Implementing ECA Kinetics and Advection Improves Nitrogen loss Predictions

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- Problem Identified
  - Houlton et al. 2015; *Nature CC*

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Representation of nitrogen in climate change forecasts

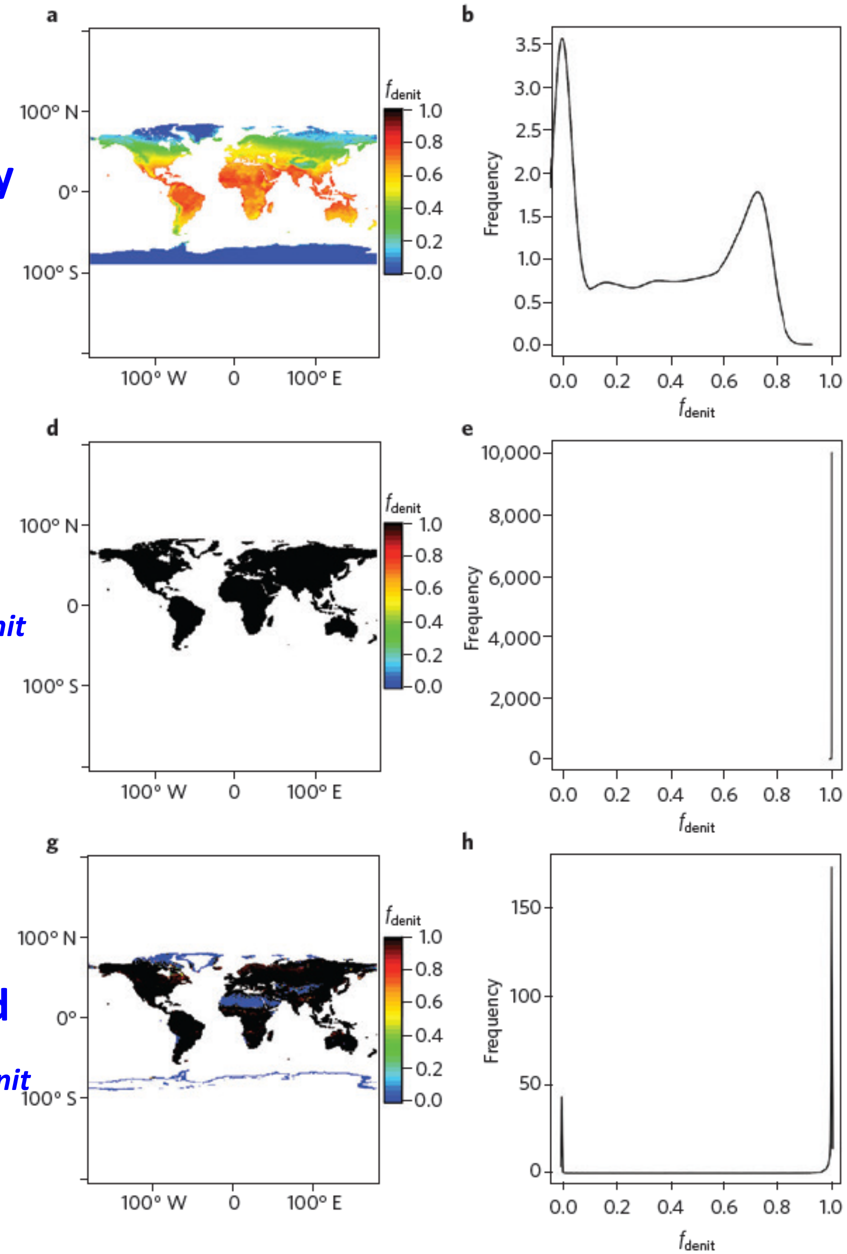
Benjamin Z. Houlton, Alison R. Marklein and Edith Bai

- Used ^{15}N observations to infer ratio of aqueous and gaseous N losses globally
- "This binary pattern and lack of spatial variation is in opposition to thousands of empirical observations of soil $\delta^{15}N$ within the terrestrial biosphere"

Observationally Inferred f_{denit}

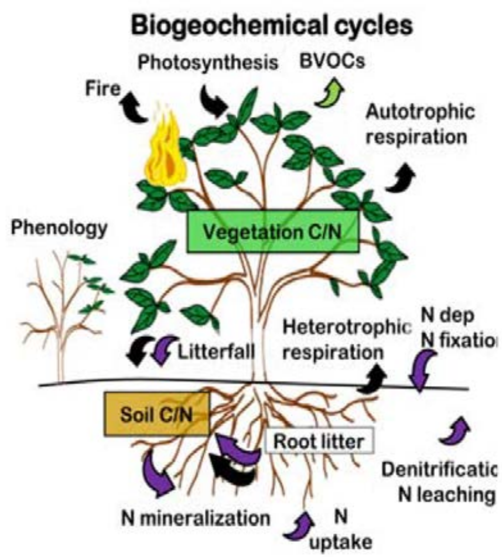
CLM4CN f_{denit}

ALM1 and CLM4.5 f_{denit}



Reasons for the Problematic N Loss Model Predictions

- CLM4.5 and ALM1 assume a sequential competitive structure:
  1. Plants and free-living decomposing and nitrifying microbes use available soil ammonium (scaled by relative demand)
  2. Denitrifiers use available nitrate
  3. Hydrological processes (i.e., leaching and runoff) use the (often depleted) residual nitrate
- The nitrification and denitrification rate calculations
- Poorly represents advective tracer fluxes
- This modeling approach:
  - Is conceptually and numerically incorrect
  - Leads to hydrological nitrogen losses that are unrealistically small compared to denitrification losses



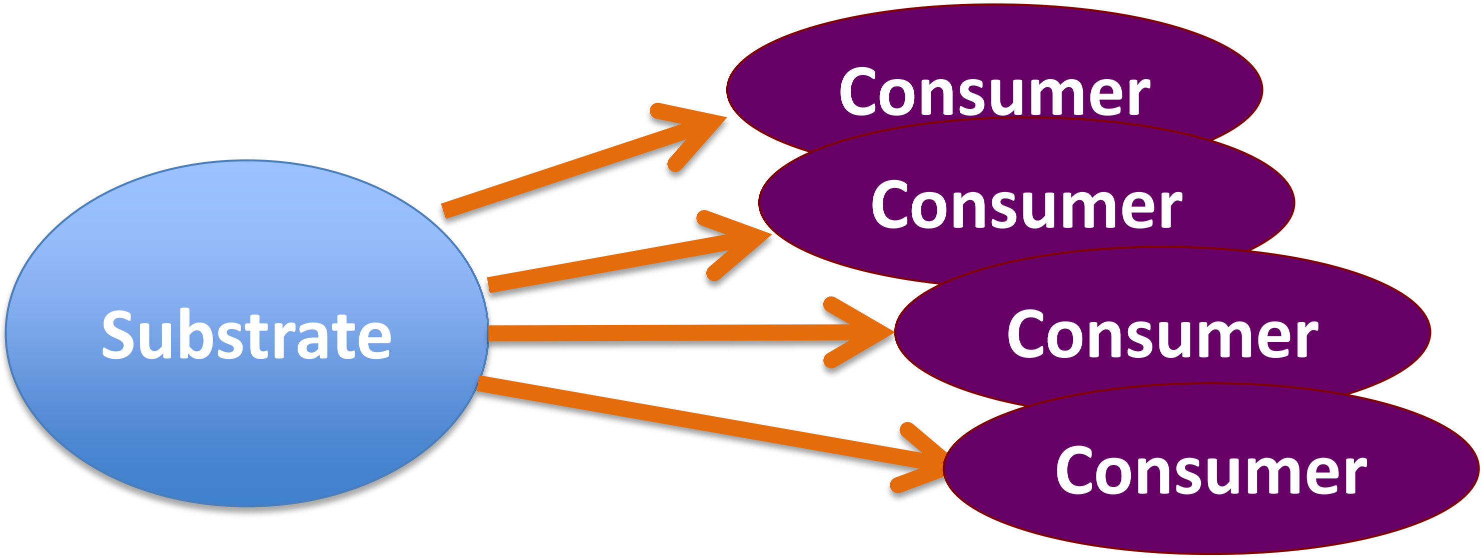
Lawrence et al. 2011

Proposed Solution

1. Use ECA kinetics (Tang and Riley 2013, 2015; Zhu et al. 2015) to represent the competitive environment for N species
2. Improve advective transport calculations
   a) Following CLM4-BeTR (Tang et al., 2013; *GMD*)

Competition for N

- Currently applied approach: linear downscaling based on individual demands (Thornton et al. 2007)
  - Expedient, but not supported by evidence (e.g., Thomas et al. 2012; Ghimire et al. 2015)
- ECA (Equilibrium Chemistry Approach)
  - New competition theory expanding on Michaelis-Menten kinetics



ECA Kinetics

Updates Michaelis Menten kinetics for multiple substrates and consumers (Tang and Riley 2013):

$$\tilde{C}_{ij} = \frac{S_{i,\mathrm{T}} E_{j,\mathrm{T}}}{K_{\mathrm{S},ij}\left(1 + \sum_{k=1}^{k=I} \frac{S_{k,\mathrm{T}}}{\tilde{K}_{\mathrm{S},kj}} + \sum_{k=1}^{k=J} \frac{E_{k,\mathrm{T}}}{\tilde{K}_{\mathrm{S},ik}}\right)}$$

Method facilitates inclusion of an arbitrary number of inhibitory mechanisms and traits

For example, for nitrifiers accessing NH_4 (Zhu et al. 2015):

$$\mathrm{ECA}_{\mathrm{NH}_4}^{\mathrm{nit}} = \frac{[\mathrm{NH}_4^+]}{\mathrm{KM}_{\mathrm{NH}_4}^{\mathrm{nit}}\left(1 + \frac{[\mathrm{NH}_4^+]}{\mathrm{KM}_{\mathrm{NH}_4}^{\mathrm{nit}}} + \frac{[E_{\mathrm{NH}_4}^{\mathrm{plant}}]}{\mathrm{KM}_{\mathrm{NH}_4}^{\mathrm{plant}}} + \frac{[E_{\mathrm{NH}_4}^{\mathrm{mic}}]}{\mathrm{KM}_{\mathrm{NH}_4}^{\mathrm{mic}}} + \frac{[E_{\mathrm{NH}_4}^{\mathrm{nit}}]}{\mathrm{KM}_{\mathrm{NH}_4}^{\mathrm{nit}}}\right)}$$

Subsurface BGC Should be Solved as a Reactive Transport Problem

$$\frac{\partial C_i}{\partial t} = -\frac{\partial}{\partial z}\left[D\frac{\partial C_i}{\partial z} + vC_i\right] + \sum_m \frac{\partial C_i}{\partial t}\bigg|_m$$

Time rate of change of species concentration

Multi-Phase Transport

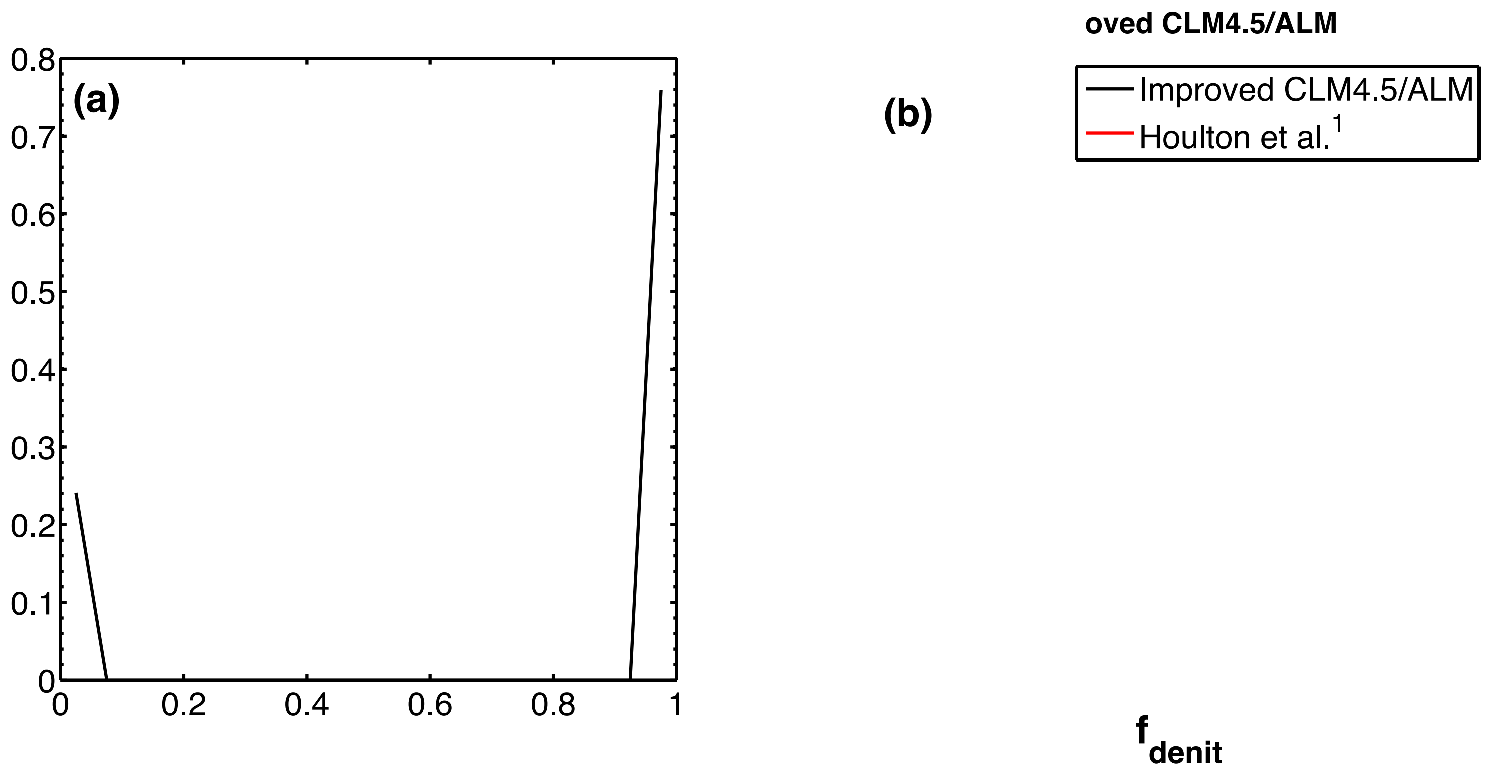
Transformations, Sources, Sinks

Tang et al. 2013

- Concurrent transport and reaction calculations are often handled with an operator splitting approach
- We applied the ECA approach for this calculation here

Results

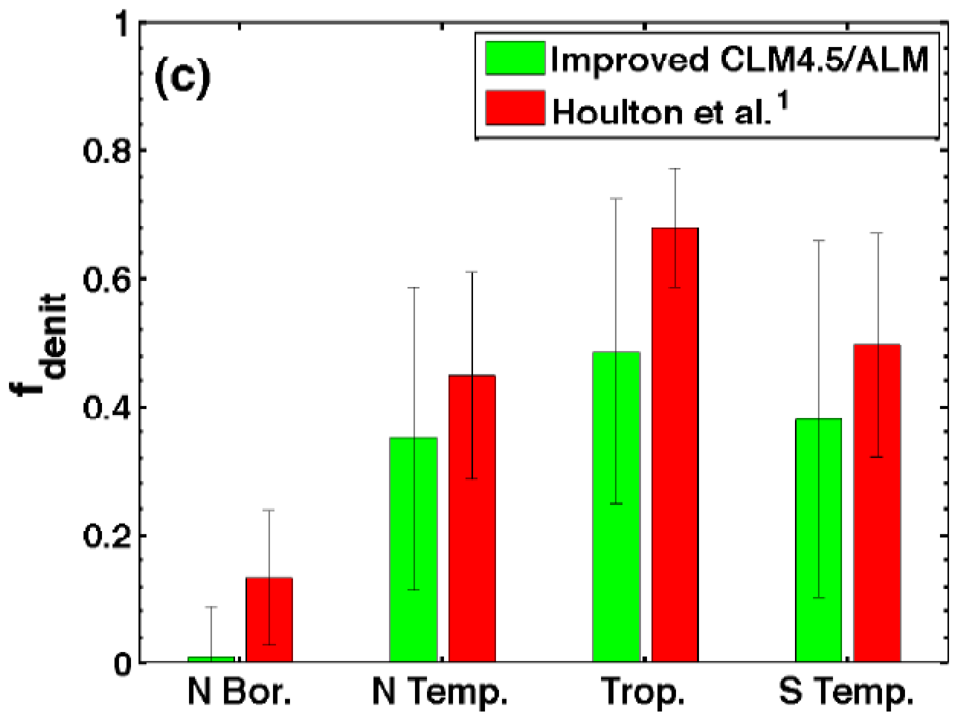
- Improved CLM4.5 and ALM1 have more reasonable distributions of f_{denit}



Zhu and Riley, accepted *Nature CC*

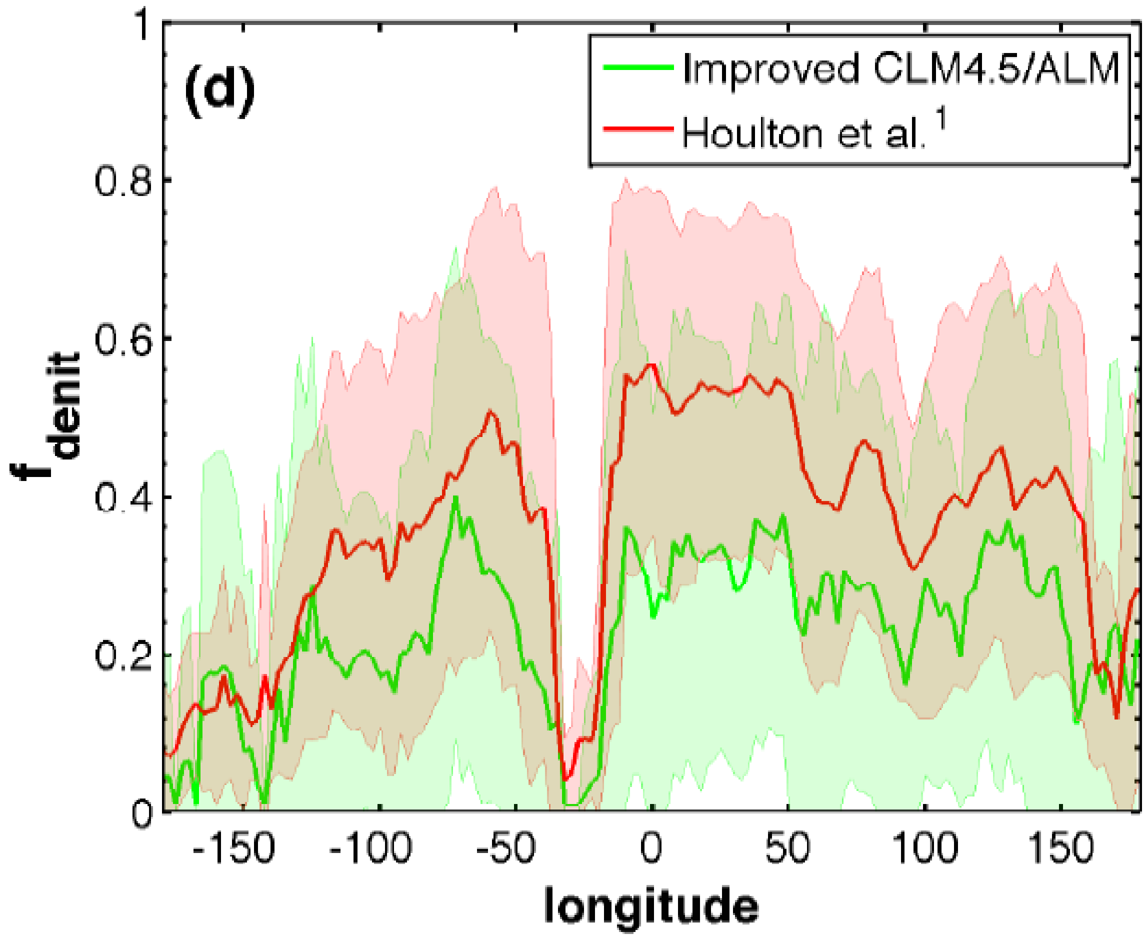
Results

- Regionally
  - Higher spatial variability in CLM4.5 and ALM1 than inferred from ^{15}N observations
  - Much lower proportion of gaseous losses in high latitudes

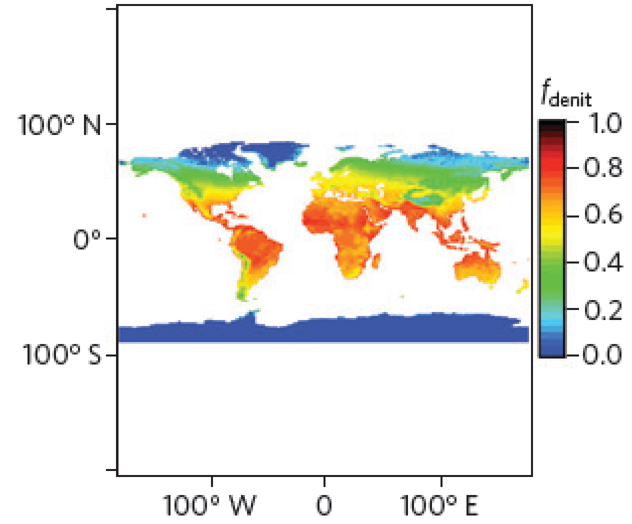


Results

- Zonally, models under-predict observationally-inferred f_{denit}, but have similar patterns



Results



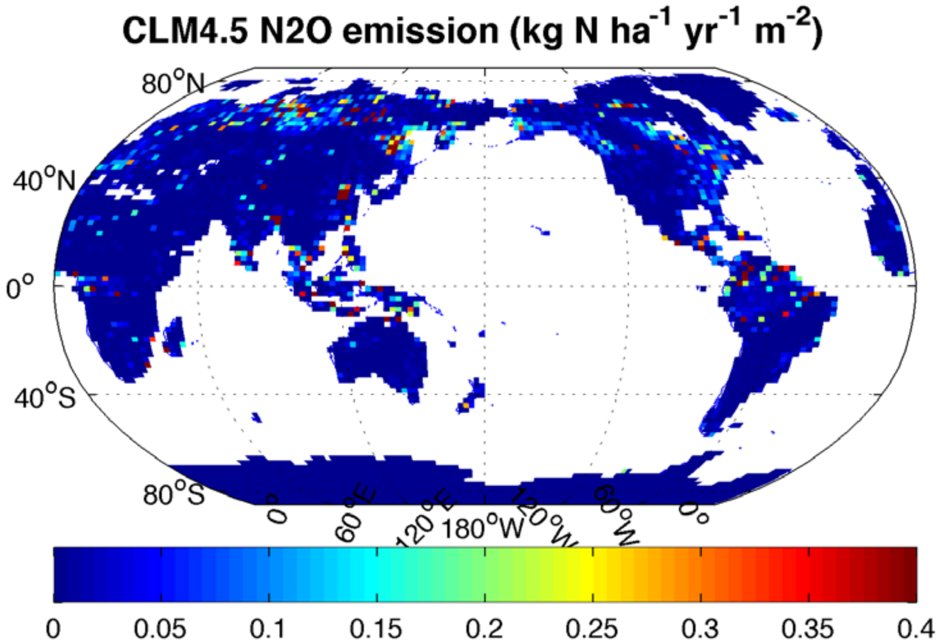
- The ^{15}N-inferred f_{denit} values are
  - Extrapolated from temperature and precipitation
- In contrast, modeled aqueous and gaseous losses are controlled by a combination of
  - Hydrological dynamics
  - Soil O_2 content
  - Temperature
  - Nutrient competition

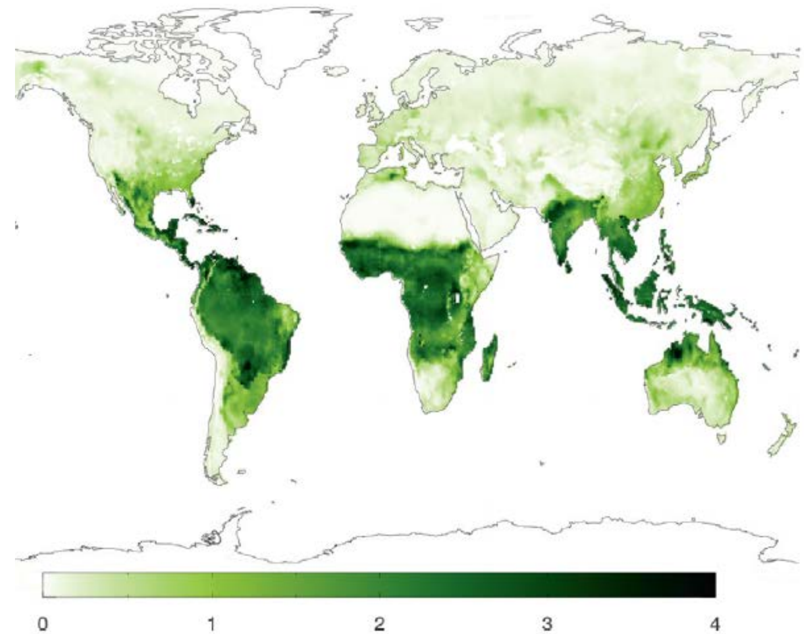
- The ^{15}N-inferred f_{denit} values are sensitive to isotope effects during denitrification
- The modeled and ^{15}N-inferred ratios of N losses can compare well, even if the underlying fluxes are poorly estimated
- CLM4.5 and ALM1 predicted soil N_2O emissions currently compare poorly to 66 global natural ecosystem site observations (Xu-Ri et al. 2012)
  - Model structural changes required to remedy this problem
- Test improved model against watershed-scale leaching measurements
    - IFEF (Indicators of Forest Ecosystem Functioning) database has 209 catchment-scale measurements across the US and Europe (Thomas 2013 GCB, MacDonald 2002 GCB)
  - Add these benchmarks to ILAMB
- Fully integrate advective mechanisms with BeTR (Tang et al. 2013)

Summary

- Nutrient controls on C-Climate interactions require accurate representation of losses, which requires
  - Reasonable representation of nutrient competition between biotic and abiotic consumers
  - Reasonable representation of aqueous fluxes
  - Reasonable numerical solution of the coupled problem
- If anyone knows of any important flaws in CLM for which some observational evidence exists, I recommend an immediate *Nature Climate Change* submission ☺

Extras





(1) CLM4.5 soil N2O loss (nitrification+denitrification) is an order of magnitude smaller than that from DyN-LPJ.
(2) CLM4.5 soil N2O loss has no clear global pattern. (e.g., high N2O emission at tropics)