Coupling Carbon and Redox Cycles in Soil Biogeochemical Models

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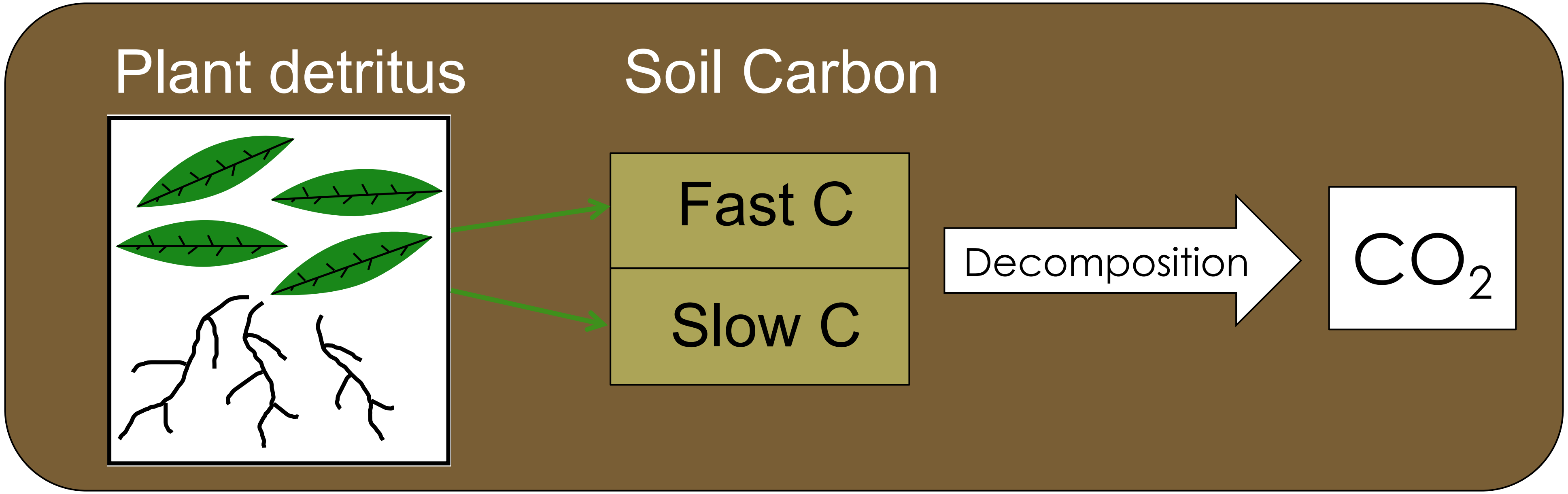
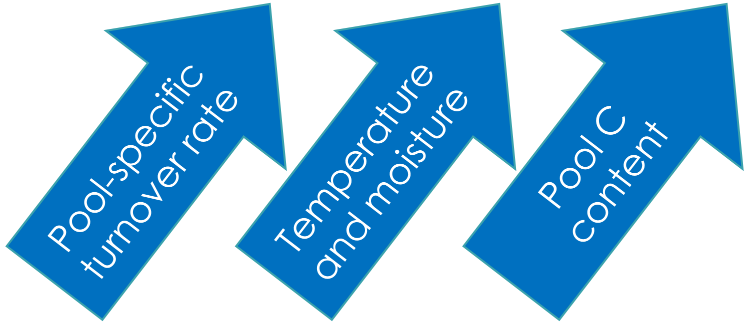
Modeling soil carbon: First-order decomposition models

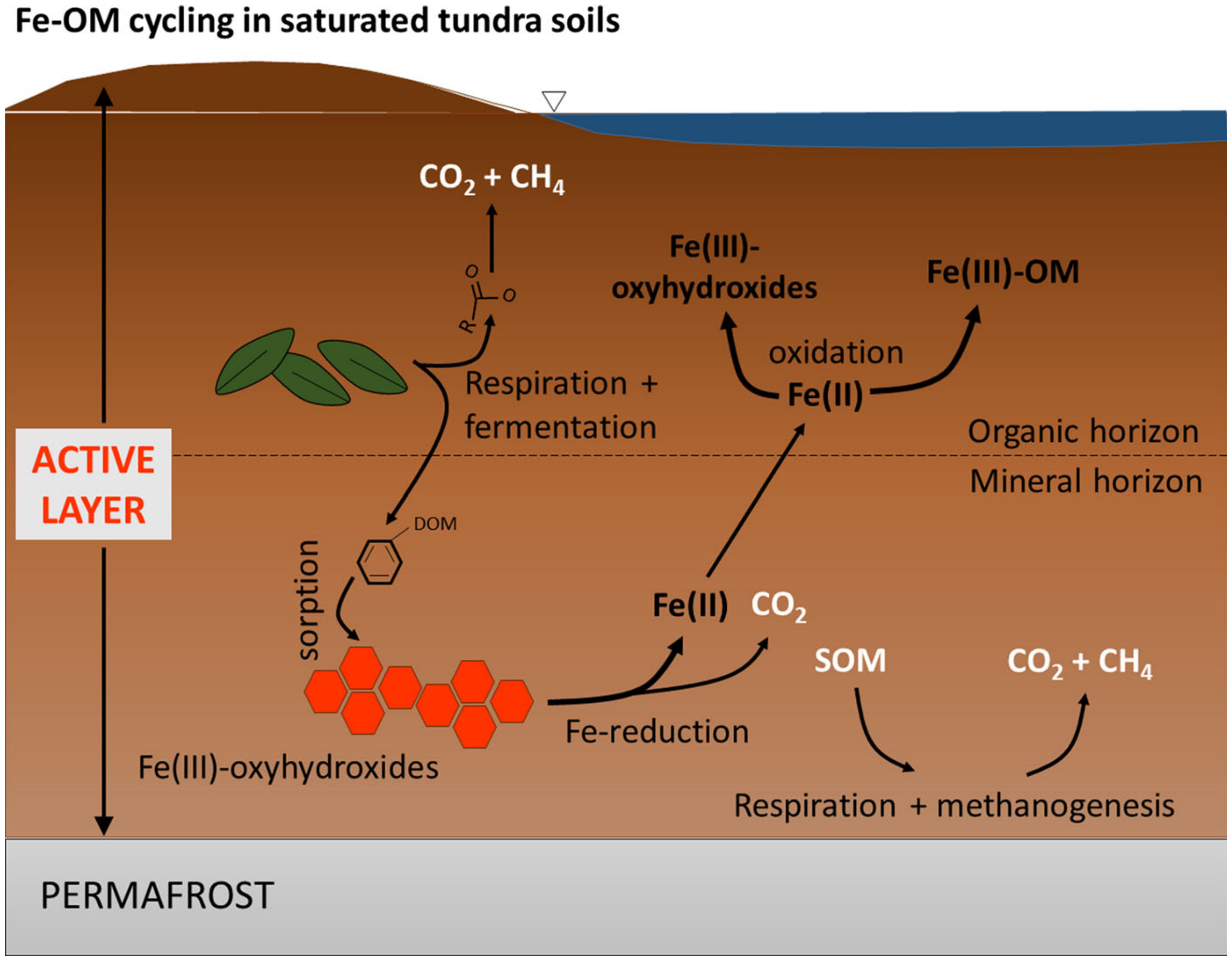


- Carbon loss rate is “first order”: Proportional to the carbon content of each pool
- Each pool has a characteristic, fixed turnover rate *k*
- Current ecosystem and larger scale models mostly use some version of this

$$\frac{dC_i}{dt} = k_i \times f(T,\theta) \times C_i$$



Iron redox cycling is important in arctic tundra soils



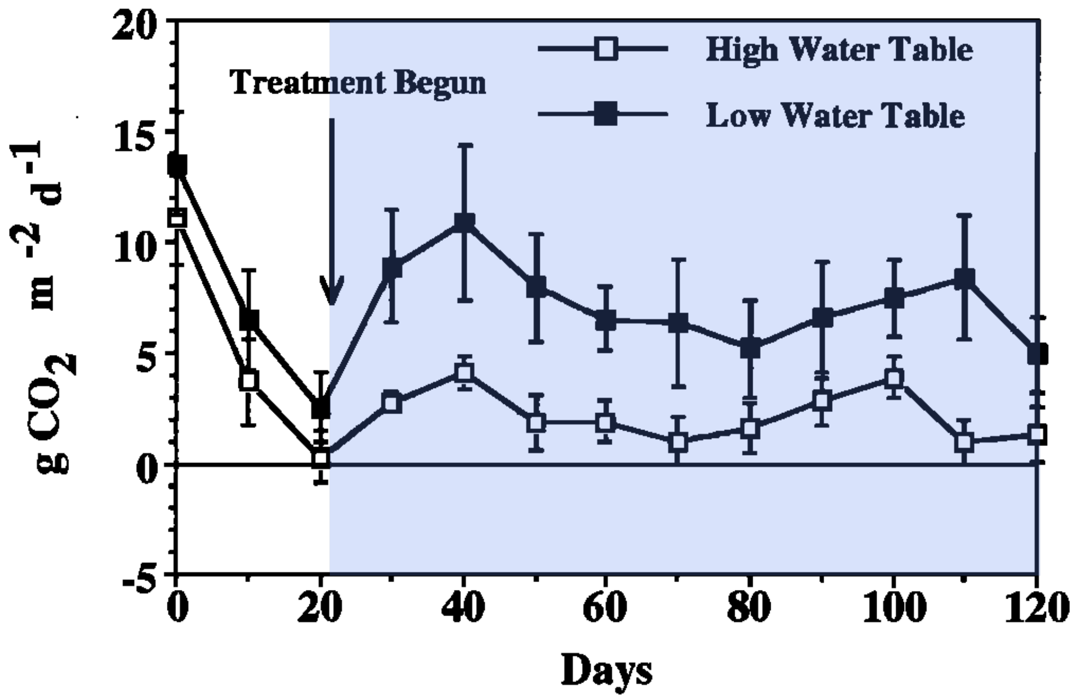
Herndon et al., 2015

Photo: Beth Herndon

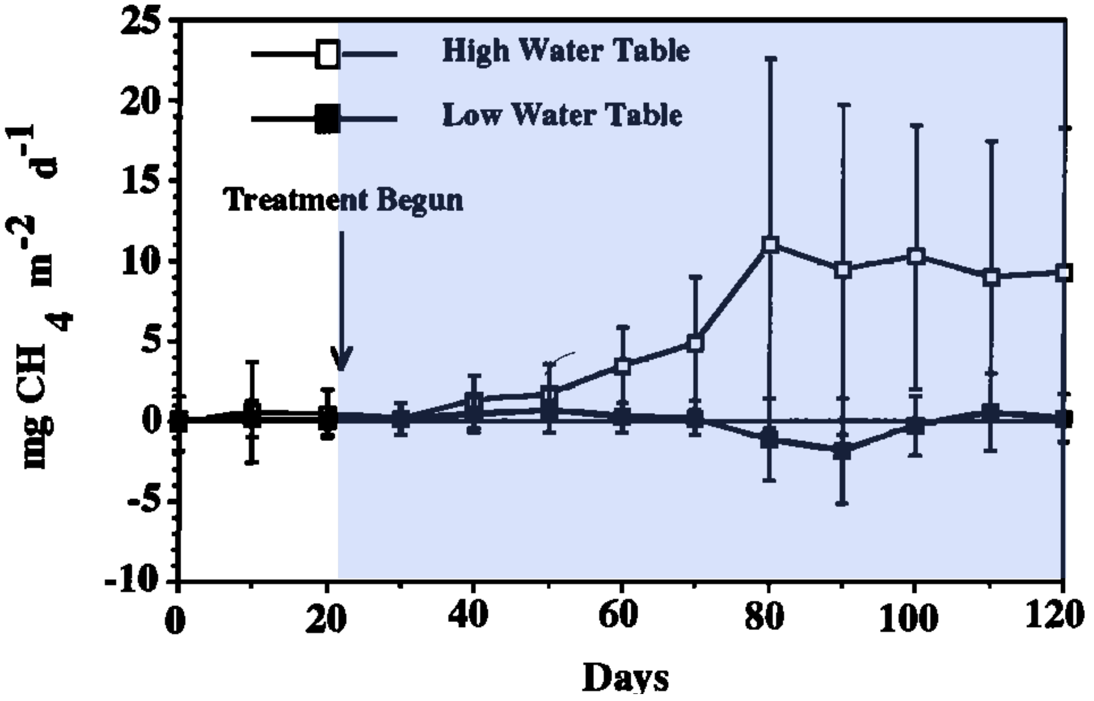
Carbon dioxide and methane fluxes respond to inundation

Funk et al., 1994: Water table manipulation

CO_2 emissions:
Decrease with inundation



CH_4 emissions:
Increase with inundation

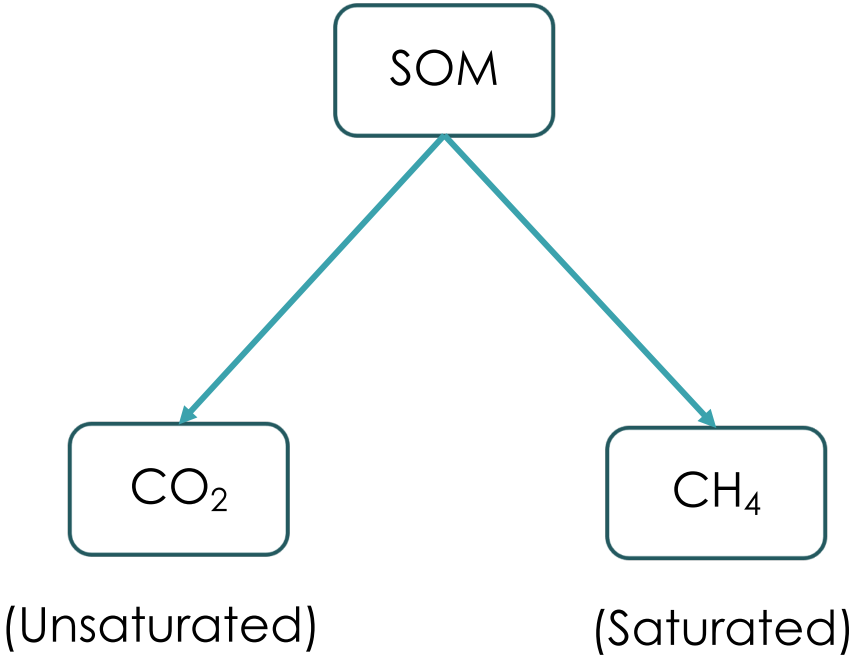


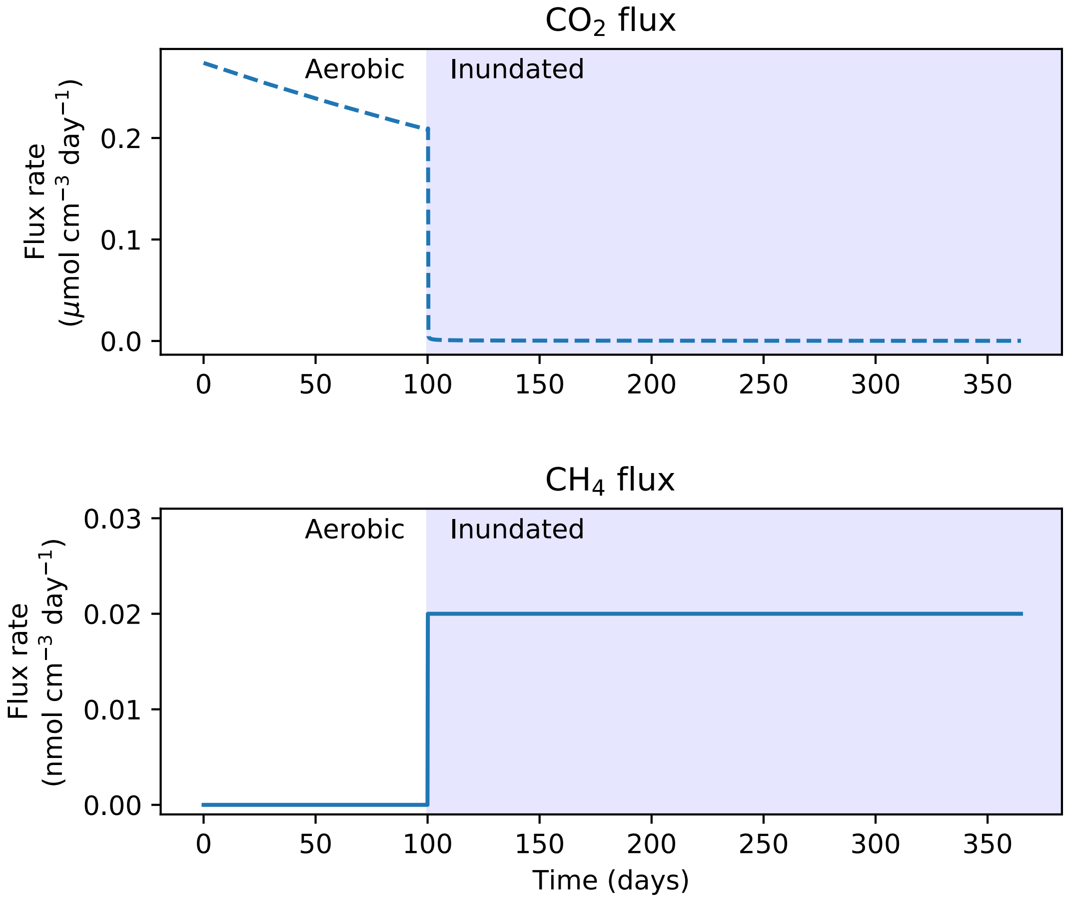
Most large-scale models calculate CH_4 fluxes based on heterotrophic respiration rate, water table position, and temperature

Model	CH_4 production (P)
CLM4Me	$P = R_{het} r_{CH4:C} f_{pH} f_{pE} Q_{10}$
DLEM	$P = P_{max} C_{labile} f_T f_{pH} f_{\Theta}$
IAP-RAS	$P = f_T$
LPJ-Bern peat	$P = R_{het} r_{CH4:C} f_{root} f_{WTP}$
LPJ-Bern wetlands	$P = R_{het} r_{CH4:C}$
LPJ-Bern rice	$P = R_{het} r_{CH4:C}$
LPJ-Bern wetsoils	$P = R_{het} r_{CH4:C} f_{\Theta}$
LPJ-WHyMe	$P = R_{het} r_{CH4:C} f_{root} f_{WTP}$
LPJ-WSL	$P = R_{het} r_{CH4:C} f_{ecosys}$
ORCHIDEE	$P = R_0 C_{labile} f_{WTP} f_T Q_{10}$
SDGVM	$P = R_{het} r_{CH4:C} f_{WTP} f_T Q_{10}$
UW-VIC	$P = R_0 f_{NPP} f_{root} f_T Q_{10}$

Wania et al., 2013, GMD

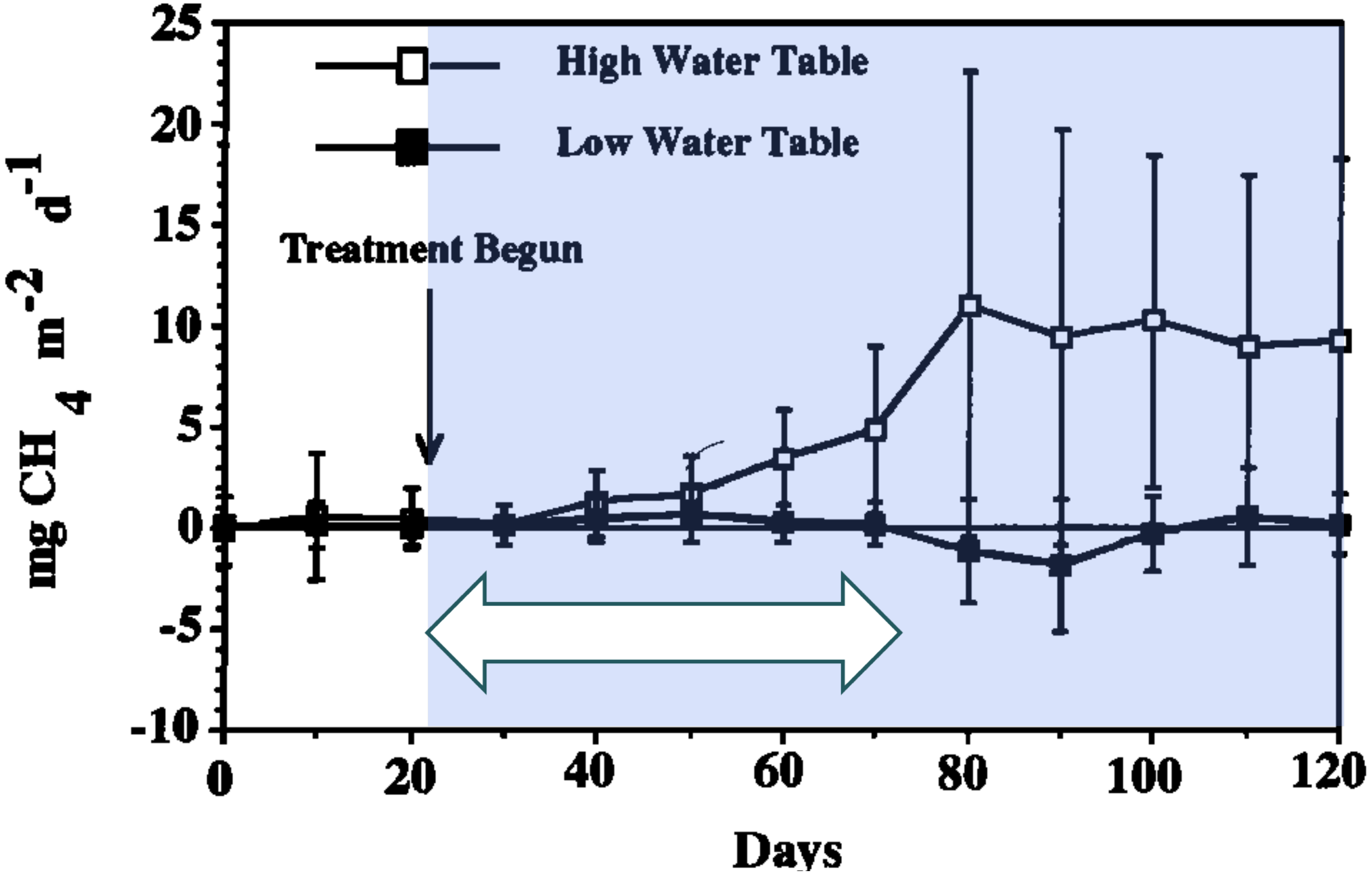
First order model formulation





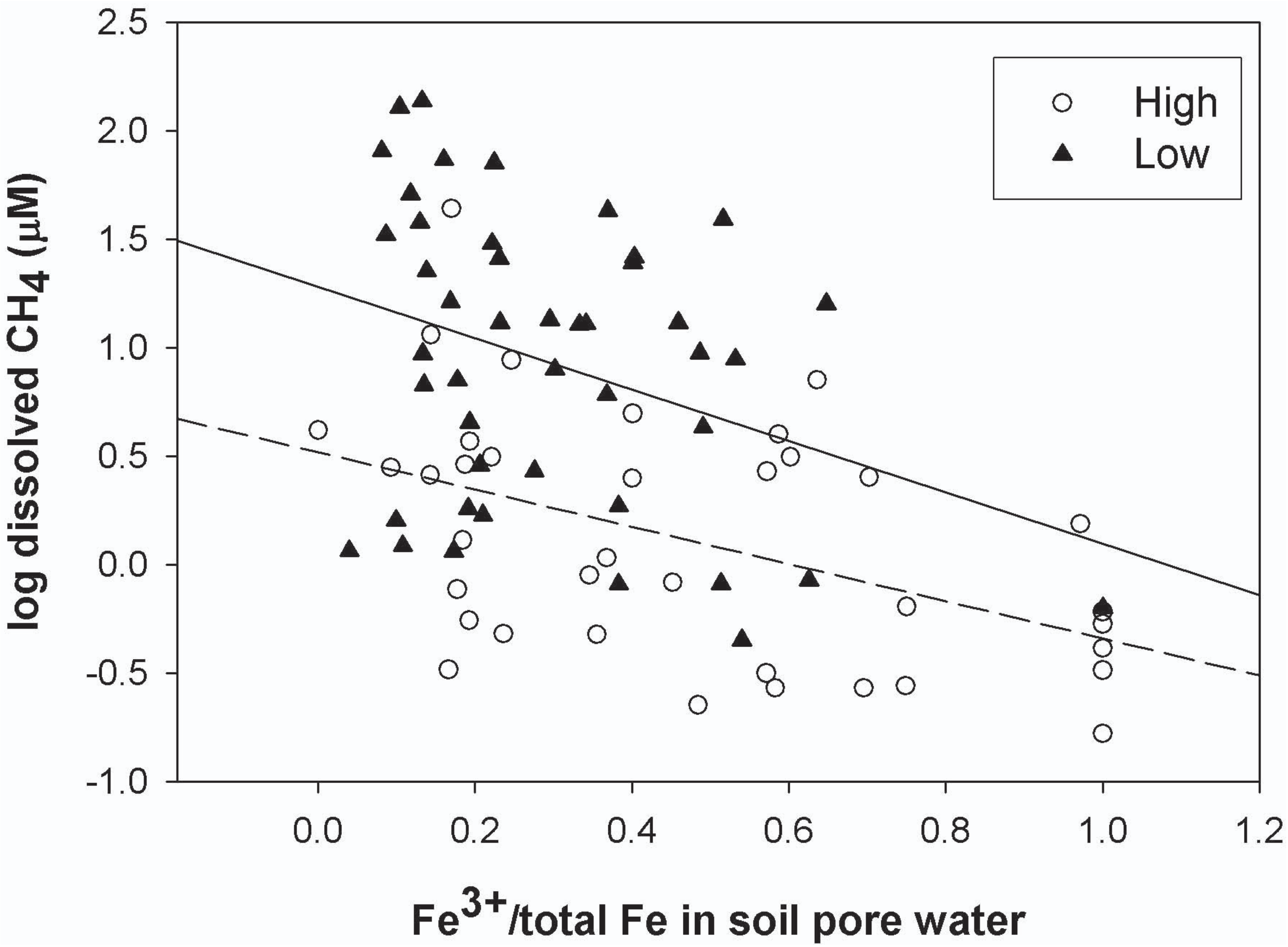
Carbon dioxide and methane fluxes respond to inundation

CH_4 emissions:
Increase with inundation (but delayed)



Funk et al., 1994: Water table manipulation

Methane emission decreases with presence of alternative electron acceptors such as Fe(III)

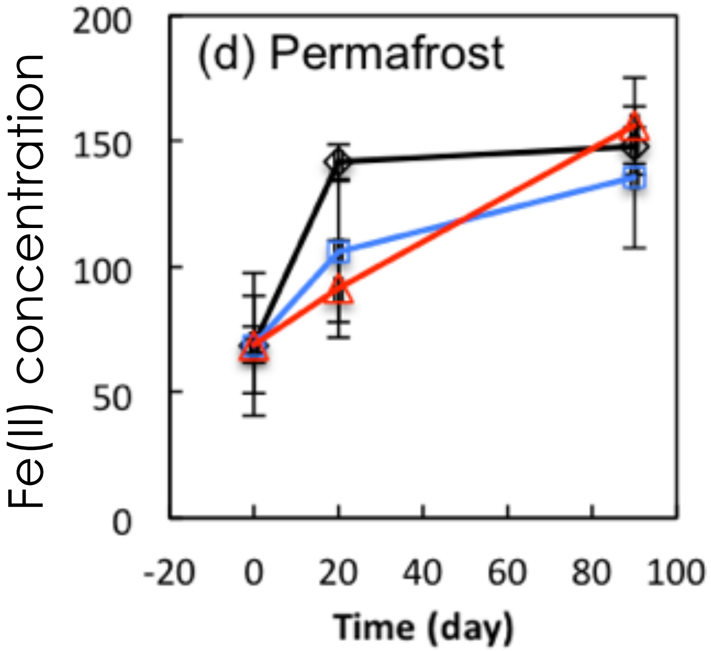


Lipson et al., Biogeosciences, 2012

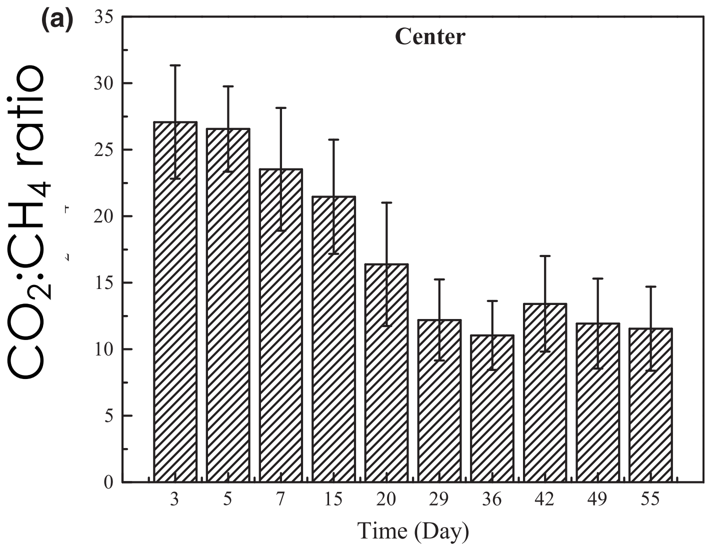
Permafrost incubations have documented Fe(III) reduction interaction

Permafrost incubations:

- Fe(II) concentration increases over time
- Methane production increases are delayed



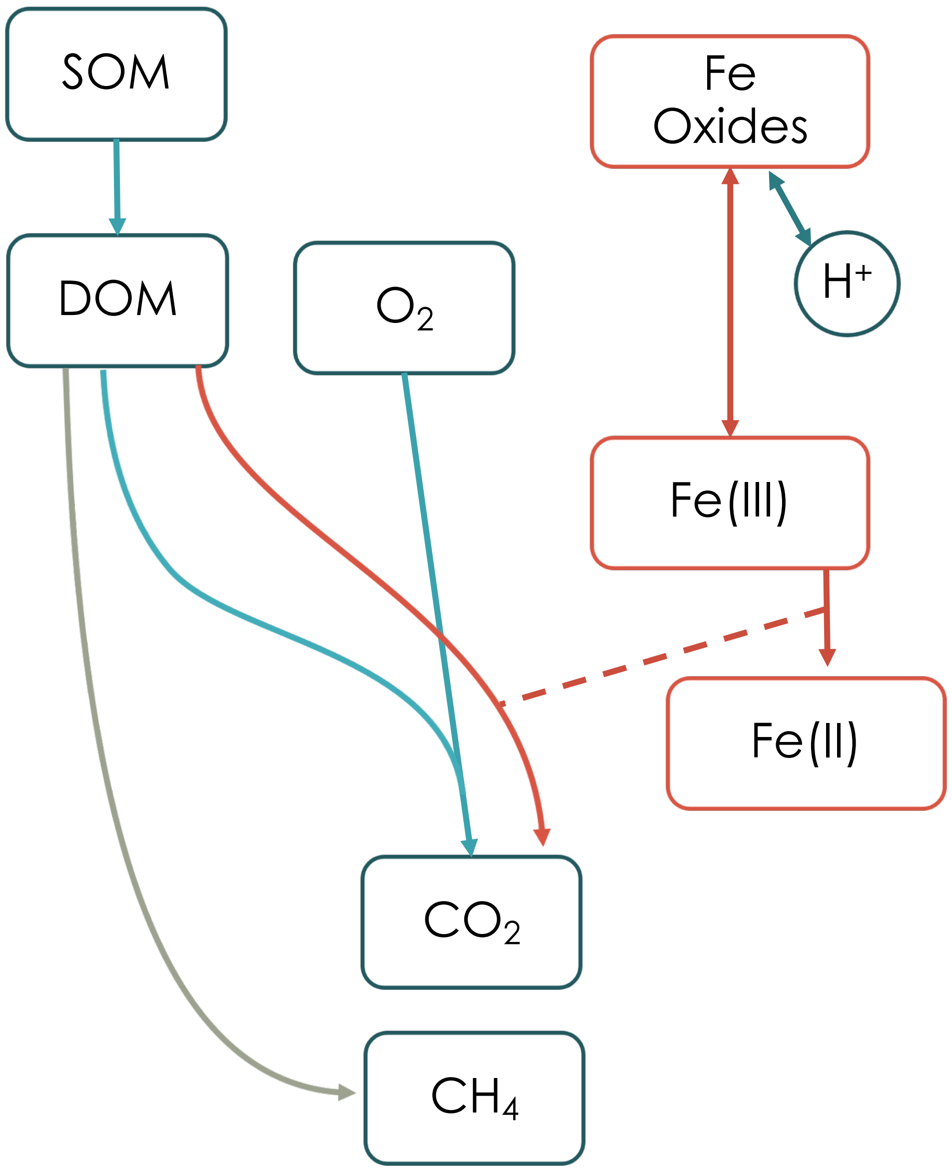
Zheng et al., 2018, Biogeosciences



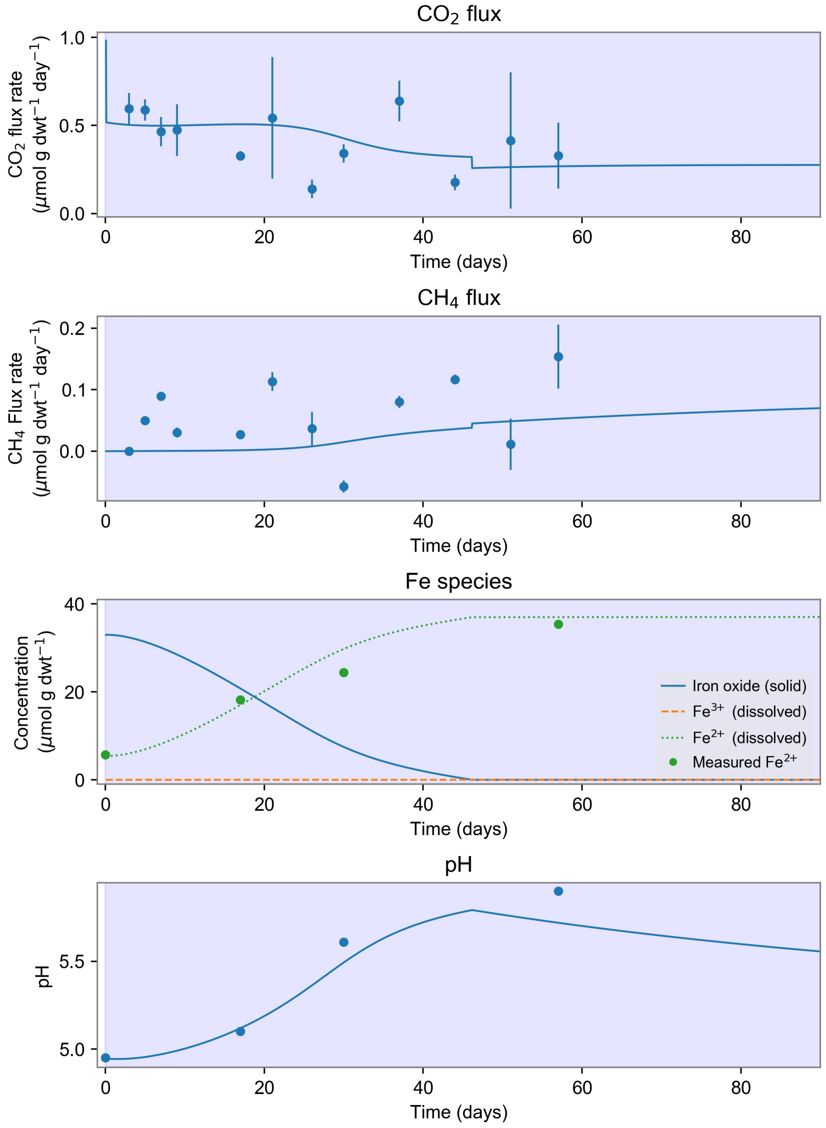
Roy Chowdhury et al, GCB, 2015

Chemically explicit model with Fe(III) reduction

Implemented in PFLOTRAN



Model compared with laboratory permafrost soil incubations (Measurements: Zheng et al., 2019)



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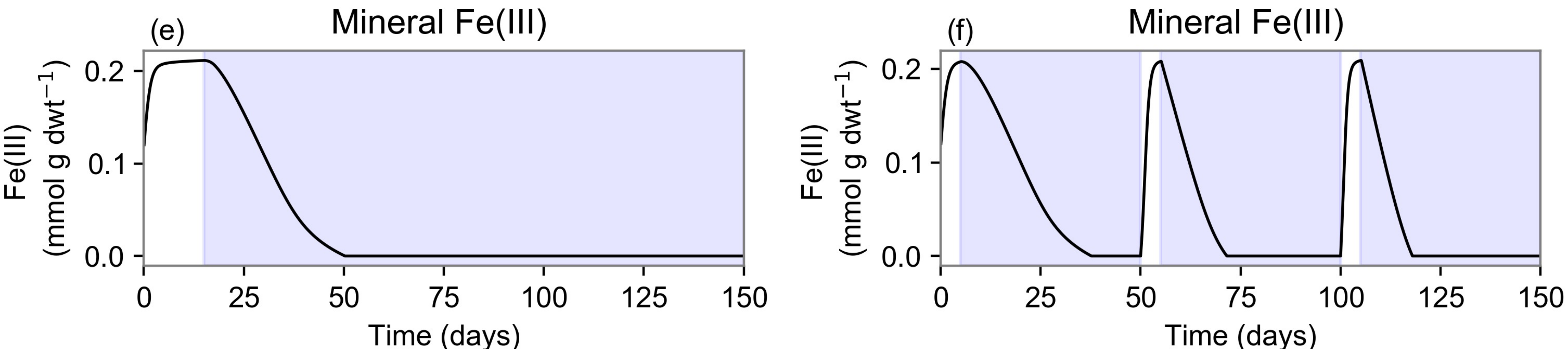
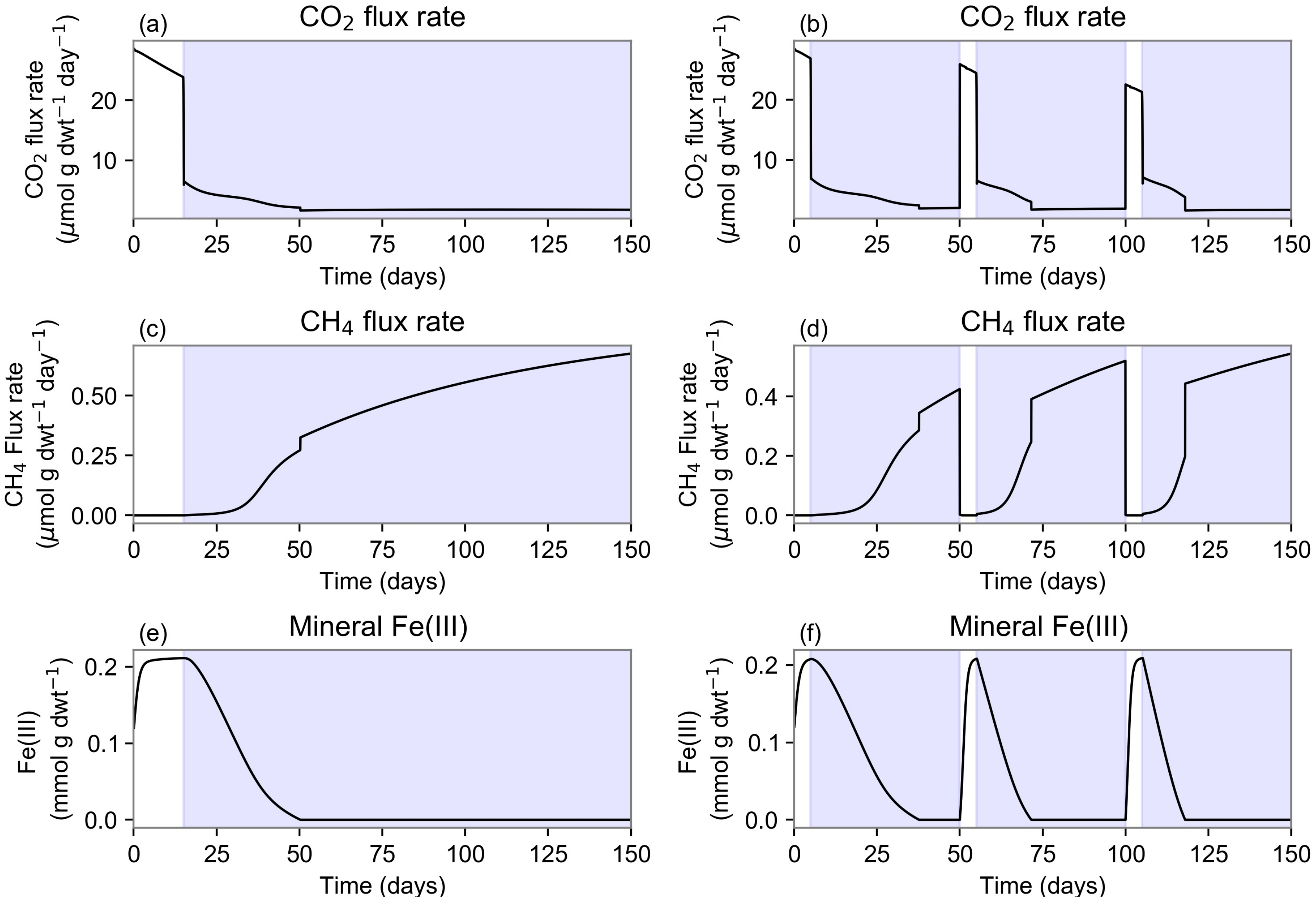
What happens under different inundation patterns?



- Oxic period renews Fe(III) availability by oxidizing Fe(II)
- Fe(III) mineral is depleted gradually during anoxic period by Fe reduction
- With repeated, shorter oxic periods, more time is spent in Fe reduction phase

Effects on gas fluxes



- CO_2 efflux is supported by Fe(III) reduction at the beginning of each anoxic period
- CH_4 efflux is suppressed until Fe(III) is depleted

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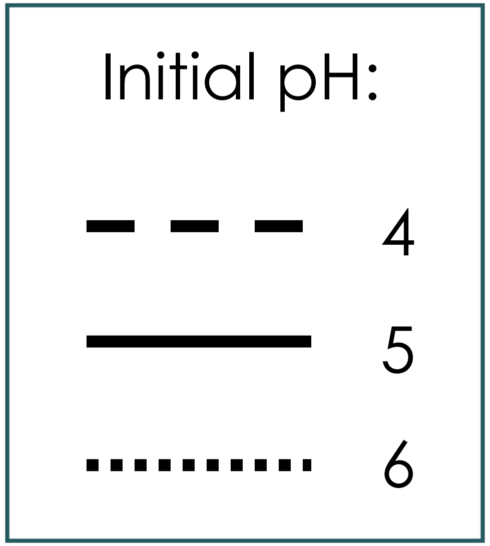
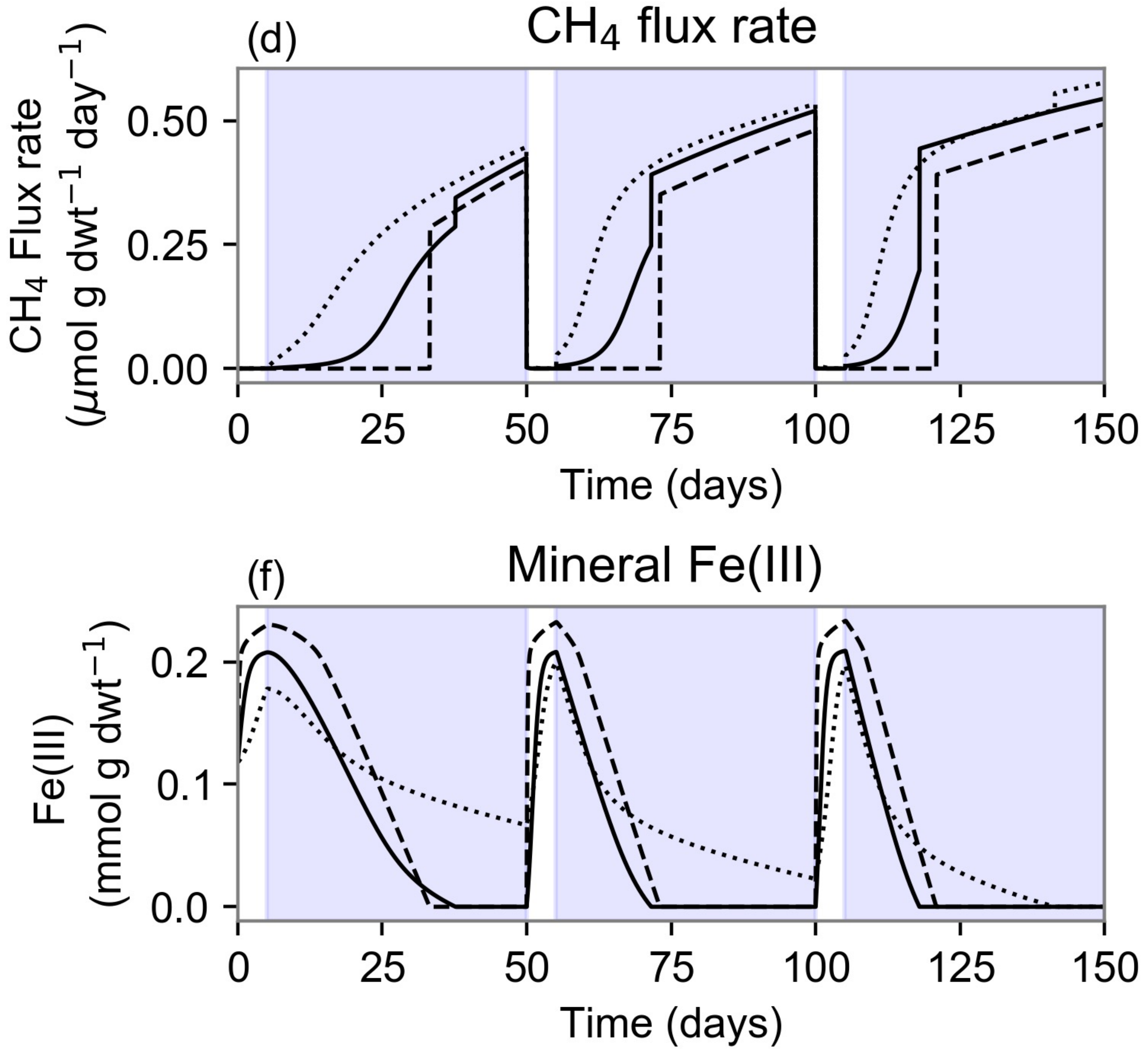
Effect of soil pH
pH is not included in ecosystem models

- Fe(III) reduction is sensitive to pH, which affects Fe oxide solubility
- Higher pH lowers Fe(III) reduction rates and increases CH_4 efflux





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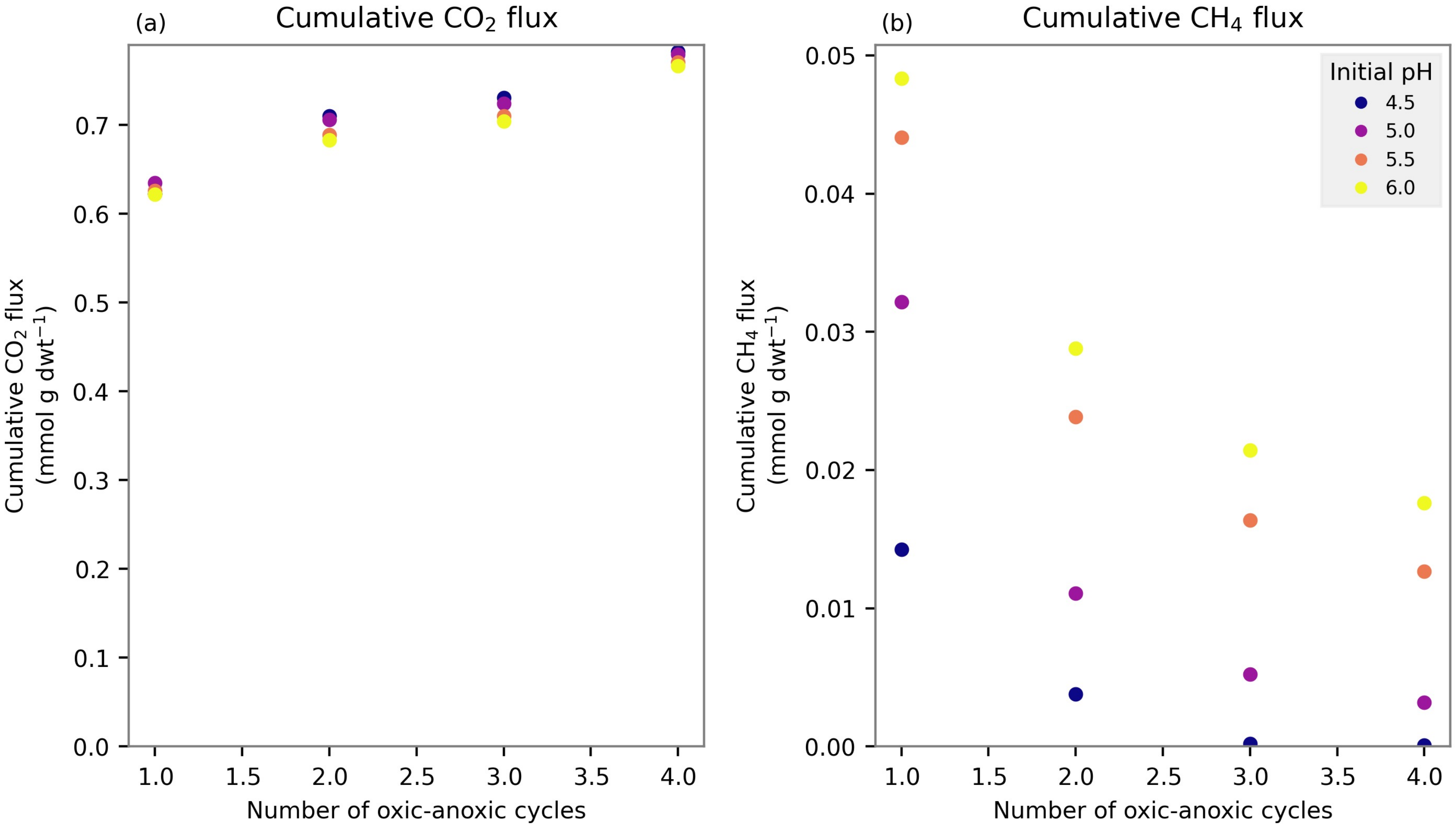
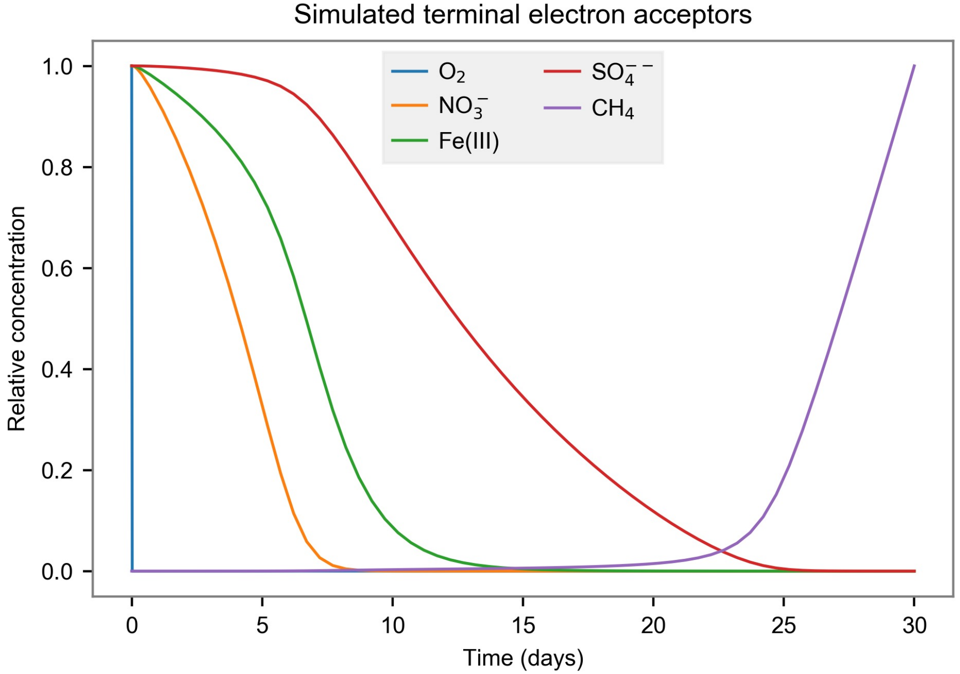
Comparing across a range of inundation patterns and pH

- CH_4 flux:
  - Decreases strongly with more inundation cycles
  - Decreases strongly with lower initial pH
- CO_2 flux:
  - Increases with more inundation cycles
  - Small relative increase but magnitude large relative to CH_4 flux
  - Weak increase with lower initial pH

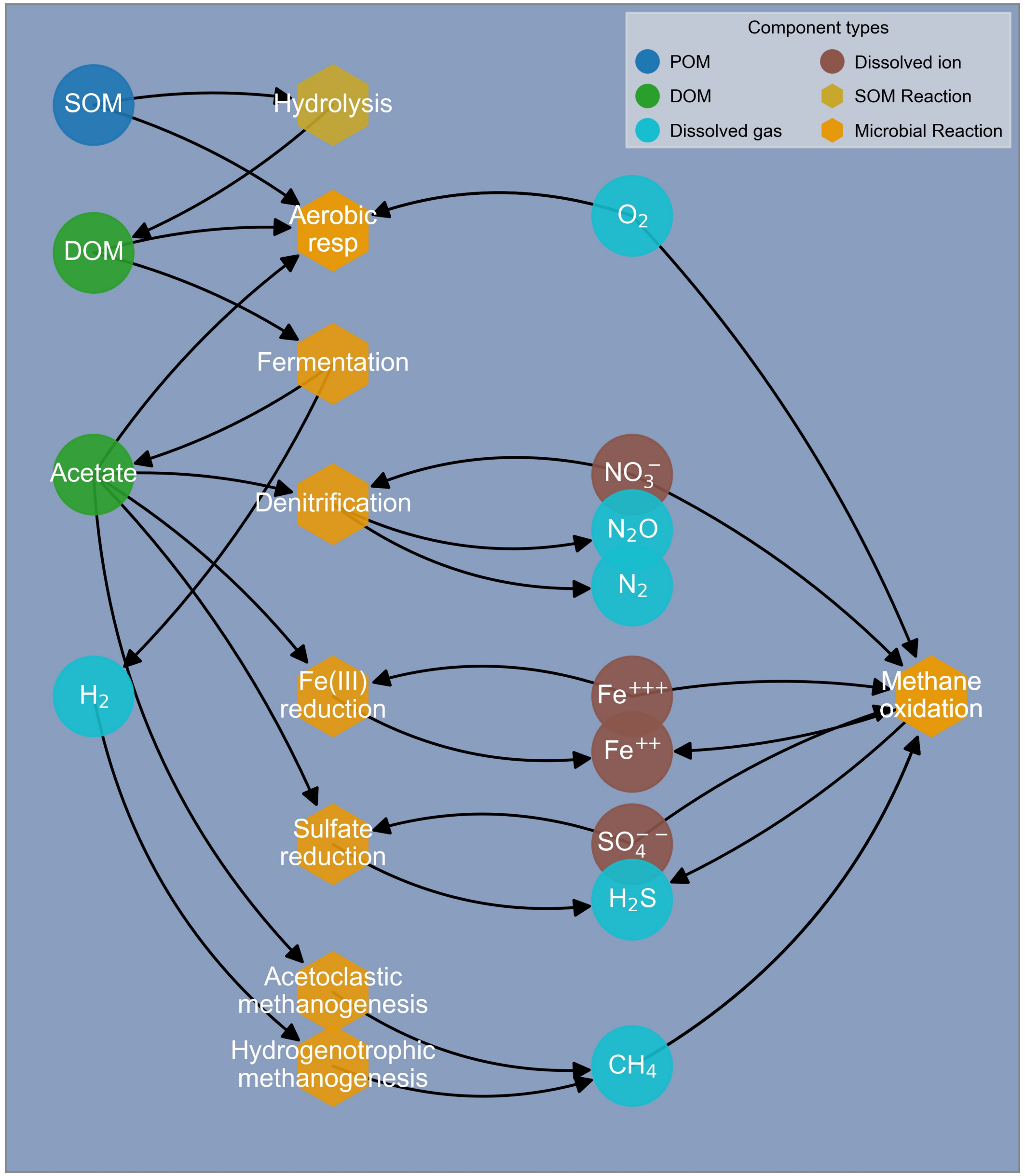


Modeling redox interactions in tidal wetlands

- SO_4^{2-} reduction important in saltwater-influenced environments
- Denitrification important at interface of rivers with high N loading



Preliminary simulation of depletion of terminal electron acceptors over time



Simulated reaction network including redox reactions (some species including CO_2 and H^+ not shown)

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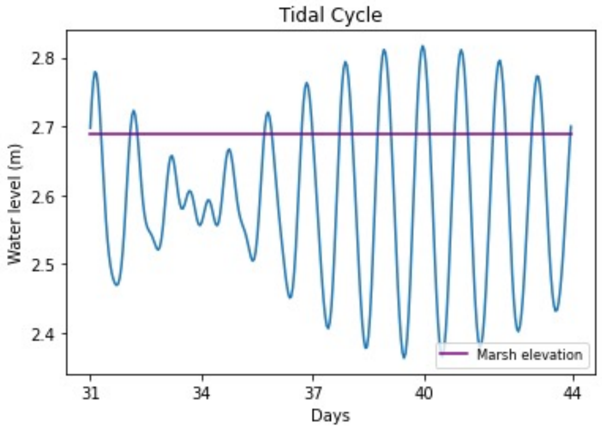
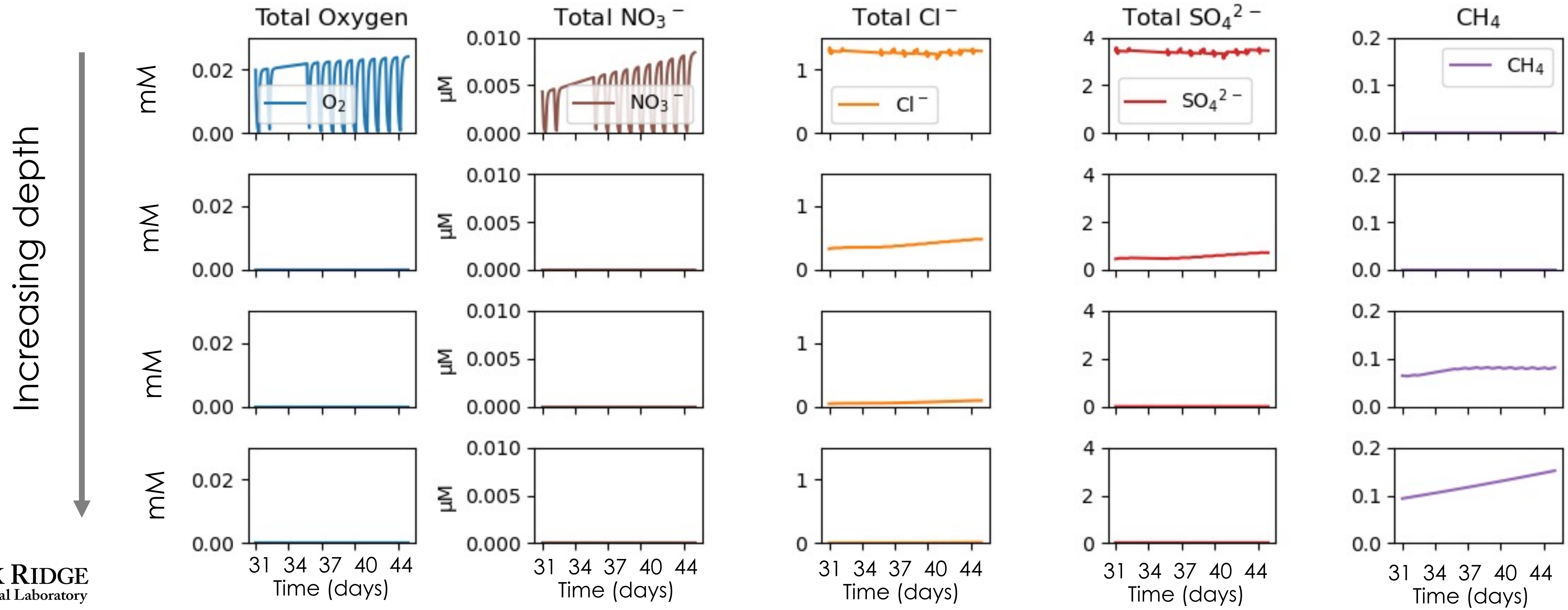
Preliminary simulations of tidal fluctuations (Jiaze Wang)

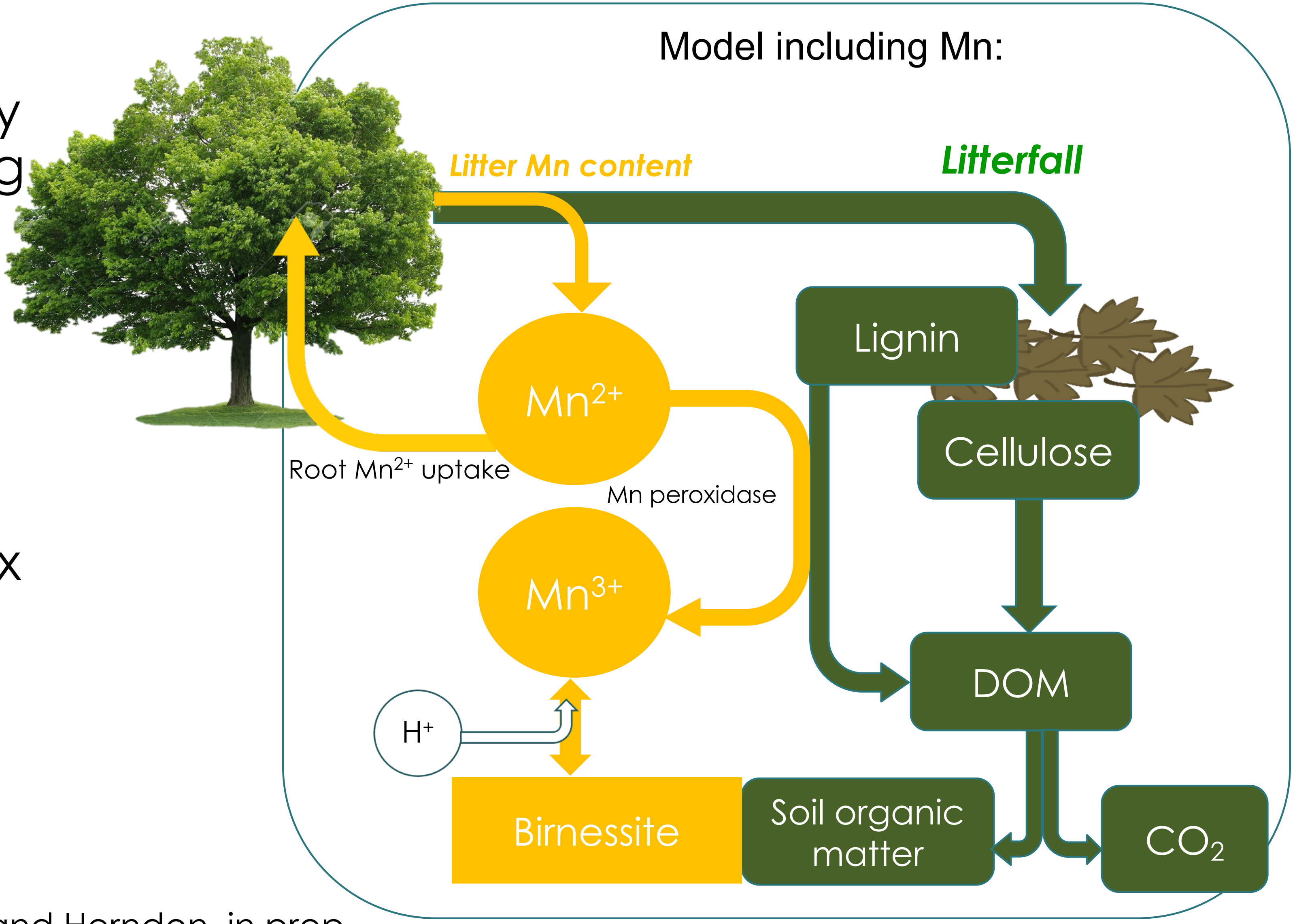


- Oxygen in top layer fluctuates with tidal flooding cycles
- Nitrate produced from decomposition under oxic conditions
- CH_4 only produced in layers where SO_4^{2-} is depleted



Geochemical interactions with upland carbon cycling

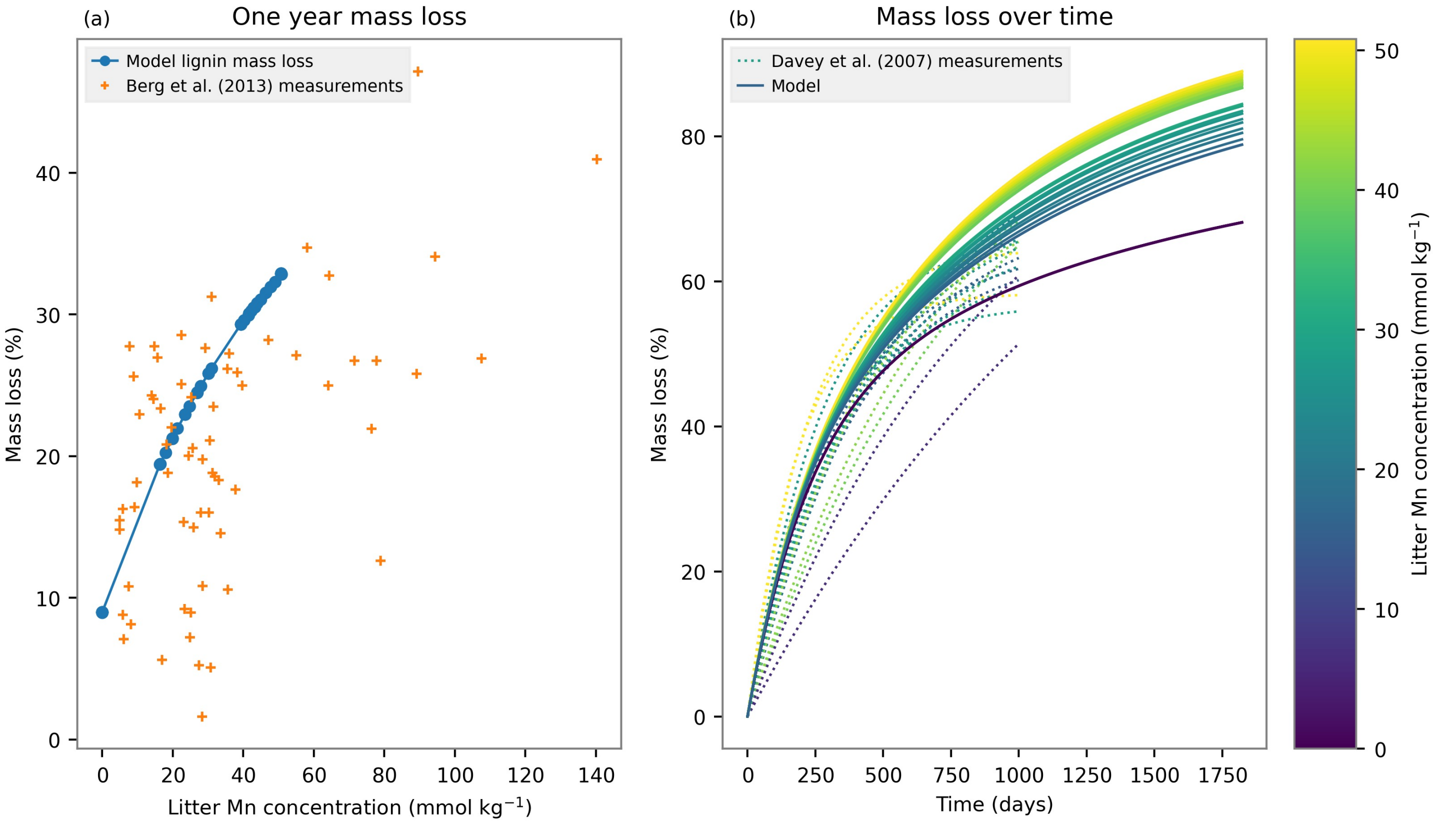
- Manganese (Mn) is a key factor in lignin-degrading enzymes
- Plants take up Mn from deeper soil layers and deposit in leaf litter
- Mn bioavailability is sensitive to pH and redox state, which control Mn-bearing mineral reductive dissolution

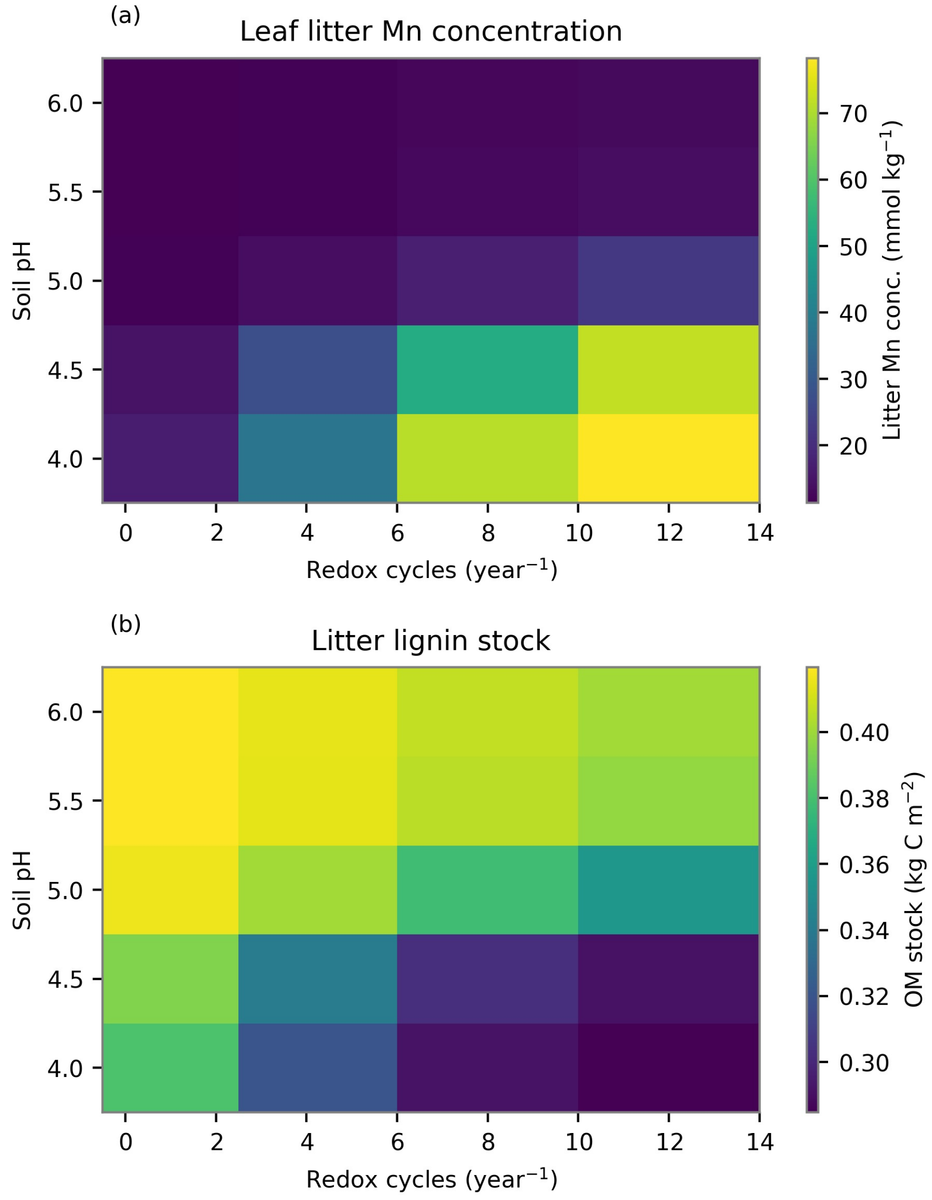


Sulman and Herndon, in prep.

Geochemical interactions with upland carbon cycling

- Manganese plays an important role in lignin decomposition
- Mn bioavailability is sensitive to soil pH and redox cycling
- Project led by Beth Herndon





Sulman and Herndon, in prep.

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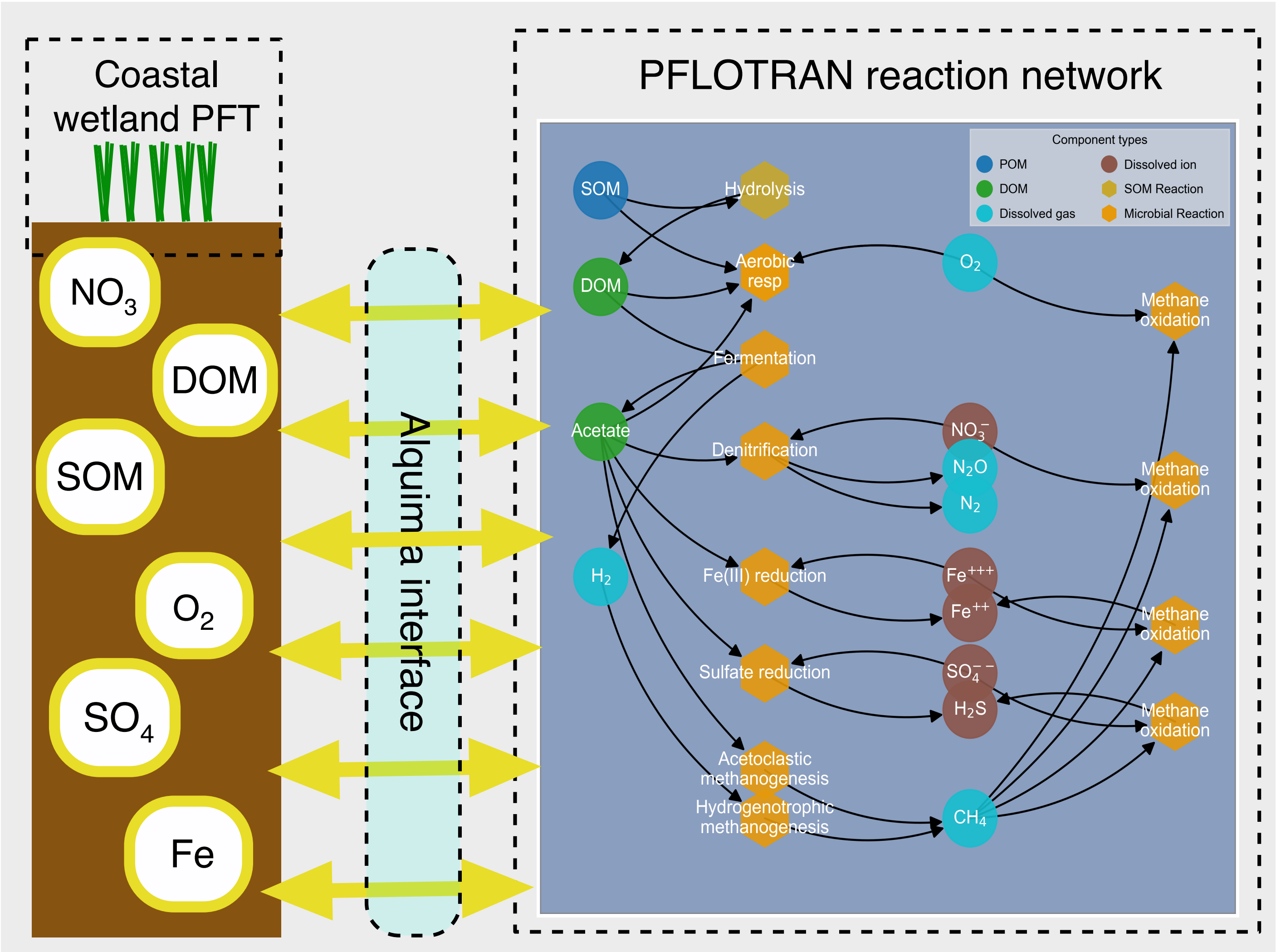
Integrating redox reactions into the E3SM Land Model

- PFLOTRAN will be coupled to ELM using the Alquimia interface via ELM's External Model Interface (EMI)
- This builds on existing interface work and allows flexibility in reactions and geochemical simulators
  - Other chem codes like Crunch, PHREEQC, etc. could be used instead of PFLOTRAN in the future
  - Reaction networks and chemical components can be modified without changing ELM code



ELM column

PFLOTRAN reactions (repeated in each layer)

Conclusions:

- CO_2 and methane emissions depend on **more than just whether soil is inundated**
- **Alternate terminal electron acceptors** such as iron can support microbial respiration and suppress methanogenesis
- Simulating **redox chemistry and pH fluctuations** can improve model representation of CO_2 and methane fluxes in wetland ecosystems
- Simulating geochemical interactions can also improve model representation of key aerobic processes such as lignin decomposition
- Models that do not include these processes may **overestimate methane emissions** and underestimate organic matter decomposition in iron-rich soils with dynamic water tables