity, soil properties)
  – Requires modeling aqueous chemistry
The Microbial Core: An integrated research core supporting the DOE mission in Climate and the Environment

Biological System Sciences Division

Genomic Science

Calcification process in model cyanobacteria Synechococcus

STXM/NEXAFS Investigation of the Role of Particle Composition in Organic Matter Stabilization

BioEnergy Research Centers

Synchrotron Imaging

Bio-Informatics

STXM

Soil biogeochemistry

Phylogenetics

Microbial Ecosystems Biology @ LBNL

Climate and Environmental Sciences Division

Environmental biochemistry & metabolomics

(Meta)-proteomics

(Meta)-transcriptomics

STXM

Advanced Light Source

Characterization of C composition and mineral interactions in soil at microbial scales

Flagship meta-genome projects:
  Deep Soil (Rothamsted)
  Great Prairie (WI, KN, IA)
  Alaskan Permafrost

Subsurface Biogeochemical Research

Terrestrial Ecosystem Science

Stable-isotope and molecular biology analysis of the metabolism and stabilization of Biochar in soils

Microbes and nucleic acids

Metabolome

Enzyme activity

Meta-genome/Meta-transcriptome

Pyrotag/PhyloChip analysis

Nanovaccine vector

Molecular analysis

ESI/APCI-QTOF

Enzyme activity

Microbes and nucleic acids

Metabolome

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Meta-genome/Meta-transcriptome

Pyrotag/PhyloChip analysis

Nanovaccine vector

Molecular analysis

ESI/APCI-QTOF
Fundamental Questions

Is there any way to experimentally answer the following questions?

- If there are no alternative electron acceptors at all, do you actually get ~50% CH4 and ~50% CO2 (or depending on the stoichiometry of the inputs)?
  - If so, then when methanogenesis is in equilibrium with organic matter inputs, does the effect of temperature on methane production go away (i.e., fully limited by substrate)? In other words, should we think of pH and temperature as primarily affecting methanogenesis by affecting soil C cycling rates overall rather than by selectively affecting methane production pathways?
  - If not, then how does this ratio respond to temperature, and pH?
  - How wide is the range of redox potential with simultaneous methanogenesis and alternative electron acceptor reduction? Is it really like a binary switch, or is there a large range with competing processes, which might have different temperature & pH sensitivities, and might mean that you will never in practice completely “run out” of alternative electron acceptors?
CLM CH$_4$ Model

- Explicit rhizosphere O$_2$ competition
- CH$_4$ production linked to soil decomposition
- Aerenchyma density linked to NPP
- Fractional inundation based on satellite estimates (Prigent et al. 2006)
- Future improvements
  - Explicit wetland vegetation and SOM dynamics
  - Fractional inundation, aqueous chemistry