A traceability framework to facilitate model evaluation

Yiqi Luo¹, Jianyang Xia¹, Ying-ping Wang², Oleksandra Hararuk¹, Shuli Niu³, and many others

1. Department of Microbiology and Plant Biology, University of Oklahoma, OK, USA.
2. CSIRO Marine and Atmospheric Research, Centre for Australian Weather and Climate Research, Aspendale, Victoria, Australia
3. Institute of Geographic Sciences and Natural Resources, the Chinese Academy of Sciences, Beijing, China

NCAR LMWG/BGCWG (Feb. 21. 2013)
Model Tractability

“There is a danger that we shall replace a world we do not understand by a model of the world we do not understand”

-----John Maynard Smith 1992 Nature
Challenges

- Models behave so differently;
- Does the uncertainty reflect natural variability or mainly result from artifacts in models? ;
- It’s essential to eliminate model artifacts as much as possible.
- How to identify them?

Friedlingstein et al. 2006
“Metrics/diagnostics for component model assessment”

--- Brian O’Neill
CESM guidance
Theoretical analysis

1. Photosynthesis as the primary C influx pathway
2. Compartmentalization,
3. Partitioning among pools
4. Donor-pool dominated carbon transfers
5. 1st-order kinetic transfers from the donor pools
Theoretical analysis

A: Basic processes

B: Shared model structure

D: General model

\[
\begin{align*}
\frac{dX(t)}{dt} &= \xi ACX(t) + BU(t) \\
X(t = 0) &= X_0
\end{align*}
\]

Luo et al. 2003 GBC
Luo and Weng 2011 TREE
Luo et al. 2012

C: Similar algorithm

\[
\begin{align*}
dX_1(t)/dt &= b_1 U(t) - \xi c_1 X_1(t) \\
&= a_{75} x_5(t) + c_6 a_{76} x_6(t) - c_7 X_7(t) \\
dX_8(t)/dt &= \xi [c_6 a_{86} x_6(t) + c_7 a_{87} x_7(t) - c_8 X_8(t)]
\end{align*}
\]
System equations

Empirical evidence
1. First-order decay of litter decomposition (Zhang et al. 2008)
2. Carbon release from soil incubation data (Schaedel et al. 2012)
3. Ecosystem recovery after disturbance (Yang et al. 2011)
4. General behavior of CMIP5 models (Todd-Brown et al. 2013)

\[
\begin{align*}
\frac{dX(t)}{dt} &= \xi(t)AX(t) + bU(t) \\
X(0) &= X_0
\end{align*}
\]

Mathematical and ecological properties (Luo et al. 2012)

Dynamic disequilibrium (Luo and Weng 2011)
working group
Applications

\[
\begin{align*}
\frac{dX(t)}{dt} &= \xi(t)AX(t) + bU(t) \\
X(0) &= X_0
\end{align*}
\]

1. Predictability of the terrestrial carbon cycle (Luo et al. in prep.)

2. Computational efficiency of spinup (Xia et al. 2012)

3. Traceability for model analysis (Xia et al. 2013)
   a. Impacts of additional modules
   b. Attribution of uncertainty to its Sources
   c. Model intercomparison

4. Facilitating data assimilation (Hararuk et al. To be submitted)
The “traceability” of terrestrial carbon cycle is mathematically solved as:

\[
\frac{dX(t)}{dt} = BU(t) - \xi(t)ACX(t)
\]  

(1)

According to equation (1), when an ecosystem at steady state, the steady-state ecosystem carbon pool size (i.e., ecosystem carbon storage capacity; \(X_{ss}\)) is:

\[
X_{ss} = \xi^{-1}(AC)^{-1}BU_{ss} = \xi^{-1}\tau'_E U_{ss} = \tau_E U_{ss}
\]  

(2)

where \(\tau'_E\) represents the baseline residence times of different carbon pools which are determined by the partitioning and transfer coefficients in equation 1 as:

\[
\tau'_E = (AC)^{-1}B
\]  

(3)

The actual residence time (\(\tau_E\)) of an ecosystem in the equation 2 is modified from \(\tau'_E\) by the environmental scalar (\(\xi\)) as:

\[
\tau_E = \xi^{-1}\tau'_E
\]  

(4)

For litter and soil carbon pools, \(\xi\) usually is calculated from temperature \(\xi_T\) and water \(\xi_W\) as:

\[
\xi = \xi_T \xi_W
\]  

(5)

Xia et al. 2013. Global Change Biology (Available online)

Part I: Framework (Carbon residence time)
The traceability framework

Climate forcing

Precipitation

Temperature

Preset Residence times

Litter lignin fraction

Soil texture

NPP ($U_{ss}$)

$\xi_w$

$\xi_T$

$\xi$

$\tau_E$

$X_{ss}$

Xia et al. 2013. Global Change Biology (Available online)

Part I: Framework
Ecosystem carbon storage capacity \((X_{ss})\) is determined by ecosystem carbon influx (i.e., NPP; \(U_{ss}\)) and ecosystem carbon residence time \((\tau_E)\).

Luo et al, 2003. GBC
Differential determinants on carbon storage capacity among biomes

Based on spin-up results from CABLE with 1990 forcings.

Long $\tau_E$ but low NPP.

High NPP but short $\tau_E$.

Based on spin-up results from CABLE with 1990 forcings.
Ecosystem carbon residence time ($\tau_E$) is modified from baseline residence time ($\tau_{E'}$) by environmental scalars ($\zeta$).
Modification of environmental scalars on baseline carbon residence times

**Tundra:**
Moderate $\tau_E'$ but very long $\tau_E$. 

[Graph showing ecosystem C residence time vs. environmental scalar and baseline C residence time]
Temperature and water scalars link environmental space (air temperature and precipitation) into the C space.

Temperature and water scalars link environmental space (air temperature and precipitation) into the C space.

Part I: Framework (Carbon residence time)
Temperature and water scalars link environmental space (air temperature and precipitation) into the C space.

Cropland is excluded in this study. Input forcing in 1990.
In CABLE model, the differences in environmental scalars among biomes are more determined by the temperature scalar.

The environmental limitation on $\tau_E$ ’is largest in Tundra and needleleaf forests.

Part I: Framework (Carbon residence time)
Litter lignin fraction and soil texture spatially modified the preset residence times into baseline carbon residence times in different grids.

\[
\tau_E, \quad \sigma, \quad \xi_T, \quad \xi_w, \quad \xi
\]

Part I: Framework (Carbon residence time)
Litter lignin fraction and soil texture influence spatially distribution of C turnover rates

Part I: Framework (Carbon residence time)
A traceable framework for terrestrial C cycle

Environmental space

Climate forcing

Precipitation

Temperature

Preset Residence times

Litter lignin fraction

Soil texture

Baseline residence times of carbon pools

Determinants of ecosystem carbon influx and actual residence time on carbon storage capacity.

Environmental scalars linking environmental and carbon spaces

NPP ($U_{ss}$)

Baseline residence times of carbon pools

Part I: Framework
Model intercomparison

Similar

Climate forcing

Precipitation

Temperature

Preset Residence times

Litter lignin fraction

Soil texture

$\xi_w$

$\xi_T$

$\xi$ $\xi$

CLM > CABLE

CABLE > CLM

NPP ($U_{ss}$)

CLM > CABLE

$\tau_E$

CLM > CABLE

CABLE > CLM

$X_{ss}$

CLM > CABLE

Part II: Model Intercomparison

http://ecolab.ou.edu
Longer residence times in CABLE than CLM-CASA

\[ \tau_E = \xi^{-1} \tau'_E \]

- **Actual residence time (year)**
- **Baseline residence time (year)**

![Graph showing residence times comparison between CABLE and CLM-CASA](image)

**Legend:**
- ENF (Evergreen forest)
- EBF (Evergreen broadleaf forest)
- DNF (Deciduous needleleaf forest)
- DBF (Deciduous broadleaf forest)
- Shrub
- C3G (C3 grassland)
- C4G (C4 grassland)
- Tundra

Part II: Model Intercomparison

[http://ecolab.ou.edu](http://ecolab.ou.edu)
Part II: Assess the effects of incorporating N cycle into C cycle

- reduces \( X_{ss} \) in all biomes in comparison with that in the carbon-only model;
- mainly by decreasing NPP in woody biomass and via shortened \( \tau_E' \) in other biomes.
Attribution of model uncertainty to its sources

\[
\frac{dX(t)}{dt} = \xi(t)AX(t) + bU(t)
\]

\[
X(0) = X_0
\]

\[
X_{ss} = \xi^{-1}\tau'E U_{ss} = \tau' E U_{ss}
\]

\[
\tau_E = \xi^{-1}\tau' E = (\xi_T \xi_W)^{-1}(A^{-1}B)
\]
Soil carbon modeled in CMIP5 vs. HWSD

Todd-Brown et al. 2012 BGD
Soil carbon modeled in CMIP5 vs. HWSD

Yan et al. unpublished
How do CLM-CASA’ and CABLE simulate Soil C?  
Hararuk et al. To be submitted
Data assimilation to improve soil C simulation by two global models:

Hararuk et al. To be submitted
Changes in temporal dynamics: CLM-CASA’

a) SOIL

2010 pool size:
Initial: 585.8 Pg C
Optimum: 1051.2 Pg C

Hararuk et al. To be submitted
Summary

• Improvement and applications of the traceability framework to make carbon cycle models more tractable. Procedure will be available at http://ecolab.ou.edu

• The traceability framework makes it possible to evaluate impacts of adding components on model performance skills before we do so.

• It is urgent to correct the initial value problem of global carbon cycle models before they are used for CMIP6. It is also relatively easy to do so.