Ambiguous numerical interpretation of nitrogen limitation results in divergent predictions of carbon-climate feedbacks

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Ecological significance of nitrogen for biogeochemistry

Biogeochemistry **13**: 87–115, 1991

Nitrogen limitation on land and in the sea: How can it occur?

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Cited by 2339 times, google scholar, accessed Mar 9, 2016.
A long (29-page) paper without beautiful figures!

Nitrogen is limited!

By Andrew J. Small

Resolving N limitation is important for modeling land carbon dynamics

- CO_2 and nitrogen fertilization effect
- Land carbon response to warming
- Land-atmosphere biogeochemical and bio-geophysical feedbacks
- As an example for resolving other nutrient/substrate limitations

Mathematical conceptualization of nitrogen limitation

$$S(t+\Delta t) = S(t) + \left(S_{input} - S_{uptake}\right)\Delta t$$

Limitation occurs, when

$$S(t+\Delta t) < 0 \quad \text{if nothing is done to the fluxes}$$

Models disagree in implementing nitrogen limitation

Double limitation in CABEL, ALM-CNP
Limitation 1: Law of the minimum (based on N, and P) in individual uptake
Limitation 2: Reset flux to avoid the negative N values.

ALM-ECA only involve Limitation 2

Three different approaches to apply limitation 2

ALM

$$\bar{S}_{uptake} = \min\left\{\frac{S(t)/\Delta t}{S_{uptake}}, 1\right\} S_{uptake}$$

Derivative clipping

$$\bar{S}_{uptake} = \min\left\{\frac{S(t)/\Delta t}{S_{uptake} - S_{input}}, 1\right\} S_{uptake}$$

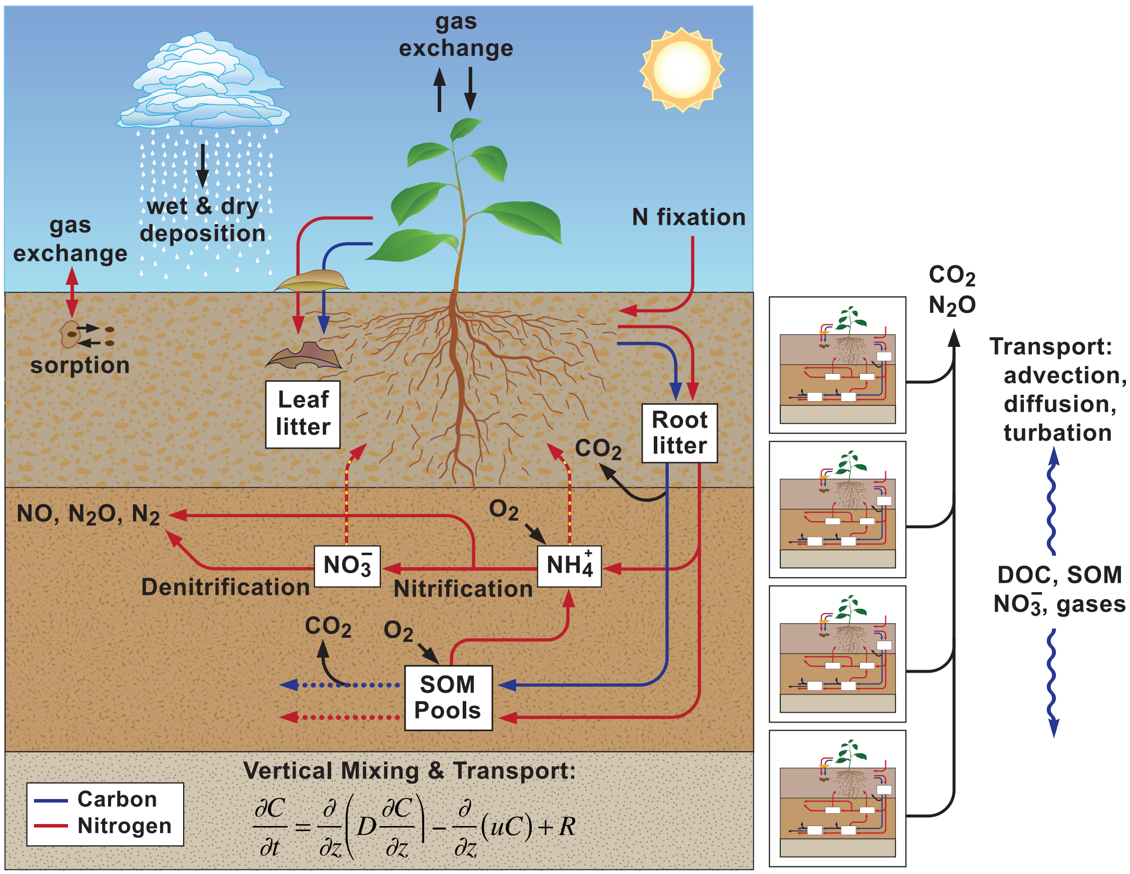
Law of minimum limiter

$$\bar{S}_{uptake} = \min\left\{\frac{S_{input} + S(t)/\Delta t}{S_{uptake}}, 1\right\} S_{uptake}$$

Limitation strength decreases

Experiments with ALM-BeTR

Reactive transport model for flexible BGC



$$\frac{\partial \mathbf{s}}{\partial t} = \mathbf{T}(\mathbf{s};\mathbf{q}) + \mathbf{r}(\mathbf{s};\mathbf{q})$$

Different BGC with identical biophysics

Experiment setup

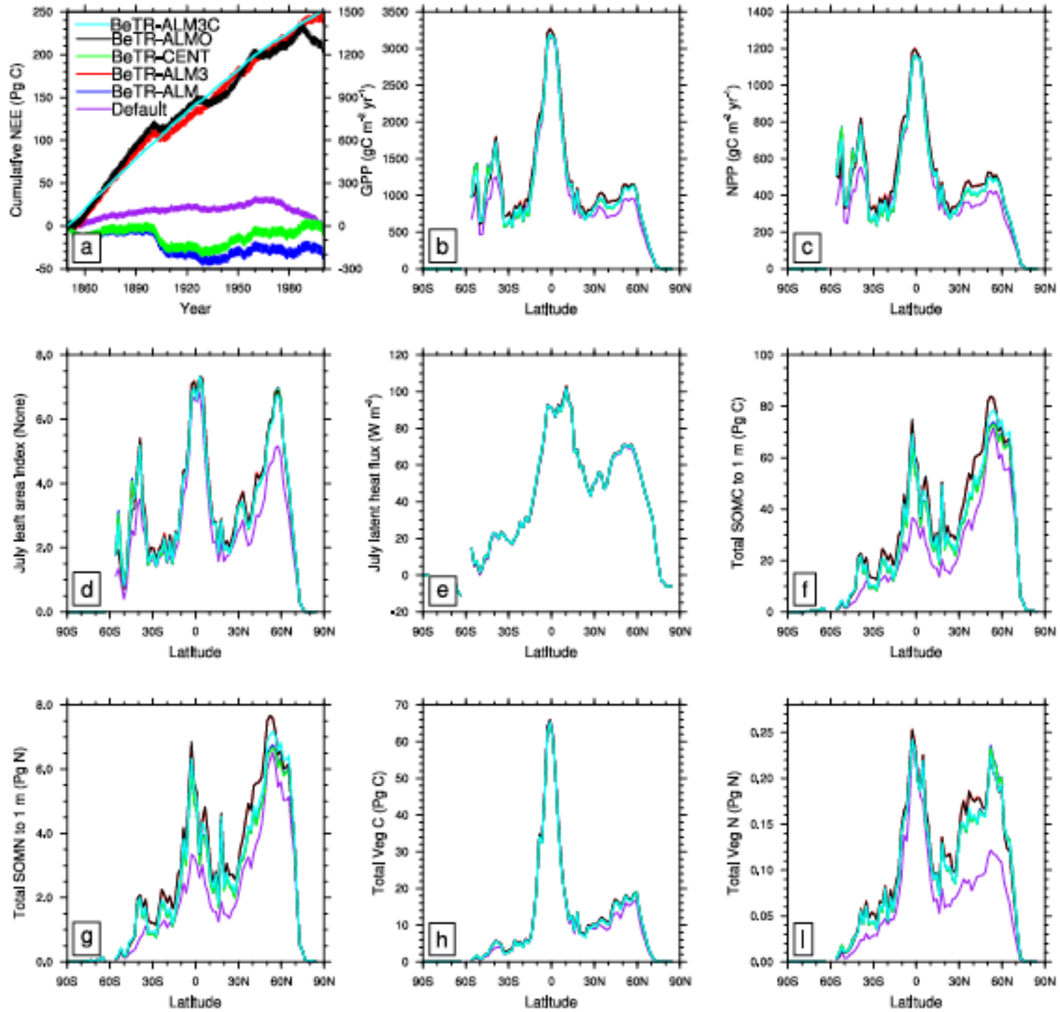
Simulation ID	Model configuration
BeTR-ALM	Mineral N from gross mineralization is not available for N-uptake at current time step. **Red**
BeTR-CENT	Mineral N demand is calculated as the residual between total mineral N demand and gross mineralization. **Blue**
BeTR-ALM3	Mineral N from gross mineralization and soil mineral N are competed equally by plants and microbes. **Green**
BeTR-ALM3C	Like BeTR-ALM3, but using initial condition from BeTR-CENT.
BeTR-ALM3O	Like BeTR-ALM3, but O_2 limitation comes after N limitation. However, a second N limitation is required to avoid model crash.
Default	BGC formulation based CLM4.5.

$$\bar{S}_{uptake} = \min\left\{\frac{S(t)/\Delta t}{S_{uptake}}, 1\right\} S_{uptake}$$

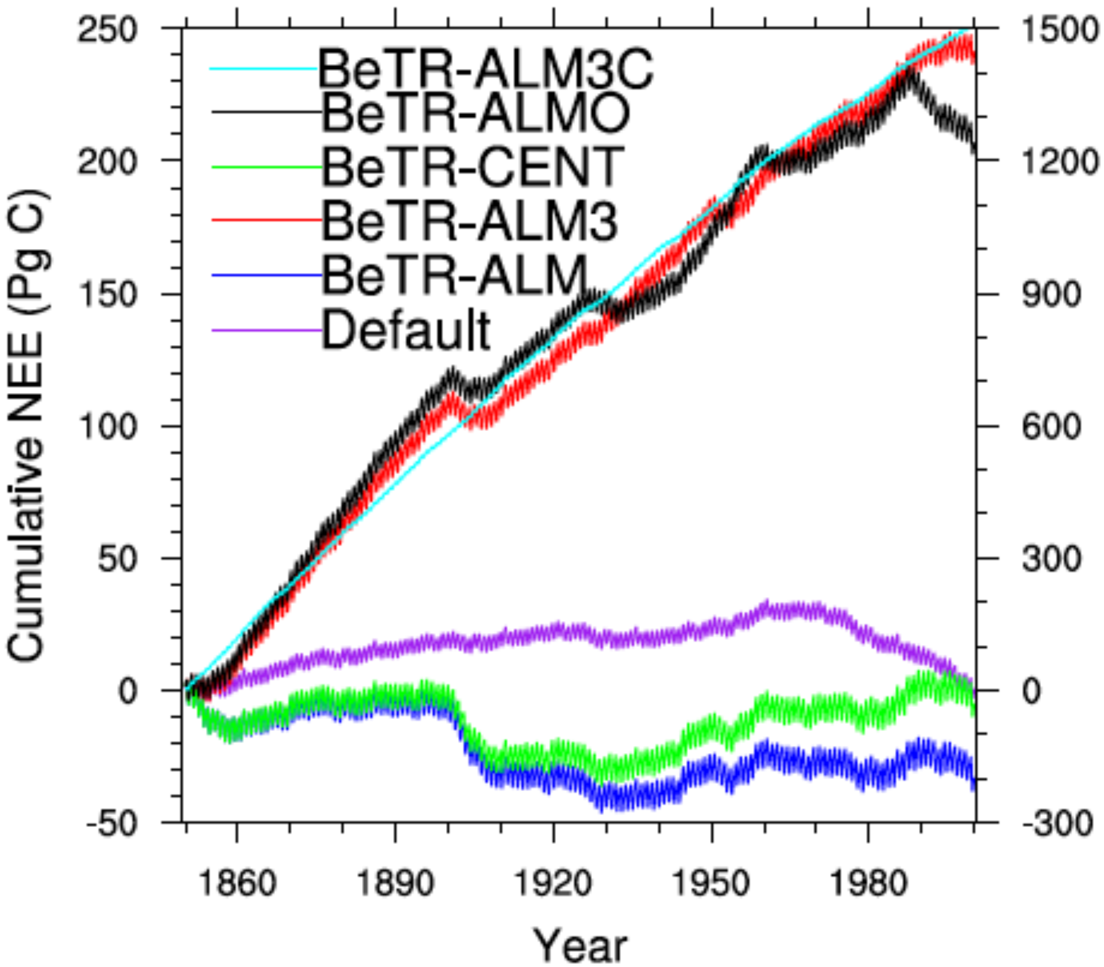
$$\bar{S}_{uptake} = \min\left\{\frac{S(t)/\Delta t}{S_{uptake} - S_{input}}, 1\right\} S_{uptake}$$

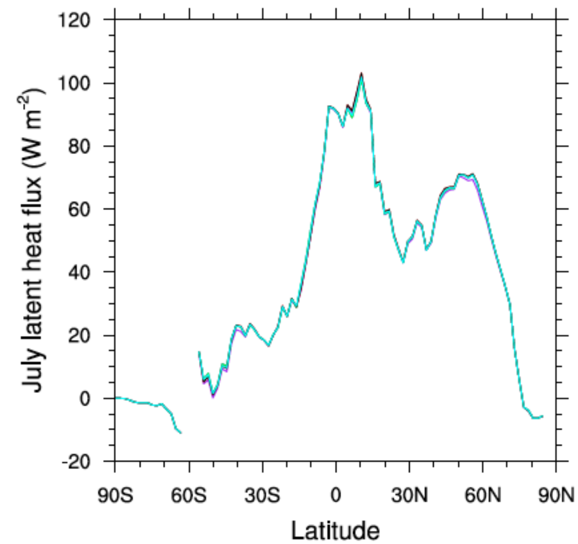
$$\bar{S}_{uptake} = \min\left\{\frac{S_{input} + S(t)/\Delta t}{S_{uptake}}, 1\right\} S_{uptake}$$

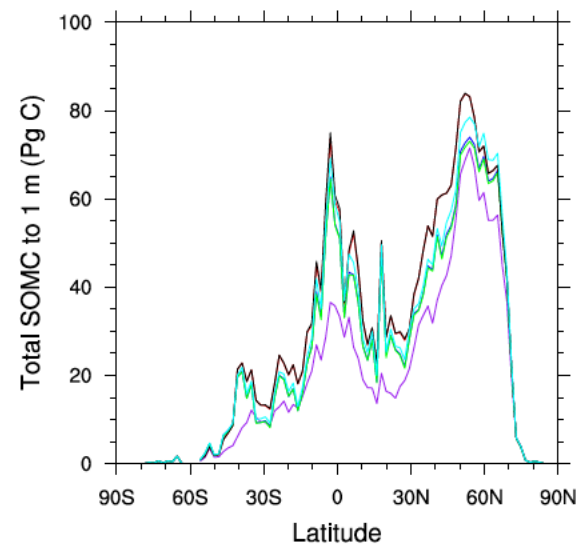
Model based ALM-BeTR benchmark: historical simulations



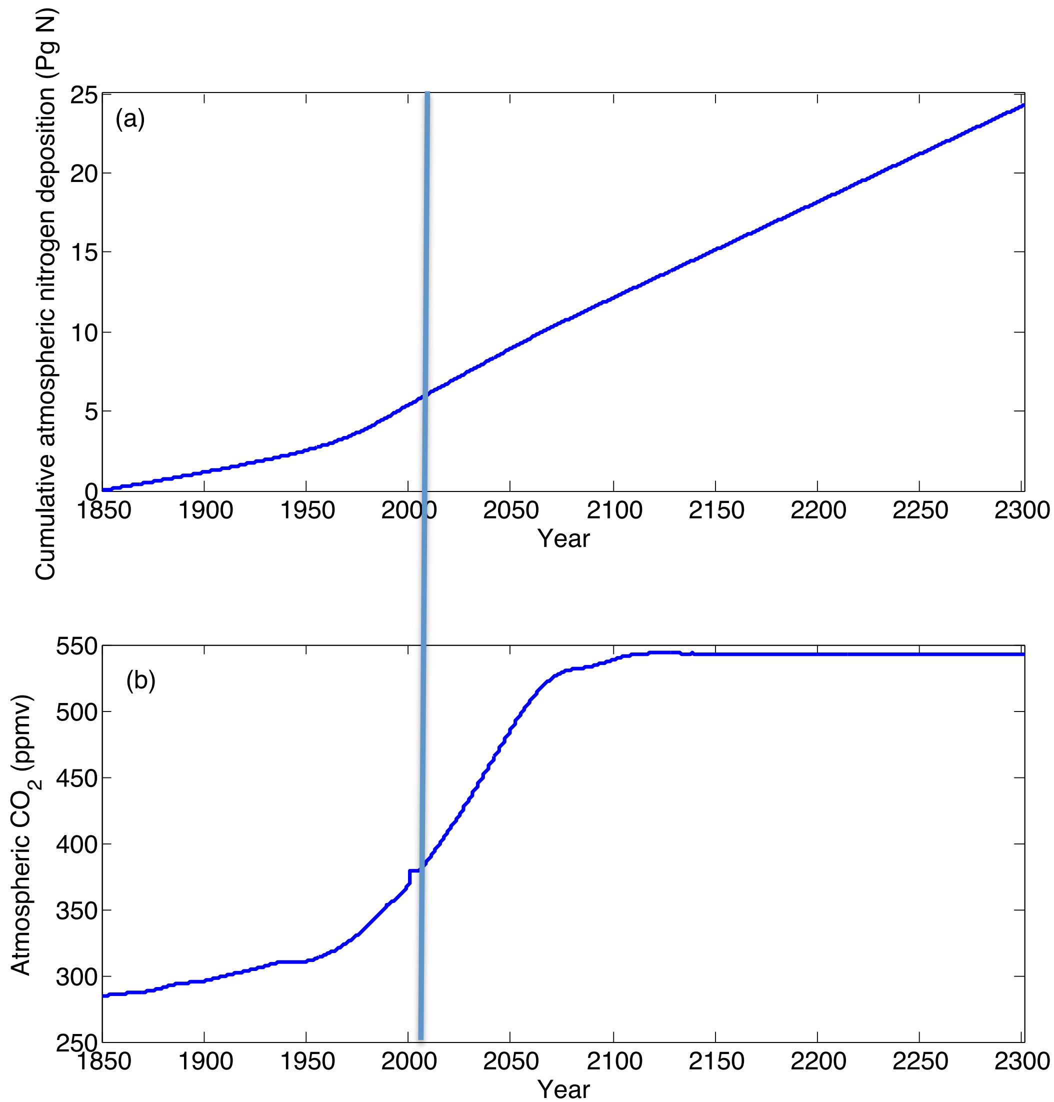
Diverging trajectories, yet similar endings





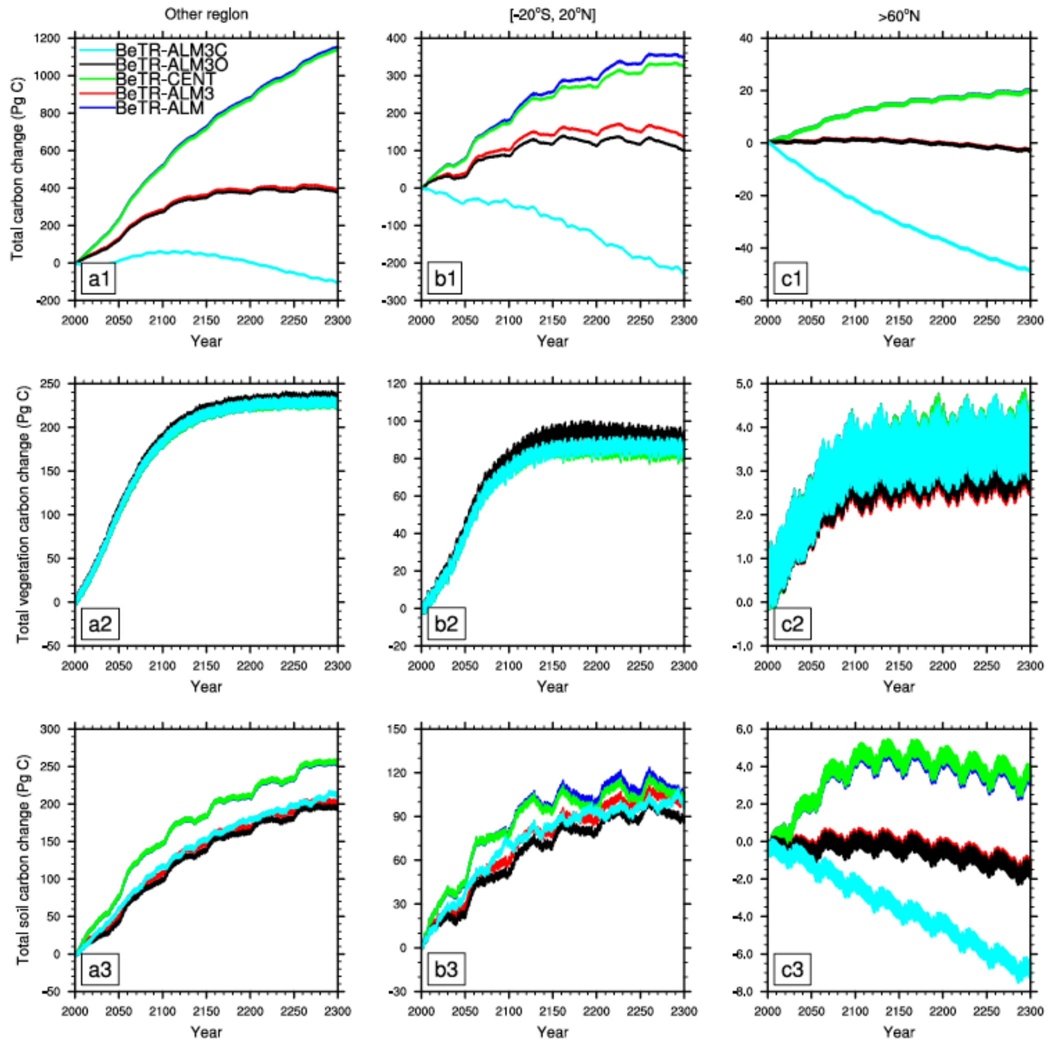


RCP4.5 divergence analyses

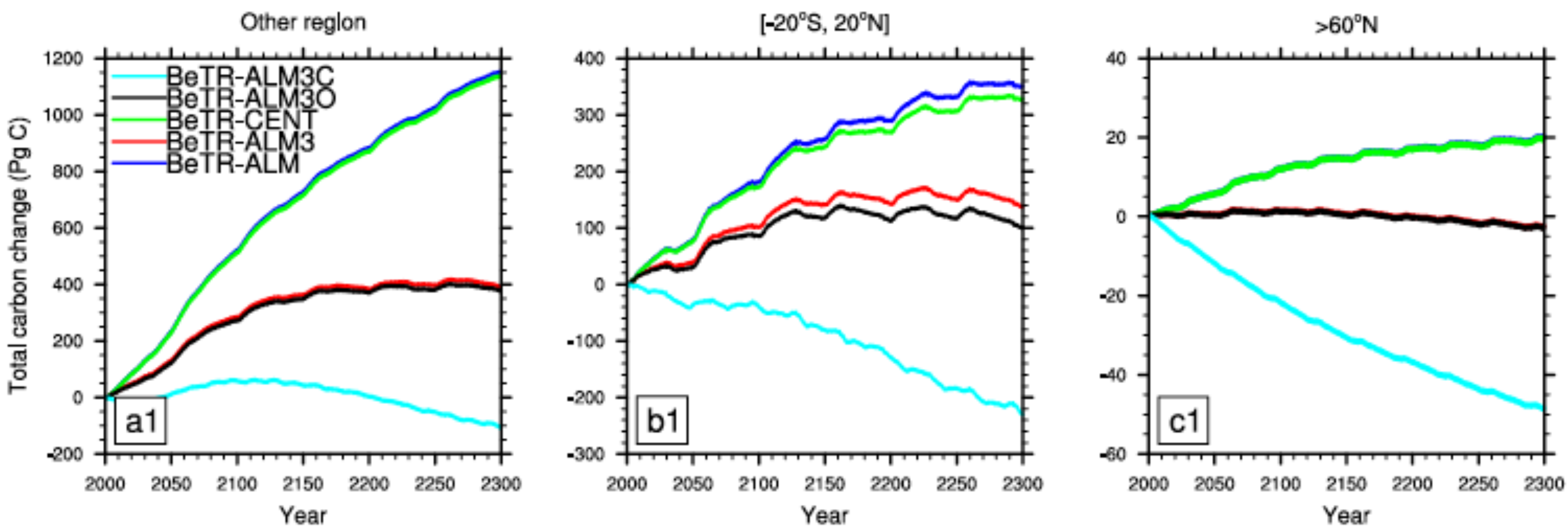


- Projected N deposition and atmospheric CO_2 concentrations
- Qian climate forcing

Divergent carbon stock changes

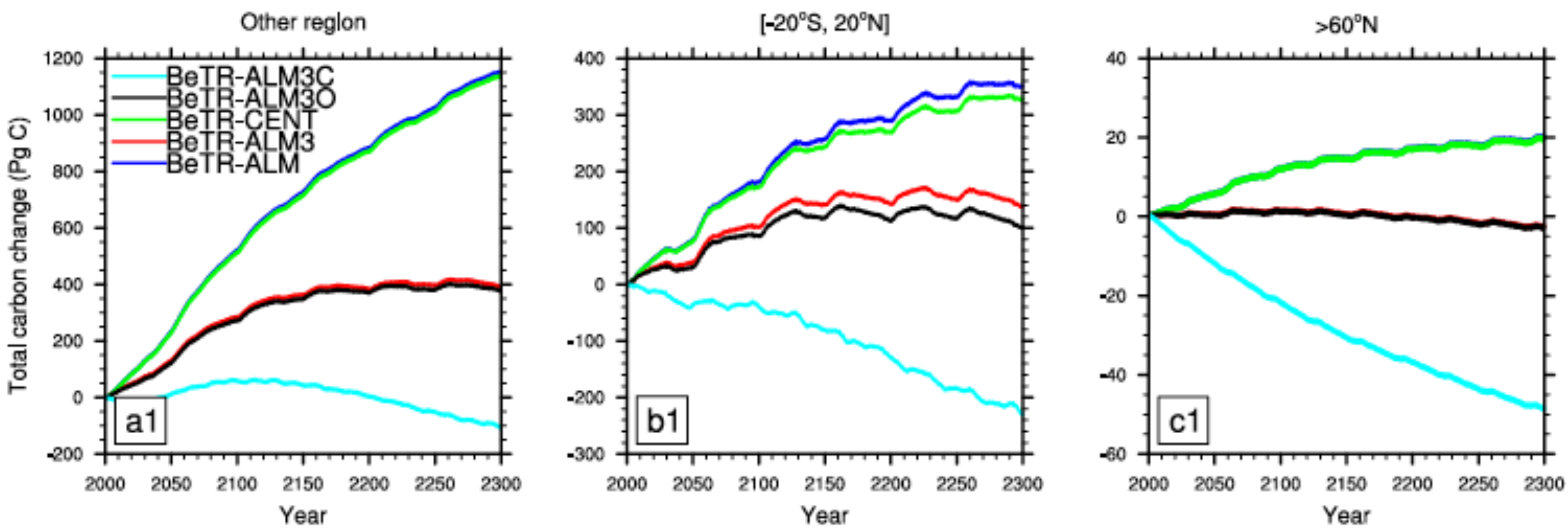


Stronger nitrogen limitation, greater response to CO_2 and nitrogen fertilization



N limitation: BeTR-ALM (blue) > BeTR-CENT (green) > BeTR-ALM3 (red)

Stronger nitrogen limitation, greater response to CO_2 and nitrogen fertilization



N limitation: BeTR-ALM (blue) > BeTR-CENT (green) > BeTR-ALM3 (red)

The CLM4.5BGC is very sensitive to initial conditions.

Milestone summary

- Ambiguous numerical interpretation of nitrogen limitation is a significant uncertainty compared to other sources: forcing data, parameterization, model structure (equations) and initial conditions.
- This uncertainty is resolvable (continued)

Pitfalls of existing approaches for multiple substrates limitation

- Double limitation for fixed stoichiometry model (CABEL and ALM-CNP)

  Limitation 1: Law of the minimum (based on N, and P) in individual uptake

  Limitation 2: Reset flux to avoid the negative N values.

- Curse of ordering

  N! options for *N* substrates. 3!=6 for O_2, N and P.

  Introducing mechanistic BGC will make ALM approach prohibitive.

We resolved the problem and published the method!

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Technical Note: A generic law-of-the-minimum flux limiter for simulating substrate limitation in biogeochemical models

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Stoichiometry based formulation of the donor-receipt network

$$\mathrm{CH_2O + O_2 \rightarrow CO_2 + H_2O}$$

$$-1 \quad -1 \quad | \quad 1 \quad 1$$

Donors | **Receipts**

$$r = f\left(\mathrm{CH_2O, O_2}\right)$$

$$\frac{dy_{\mathrm{CH2O}}}{dt} = \frac{dy_{\mathrm{O2}}}{dt} = -r, \frac{dy_{\mathrm{CO2}}}{dt} = r$$

Receipt based solution for reaction networks

$$\sum_i \nu^-_{i,j} A_{i,j} \rightarrow \sum_m \nu^+_{m,j} B_{m,j}$$

$$\frac{d\mathbf{x}}{dt} = \left(\mathbf{S}^+ - \mathbf{S}^-\right)\mathbf{r}$$

Law of the minimum flux limiter

```
!M1 is number of state variables.
!N1 is number of reactions.
!xt is vector of state variables at current time step.
!xtnew is vector of temporary state variables for
  next time step.
!q is vector of flux limiters for all reactions.
!dt is time step size.
lneg = .false. !Initialize negative state variable
  indicator to zero
do m = 1, M1! Loop over all state variables
  xtnew(m) = xt(m)
  Fp = 0.0 !Initialize production flux accumulator
    to zero
  Fm = 0.0 !Initialize consumption flux accumulator
    to zero
  do n = 1, N1! Loop over all reactions
    xtnew(m) = xtnew(m) + (sp(m,n) - sm(m,n))
      *r(n)*dt
    Fp = Fp + sp(m,n)*r(n)
    Fm = Fm + sm(m,n)*r(n)
  enddo
  if(xtnew(m) < 0) then !The state variable tends
    to be negative
    !Calculate the limiting factor
    p(m) = (xt(m) + Fp*dt) / (dt*Fm)
    lneg = .true.
  endif
enddo
!Now compute and apply the flux limiter
!when there is any negative state variable
if(lneg) then
  do n = 1, N1
    !minp finds the minimum of p,
    !where the corresponding entry in sm is > 0.
    q(n) = minp(p(1:M1), sm(1:M1, n))
    r(n) = r(n)*q(n)
  enddo
endif
```
(6)

- A reaction is limited by its most limiting substrate.
- The limitation comes from consumption.

Tests with the CENTURY CNP model

ID	Reactions
1	$LIT1 \rightarrow 0.45SOM1 + 0.55CO_2 + \left(\frac{1}{CN_{LIT1}} - \frac{0.45}{CN_{SOM1}}\right)N_{min} + \left(\frac{1}{CP_{LIT1}} - \frac{0.45}{CP_{SOM1}}\right)P_{min}$
2	$LIT2 \rightarrow 0.5SOM1 + 0.5CO_2 + \left(\frac{1}{CN_{LIT2}} - \frac{0.5}{CN_{SOM1}}\right)N_{min} + \left(\frac{1}{CP_{LIT2}} - \frac{0.5}{CP_{SOM1}}\right)P_{min}$
3	$LIT3 \rightarrow 0.5SOM2 + 0.5CO_2 + \left(\frac{1}{CN_{LIT3}} - \frac{0.5}{CN_{SOM2}}\right)N_{min} + \left(\frac{1}{CP_{LIT3}} - \frac{0.5}{CP_{SOM2}}\right)P_{min}$
4	$CWD \rightarrow 0.76LIT2 + 0.24LIT3 + \left(\frac{1}{CN_{CWD}} - \frac{0.76}{CN_{LIT2}} - \frac{0.24}{CN_{LIT3}}\right)N_{min} + \left(\frac{1}{CP_{CWD}} - \frac{0.76}{CP_{LIT2}} - \frac{0.24}{CP_{LIT3}}\right)P_{min}$
5*	$SOM1 \rightarrow f_1 SOM2 + f_2 SOM3 + (1 - f_1 - f_2)CO_2$ $+ \left(\frac{1}{CN_{SOM1}} - \frac{f_1}{CN_{SOM2}} - \frac{f_2}{CN_{SOM3}}\right)N_{min} + \left(\frac{1}{CP_{SOM1}} - \frac{f_1}{CP_{SOM2}} - \frac{f_2}{CP_{SOM3}}\right)P_{min}$
6	$SOM2 \rightarrow 0.42SOM1 + 0.03SOM3 + 0.55CO_2$ $+ \left(\frac{1}{CN_{SOM2}} - \frac{0.42}{CN_{SOM1}} - \frac{0.03}{CN_{SOM3}}\right)N_{min} + \left(\frac{1}{CP_{SOM2}} - \frac{0.42}{CP_{SOM1}} - \frac{0.03}{CP_{SOM3}}\right)P_{min}$
7	$SOM3 \rightarrow 0.45SOM1 + 0.55CO_2 + \left(\frac{1}{CN_{SOM3}} - \frac{0.45}{CN_{SOM1}}\right)N_{min} + \left(\frac{1}{CP_{SOM3}} - \frac{0.45}{CP_{SOM1}}\right)P_{min}$

* In this study, we set $f_1 = 0.6235$ and $f_2 = 0.0025$.

CLM-1

$$\bar{S}_{uptake} = \min\left\{\frac{S(t)/\Delta t}{S_{uptake}}, 1\right\} S_{uptake}$$

CLM-2

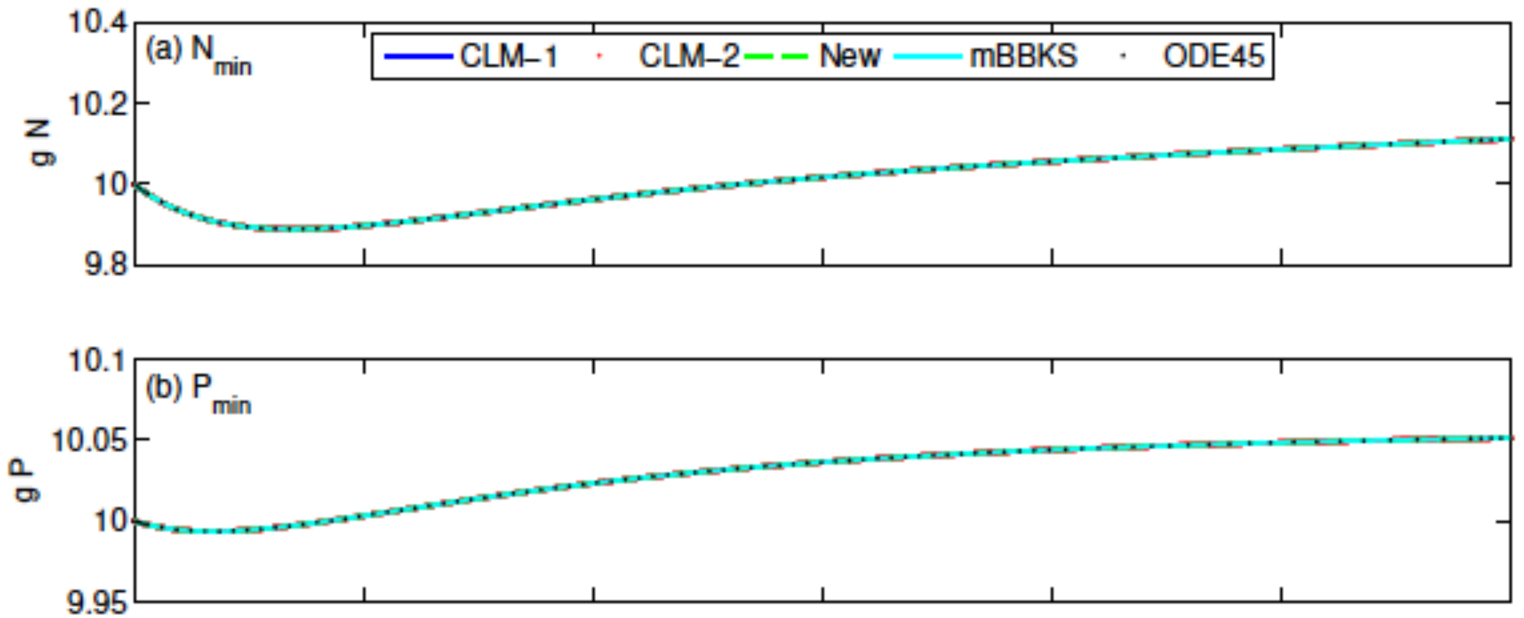
$$\bar{S}_{uptake} = \min\left\{\frac{S(t)/\Delta t}{S_{uptake} - S_{input}}, 1\right\} S_{uptake}$$

mBBKS

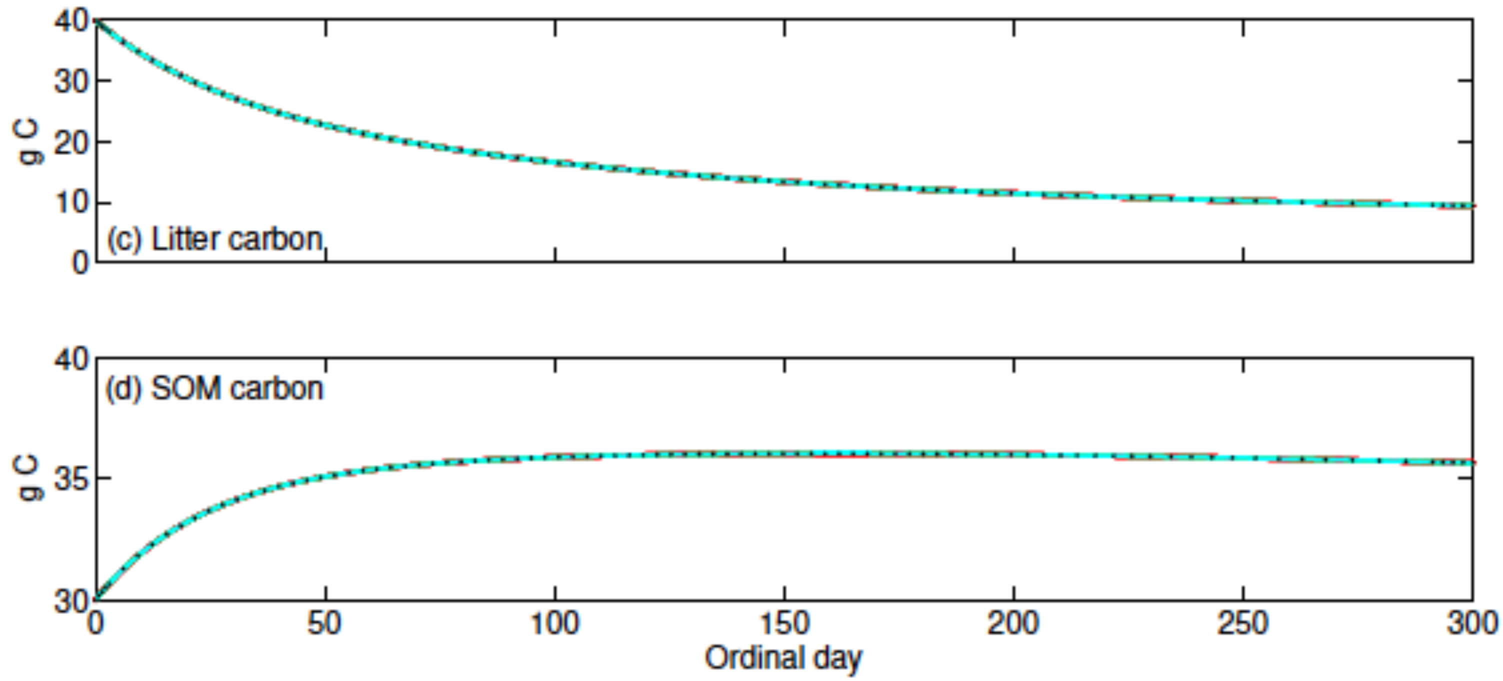
Global flux limiter

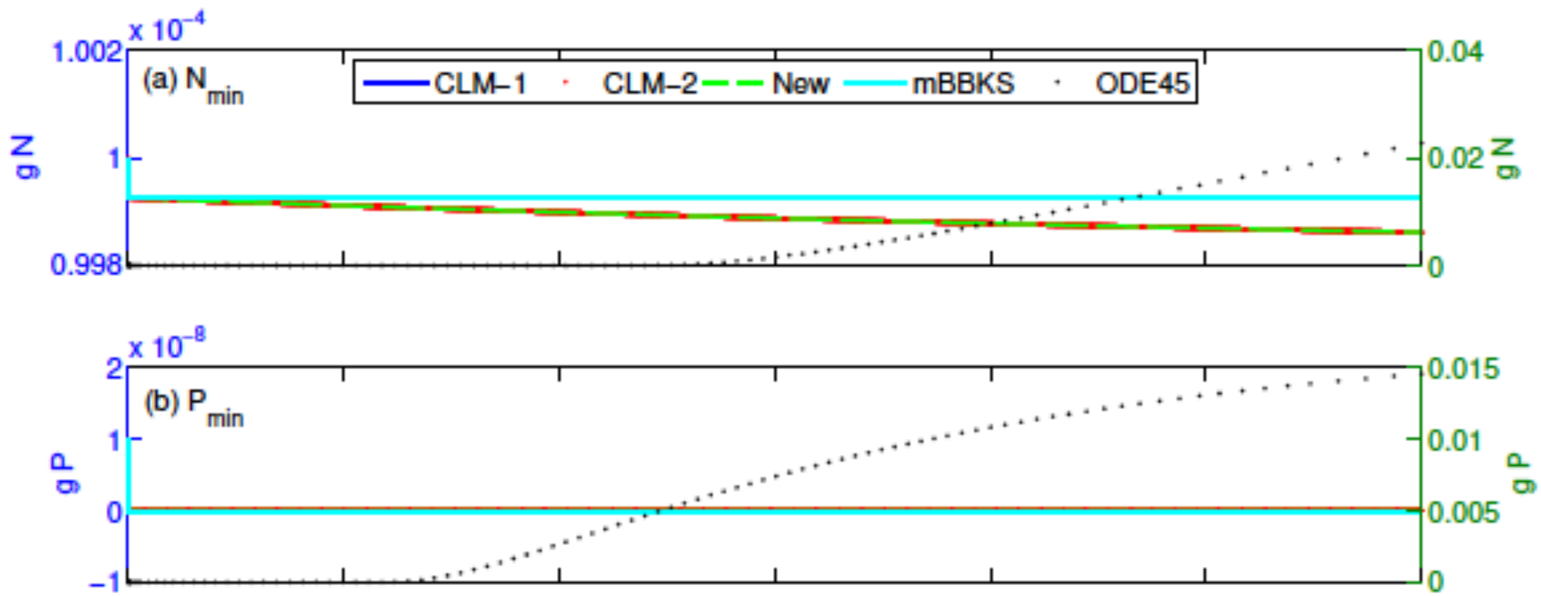
ODE45

Classic derivative clipping

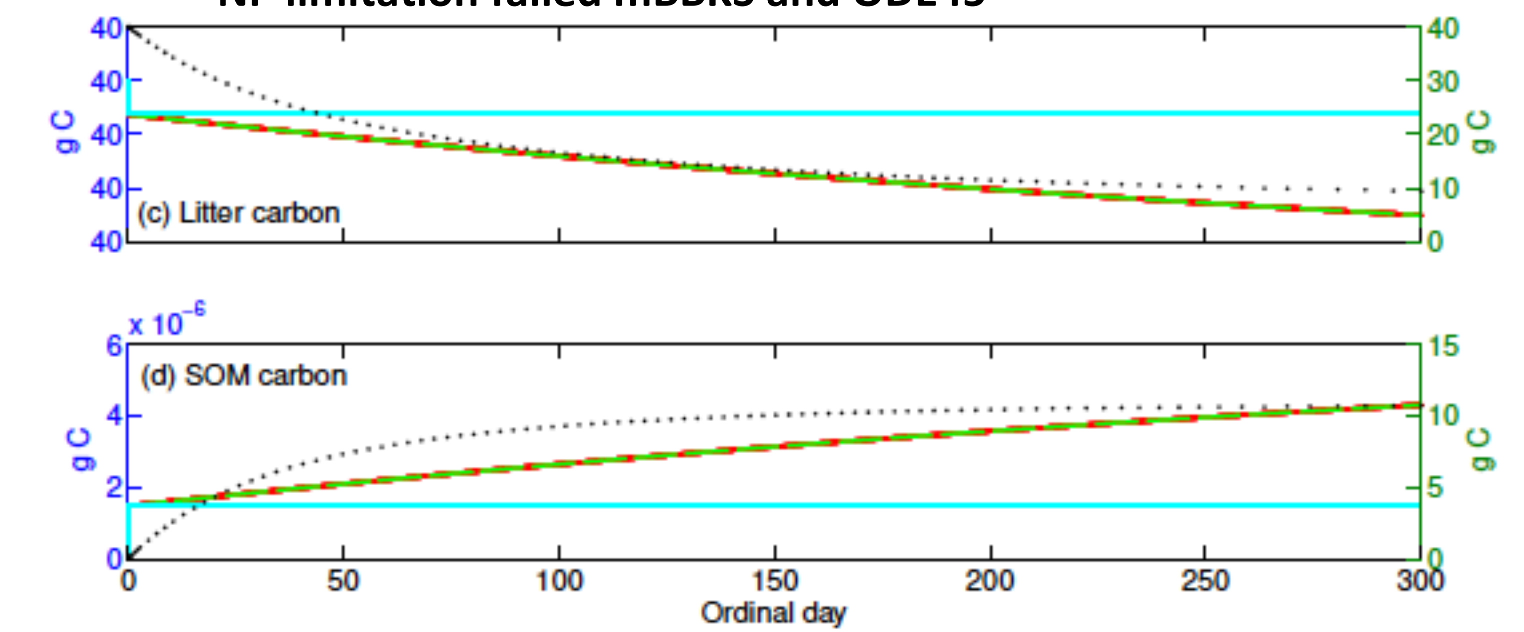


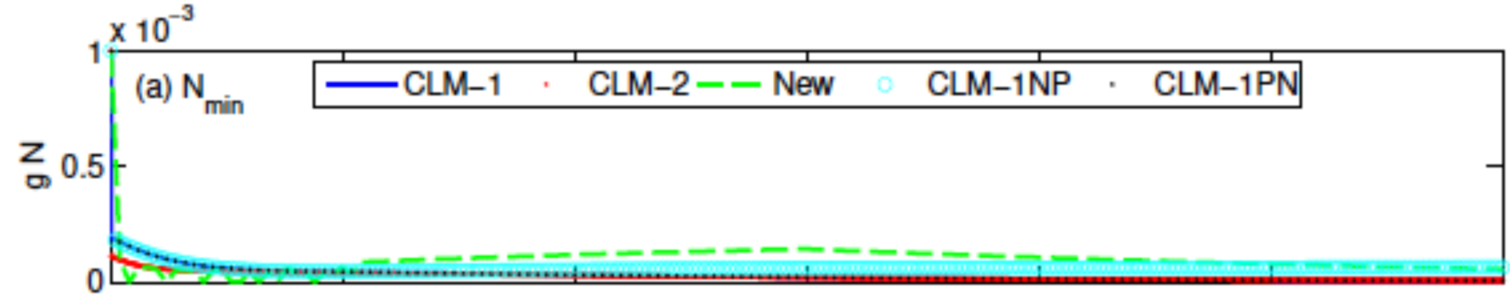
All are good without NP limitation.



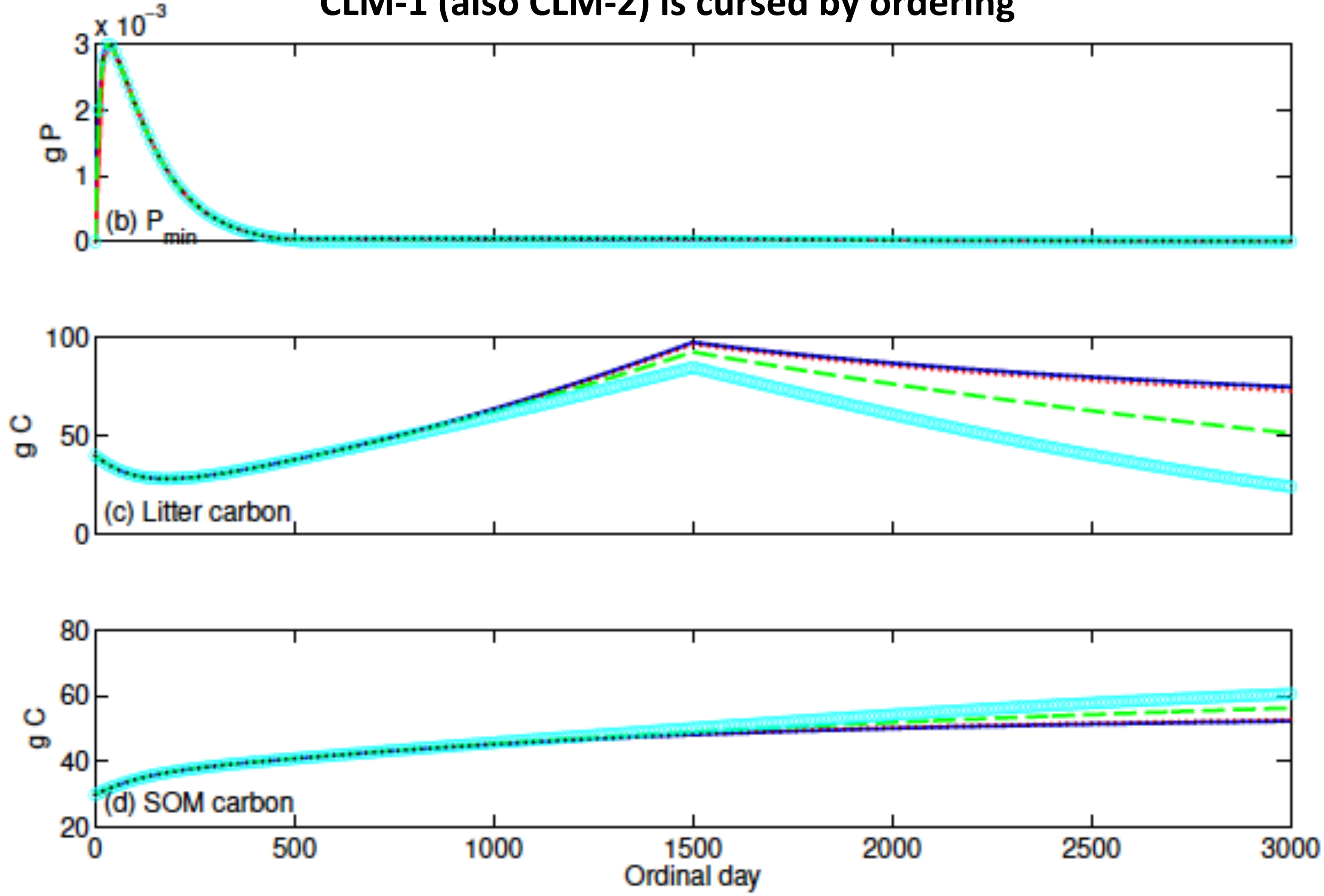


NP limitation failed mBBKS and ODE45





CLM-1 (also CLM-2) is cursed by ordering



Road towards a consistent and scalable BGC model

- **Stoichiometry based formulation of biogeochemical reactions**
  - this rules out ALM-CNP, because its stoichiometry requires prediction-correction.
- **All reactions should be organized in a donor-receipt network to allow consistent implementation of substrates limitation.**
- **Consistent analytical scaling**
  - ECA kinetics for networks (Tang and Riley, 2013).
  - wrong kinetics is fatal (Tang, 2015).

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