Matrix Approach to Accelerate Spin-Up of CLM5

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Background

- " Spin-up "

Spin-up is a process to make a model to reach a steady state.

It is an essential procedure to define the initial conditions of biogeochemical models before the models are used to predict ecosystem response to climate change.

Background

Spin-up methods ：

1. Native dynamic (ND), 1000-10,000 years (Thornton and Rosebloom, 2005)
2. Accelerated decomposition (AD), ～4000 years (Randerson et al., 2009)

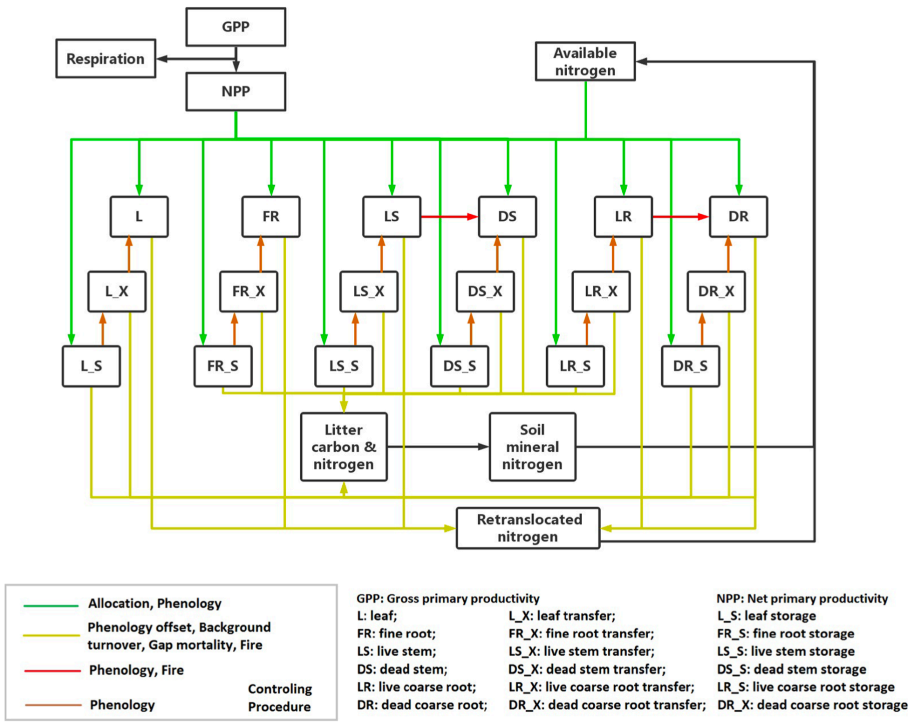
Traditional Spin-up methods take lots of simulation time.

An efficient spin-up method with high quality results is needed.

3. Semi-analytic spin-up (SASU), ～500 years (Xia et al. 2012)

Method

- SASU is applied to matrix models of the terrestrial carbon cycle, such as CLM5 matrix model



(Xingjie Lu et al., 2020)

input output

$$\frac{dC_{veg}}{dt} = BI_{Cin} + \left(A_{phc}(t)K_{phc} + A_{gmc}(t)K_{gmc} + A_{fic}(t)K_{fic}\right)C_{veg}(t) \quad (1)$$

$$\frac{dN_{veg}}{dt} = BI_{Cin} + \left(A_{phc}(t)K_{phc} + A_{gmc}(t)K_{gmc} + A_{fic}(t)K_{fic}\right)N_{veg}(t) \quad (2)$$

$$\frac{dC_{soil}}{dt} = I_{Csoil} + \left(A_{hc}\xi(t)K_h + V(t) + K_f(t)\right)C_{soil}(t) \quad (3)$$

$$\frac{dN_{soil}}{dt} = I_{Nsoil} + \left(A_{hc}\xi(t)K_h + V(t) + K_f(t)\right)N_{soil}(t) \quad (4)$$

Method

- **Calculation of analytic solution**

The system converges to a steady state when Input = output.

$$\frac{dC_{veg}}{dt} = BI_{Cin} + \left(A_{phc}(t)K_{phc} + A_{gmc}(t)K_{gmc} + A_{fic}(t)K_{fic}\right)C_{veg}(t) = \mathbf{0}$$

$$\frac{dN_{veg}}{dt} = BI_{Cin} + \left(A_{phc}(t)K_{phc} + A_{gmc}(t)K_{gmc} + A_{fic}(t)K_{fic}\right)N_{veg}(t) = \mathbf{0}$$

$$\frac{dC_{soil}}{dt} = I_{Csoil} + \left(A_{hc}\xi(t)K_h + V(t) + K_f(t)\right)C_{soil}(t) = \mathbf{0}$$

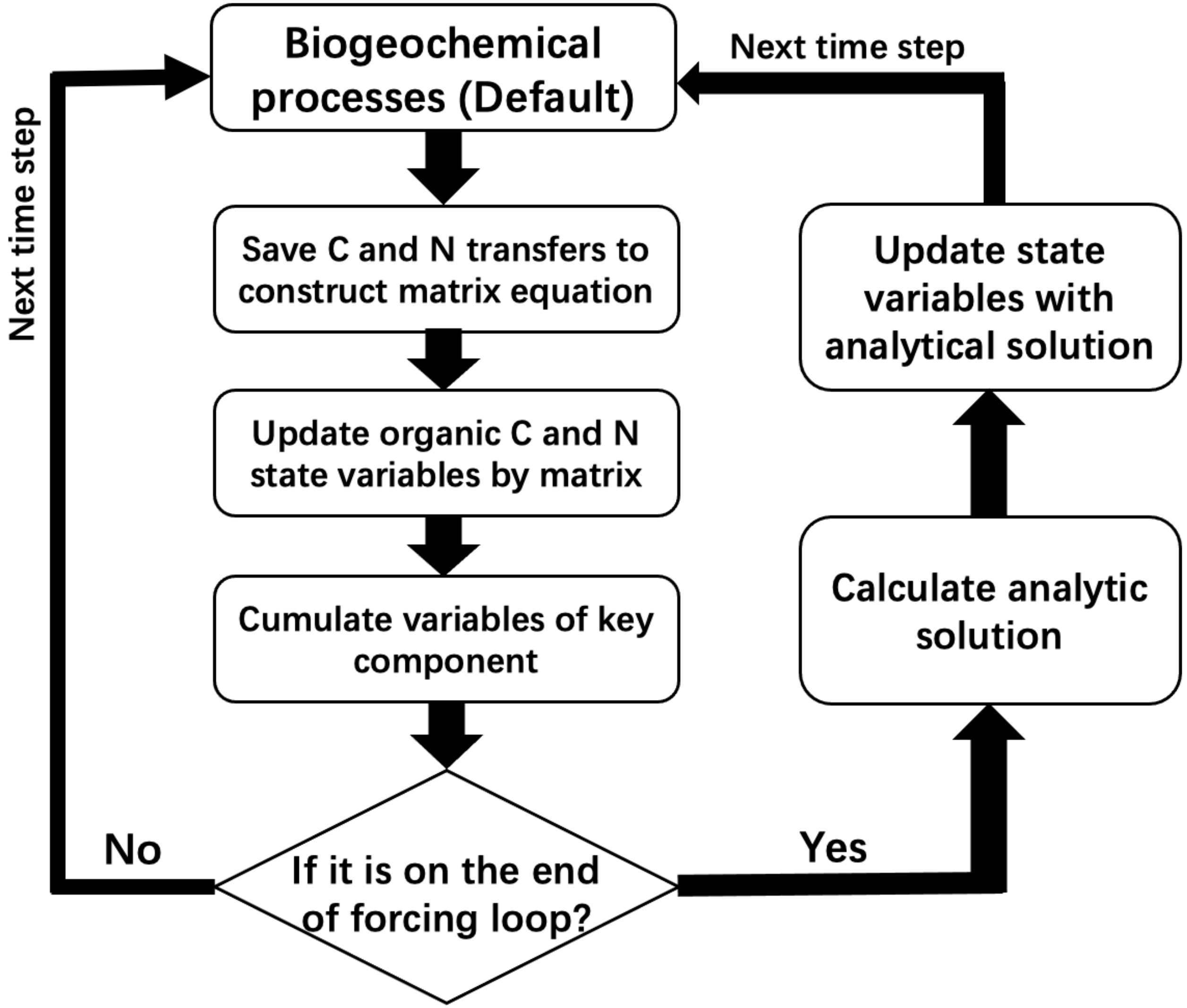
$$\frac{dN_{soil}}{dt} = I_{Nsoil} + \left(A_{hc}\xi(t)K_h + V(t) + K_f(t)\right)N_{soil}(t) = \mathbf{0}$$

$$\boldsymbol{C_{soil}} = \left(A_{hc}\,\bar{\xi}\,K_h + \overline{\boldsymbol{V}} + \overline{K_f}\right)^{-1}\overline{\boldsymbol{I_{Csoil}}}$$

Theoretical steady state

Method

- The workflow of SASU in CLM5



- The matrix module is used instead of the original update mode.
- SASU module is called at the end of each loop.
- Analytic solution is used as pool sizes of next loop.

Model simulation

- **Brazil site Verification**
  - Native dynamics (ND) / Accelerated decomposition (AD)
  - Semi-analytic Spin-up (SASU)

- **Global Verification**
  - Accelerated decomposition (AD)
  - Semi-analytic Spin-up (SASU)

- Derived by CLM5 spin-up using 20-year recursive from Global Soil Wetness Project Phase 3 (GSWP3)
- 4° × 5° resolution grid

Results

- **Brazil site Verification**

Mean steady state values (KgC/m²) of state variables with SASU and ND

State Variable	**SASU-ND** (KgC/m²)	**SASU** Pool size (KgC/m²)	**ND** Pool size (KgC/m²)
Coarse Wood Debris	-6.51E-5	2.34	2.34
Total Soil Carbon	1.45E-3	7.32	7.32
Total Vegetation Carbon	-3.57E-4	15.3	15.3
Total Ecosystem Carbon	1.02E-3	25.2	25.2

(threshold = 0.05 g/m²)

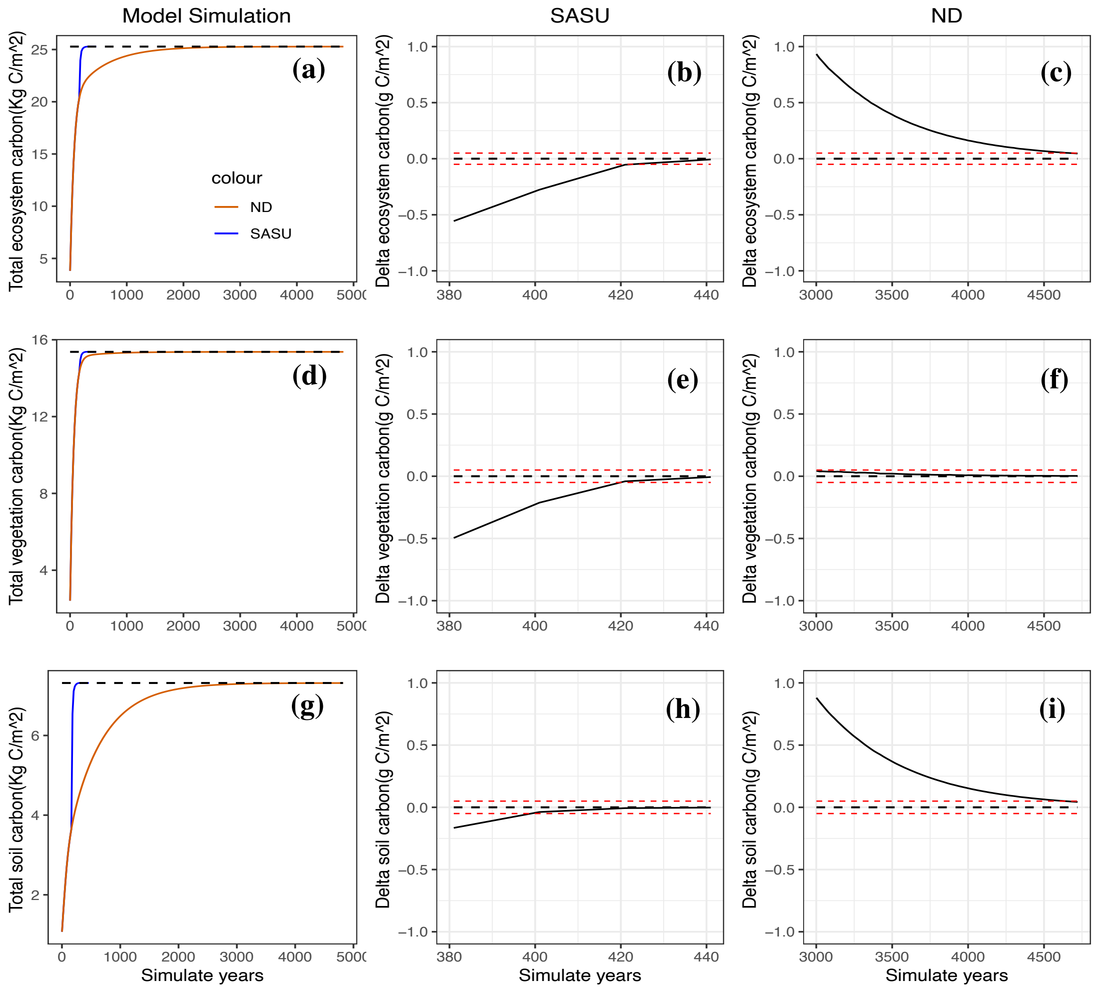
The steady states in Brazil obtained by the two methods are highly consistent.

Results

● Brazil site Verification

- SASU take 480 years and ND/AD use 4720 years to reach the same steady state in Brazil.

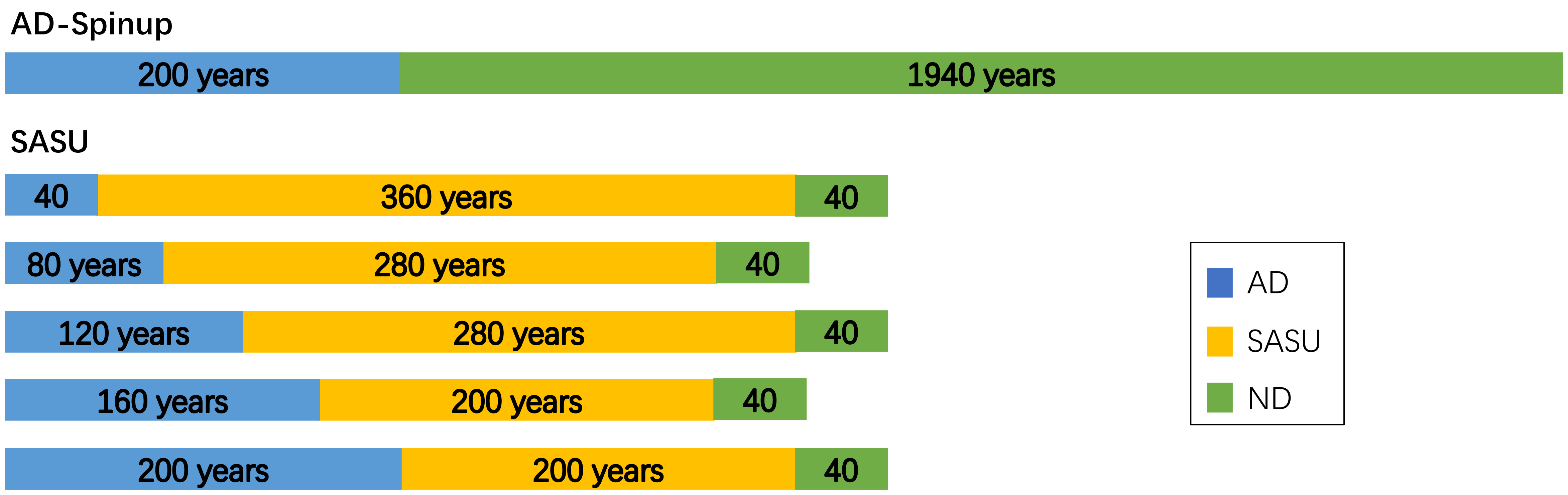
- SASU use 480 years that is nearly 89.83% simulation time less than ND to reach the same state.



Carbon state trajectories **(a, d, g)** and the change of carbon between loops for SASU **(b, e, h)** and ND **(c, f, i)** on Brazil site.

Results

Global Verification



- Steady state defined as more than 97% areas achieved equilibrium.
- Global threshold for total ecosystem carbon equilibrium is 0.02 PgC / yr.

Results

Global Verification

	SASU-AD Pool size (PgC)	AD Pool size (PgC)	SASU Pool size (PgC)
CWD	-0.42	144.6	144.2
SOIL 1	-0.59	17.15	16.56
SOIL 2	-8.50	547.5	539.0
SOIL 3	-0.29	1015	1015
TOTSOMC	-9.39	1580	1570
TOTECOSYSC	-10.9	2361	2350
TOTVEGC	-0.53	595.3	594.8

The top 2.72m soil layers reach a similar steady state.

Results

Global Verification

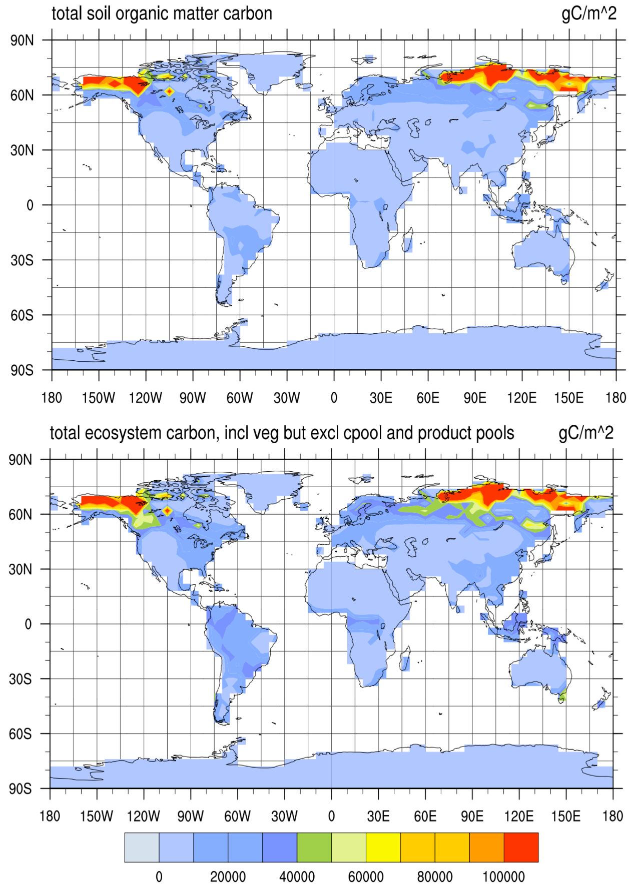
	Ecosystem C (Pg C)	Vegetation C (Pg C)	Soil C (Pg C)	Unequilibrium Percentage（%）	Total Simulate year
AD Spin-up	3131.3	594.7	2352.4	2.99	2140
SASU 40+360+40	2410.9	595.9	1629.8	3.99	440
SASU 80+280+40	2408.8	595.6	1628.0	2.90	400
SASU 120+280+40	2416.5	595.7	1635.5	2.52	440
SASU 160+200+40	2410.0	595.3	1629.1	2.75	400
SASU 200+200+40	2417.9	595.6	1636.9	2.59	440

In general, AD-Spinup takes about 2,140 years to reach steady state, while SASU just take 400~440 years. SASU will save about 80% simulate time than AD-spinup.

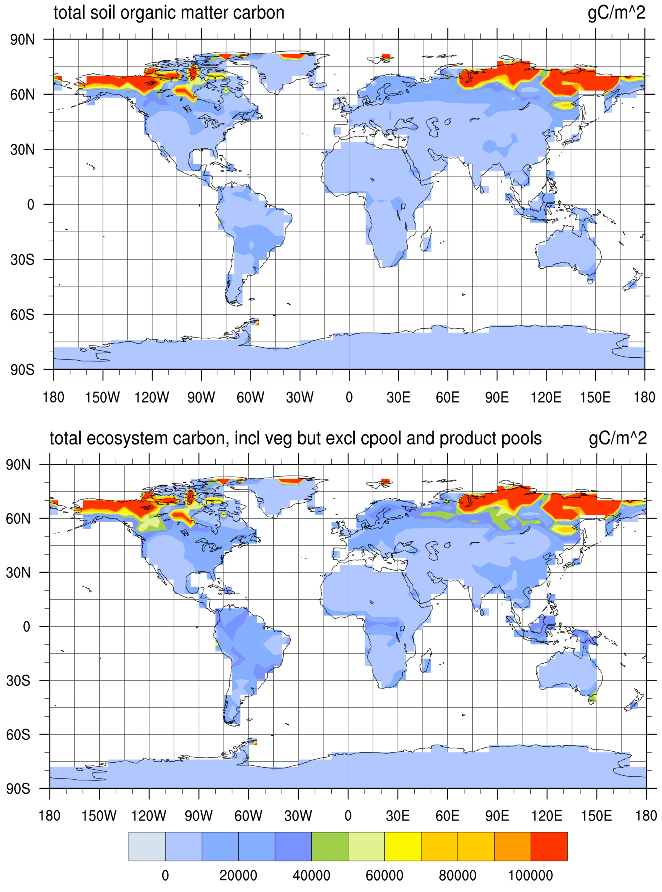
Results

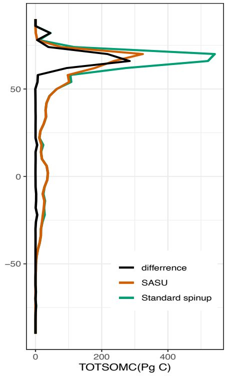
Global Verification

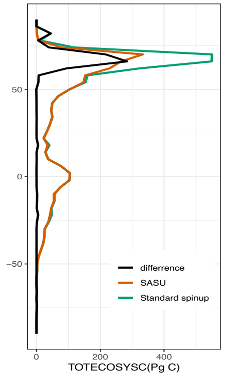
SASU



AD-SPINUP



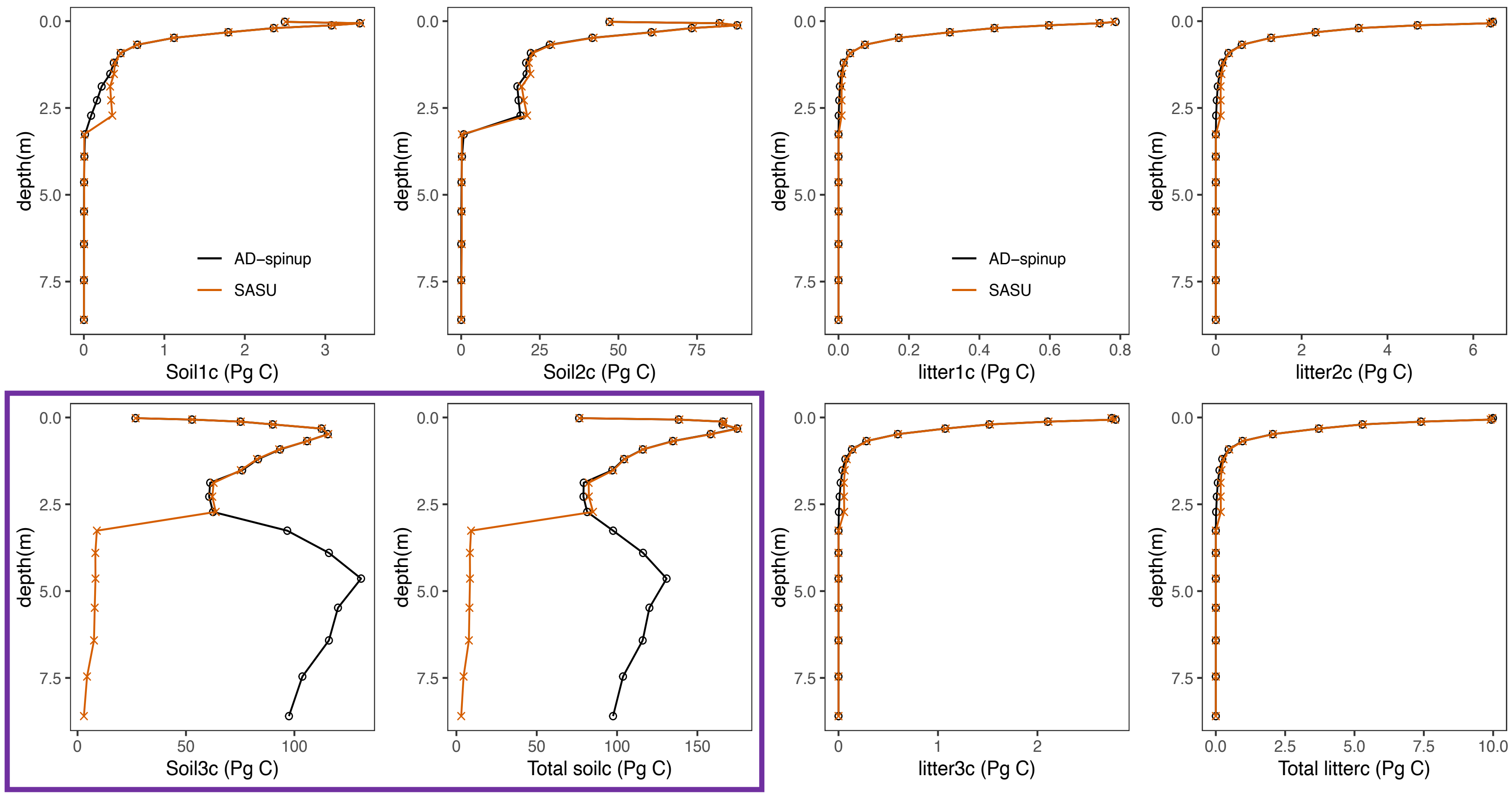




- AD-spinup results will larger than SASU in high-latitude region.
- Typically, these areas are in the permafrost.
- There will never be an input or output of carbon in the deeper soil, especially for passive soil carbon pool.

Results

Global Verification

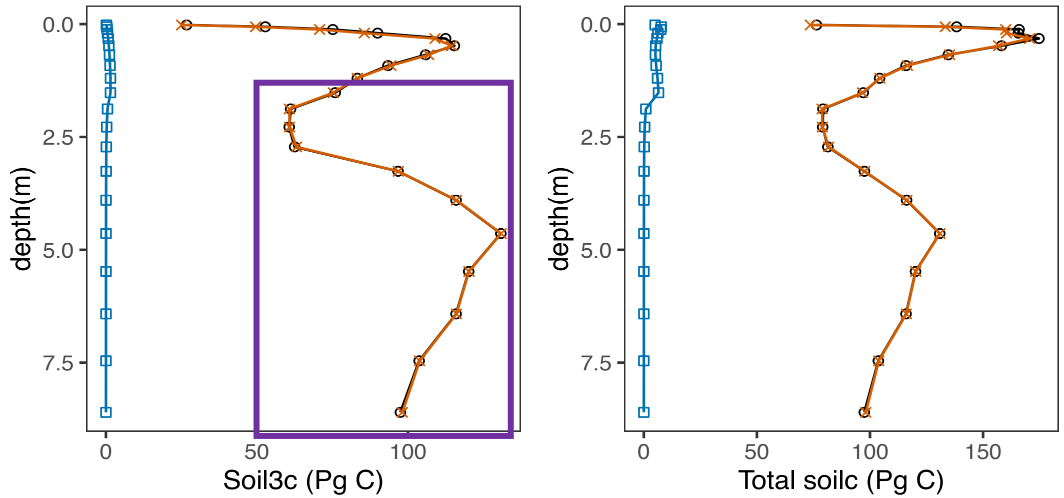


- **Most of pool sizes along depth from two methods are consistent.**
- **Passive soil carbon in deep layers shows high difference. SASU keep it in a low values.**

Results

Global Verification

AD-Spinup



- Even after 2000 years model running, passive soil carbon in deep layers does not change much.
- The steady state of deep soil carbon pool (passive carbon pool) from AD largely depends on the initial state and expansion multiple.

SASU

$$\boldsymbol{C_{soil}} = \left(A_{hc}\,\bar{\xi}\,K_h + \overline{\boldsymbol{V}} + \overline{K_f}\right)^{-1}\overline{\boldsymbol{I_{Csoil}}}$$

- When there is no input and output, the analytic solution will be 0.

Conclusion

- The steady states obtained by SASU and other methods are highly consistent.
- SASU is an efficient method to accelerate coupled carbon and nitrogen cycle to equilibrium.
- SASU is expected to improve the estimation accuracy of steady-state pool sizes, especially for the permafrost regions.

Thank you!

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