Evaluation and Improvement of Land Carbon Cycle Models: Theory and Techniques

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ILAMB meeting, May 16-18, 2016

Contributors

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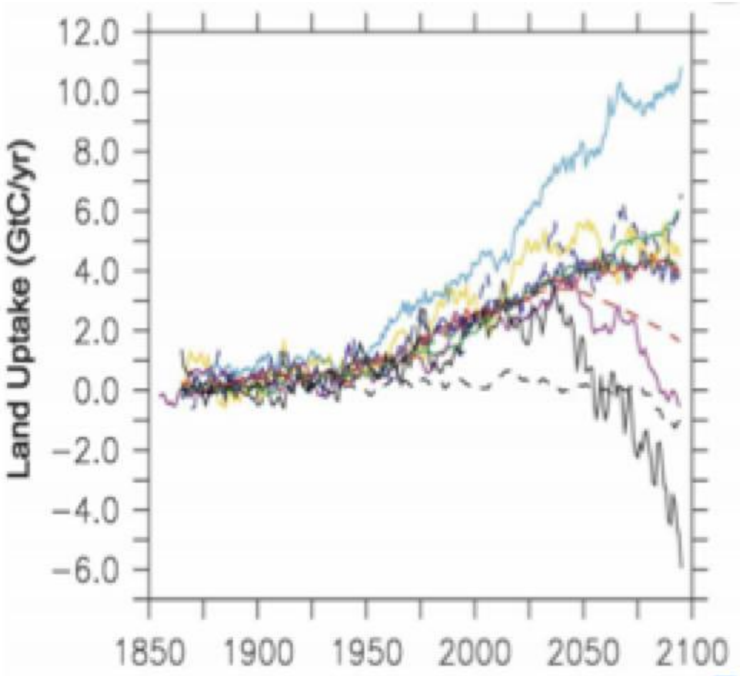
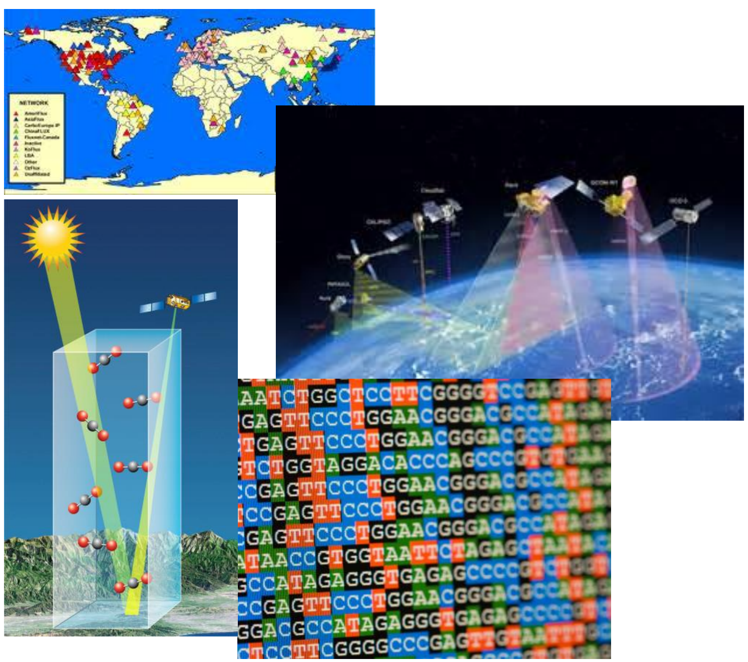
- **Other collaborators**: Anders Ahlström, Chris Lu, Christopher Schwalm, Sha Zhou



Two issues

- Why do land models behave so differently?
- How could big data be integrated into big models (BDBM challenges)?



New theory and techniques

- A theoretical framework of carbon storage

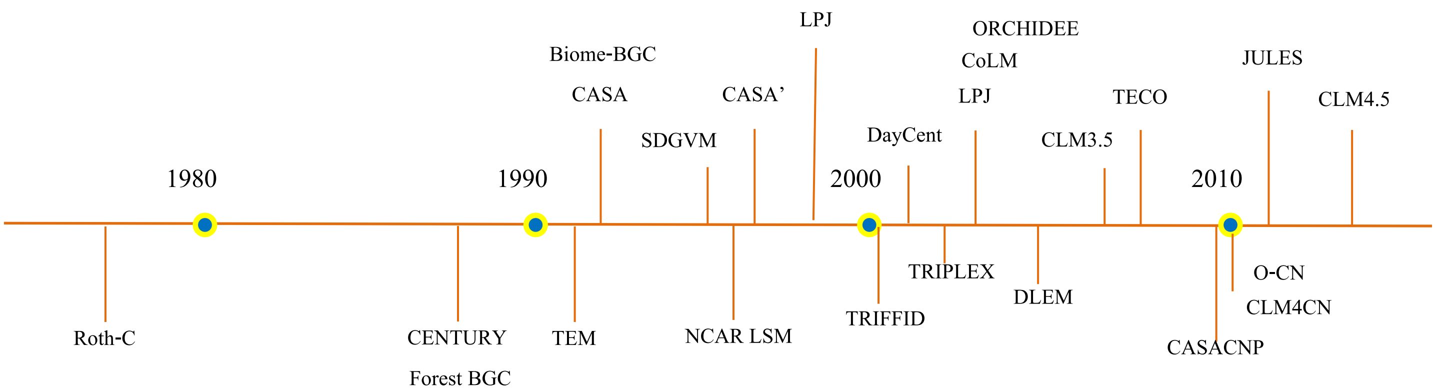
  $$X(t) = Xe(t) - Xp(t)$$

- High-fidelity emulators of carbon cycle models
  - Model evaluation via 3D parameter space, traceability framework, variance decomposition
  - Model improvement via semi-analytic spin-up and data assimilation
  - Model development via component evaluation

Recommendations

- ***Tier 0*** You do nothing, we will find ways to analyze your results
- ***Tier 1*** Model outputs: GPP, residence time (τ_E) to estimate the equilibrium capacity (X_E) and potential (X_p)
- ***Tier 2*** Developing an emulator for your model to enable analytic spin-up, traceability, parameter space, variance decomposition, and data assimilation
- ***Tier 3*** Establishing a library of emulators to allow various analyses

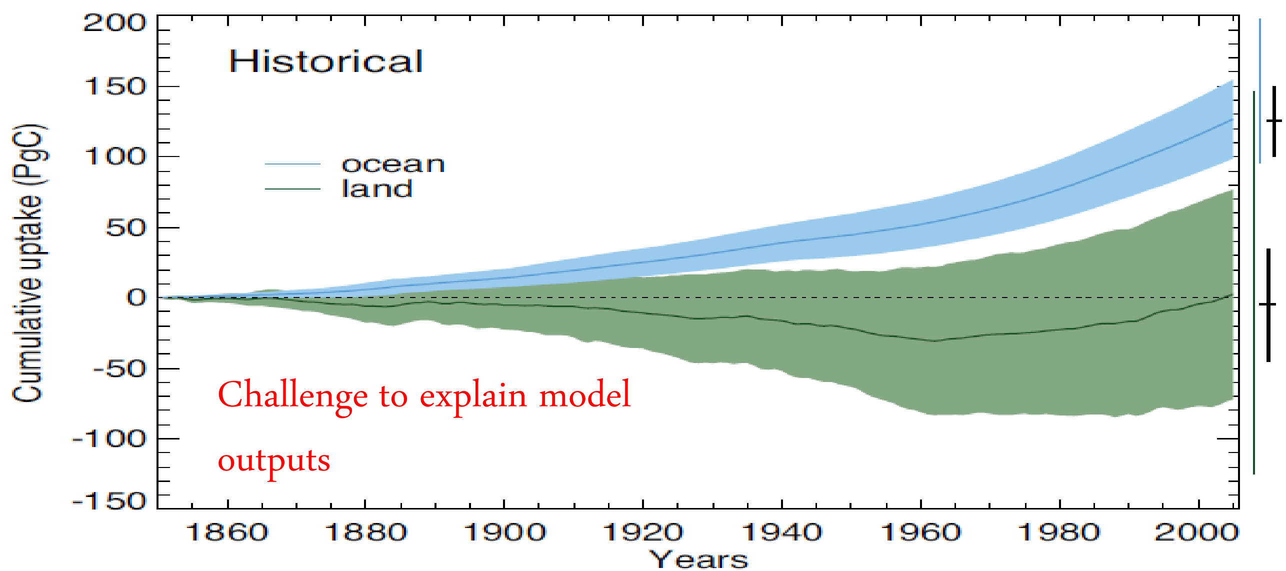
Challenge



Soil microbial dynamics
Soil depth
Priming effect
Wetland
Land use
Erosion
DOC
Fire
... ...

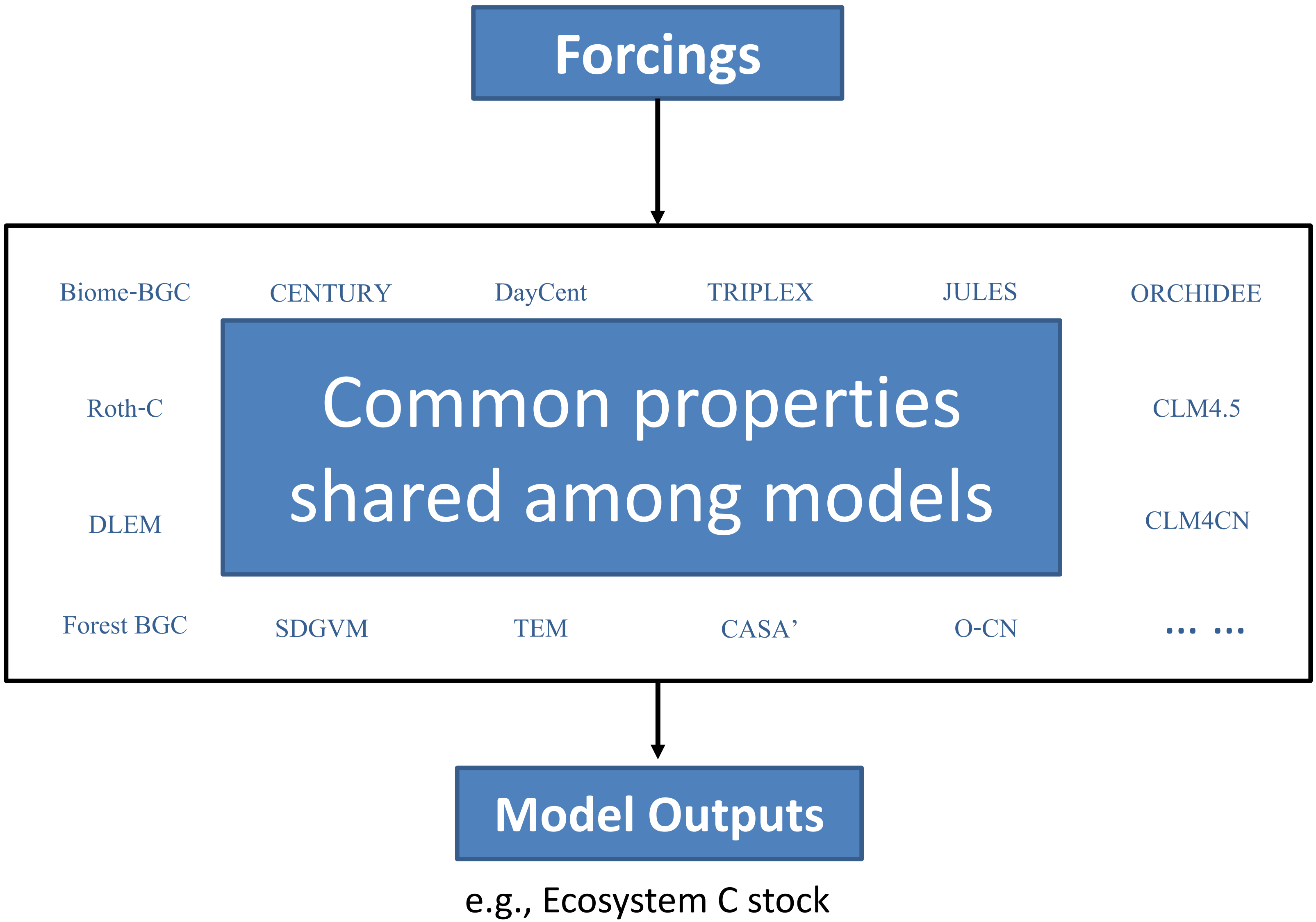
Low **Complexity** High

High **Tractability** Low

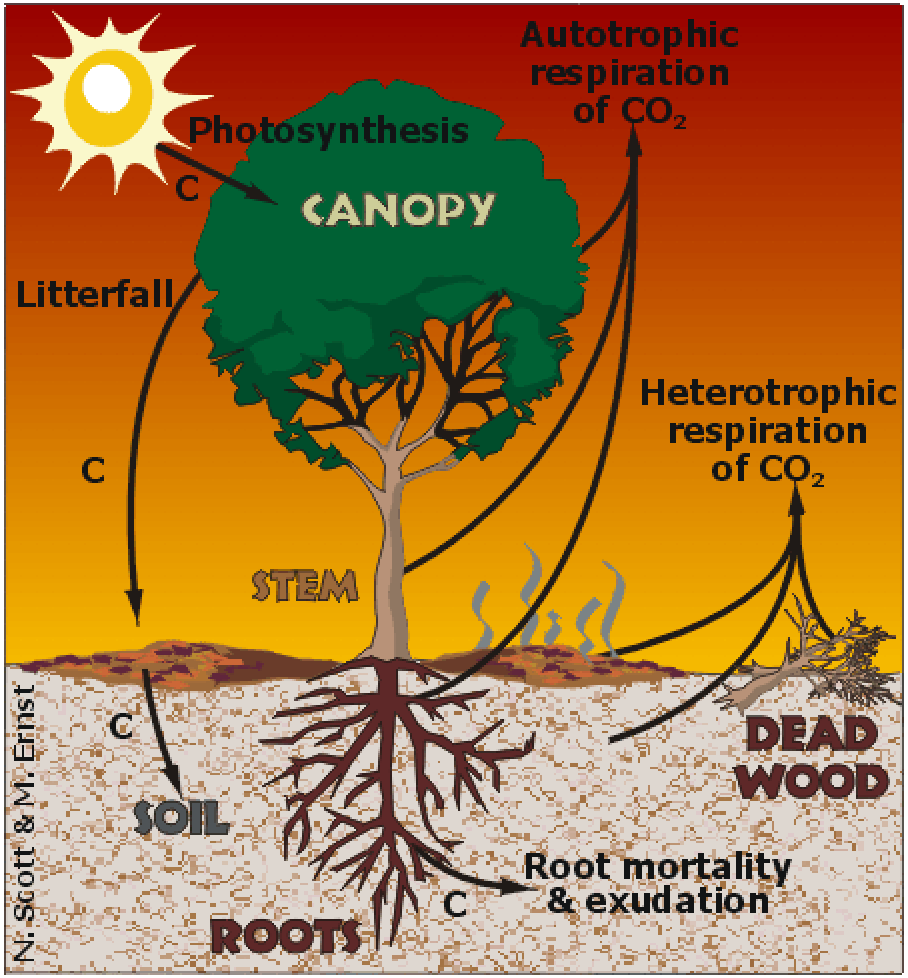


IPCC AR5
Chapter 6

What we have searched for



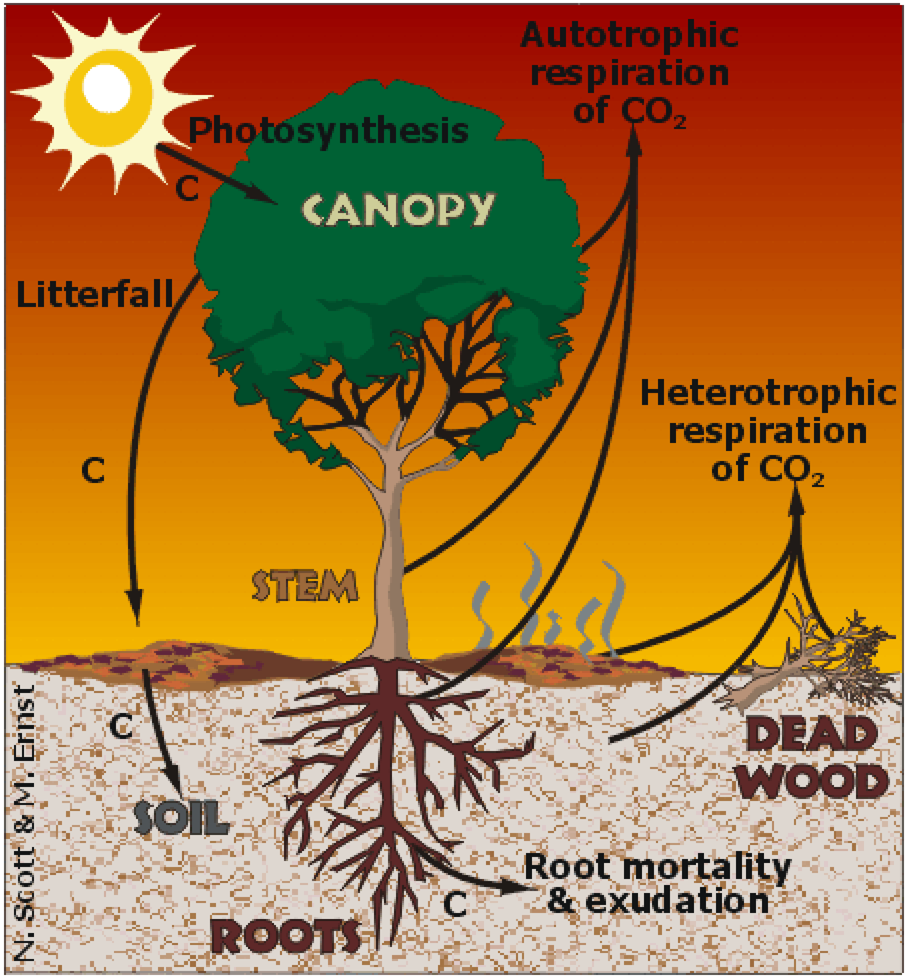
Fundamental properties of the terrestrial carbon cycle



1. Photosynthesis as the primary C influx pathway
2. Compartmentalization,
3. Partitioning among pools
4. Donor-pool dominated carbon transfers
5. 1st-order kinetics of carbon transfers

Luo and Weng 2011 TREE

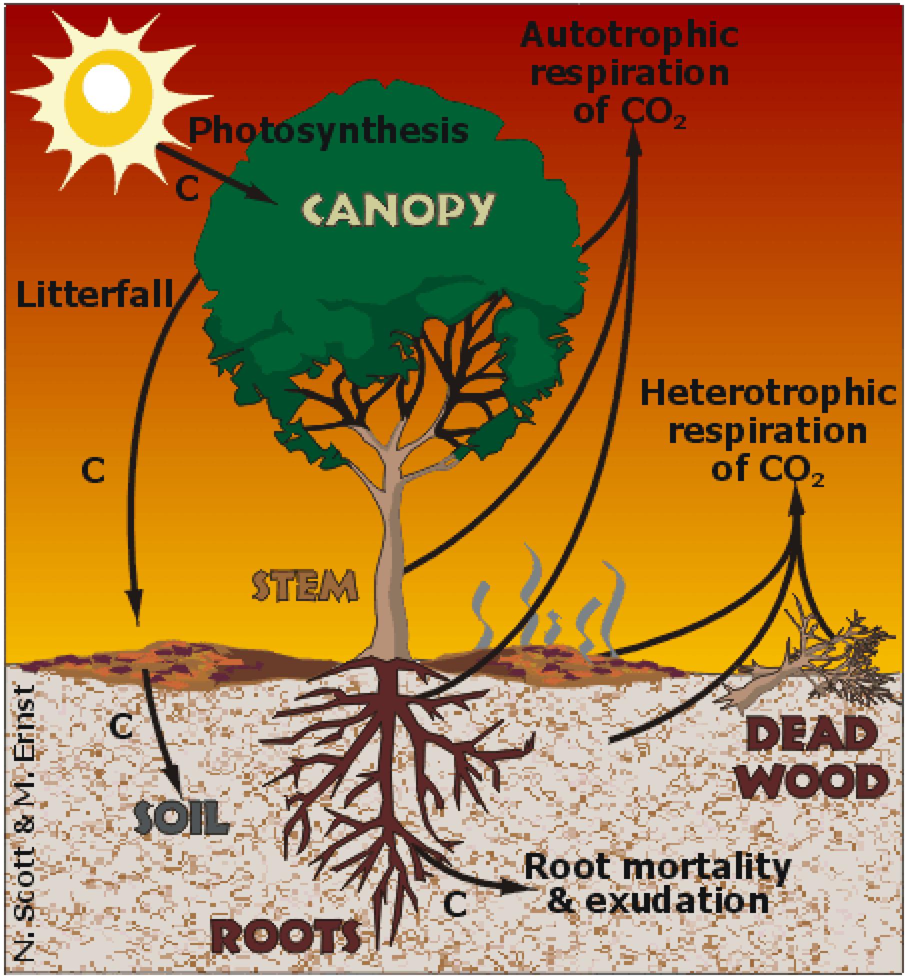
Fundamental properties of the terrestrial carbon cycle



1. Photosynthesis as the primary C influx pathway
2. Compartmentalization,
3. Partitioning among pools
4. Donor-pool dominated carbon transfers?
5. 1st-order kinetics of carbon transfers?

Luo and Weng 2011 TREE

Fundamental properties of the terrestrial carbon cycle



1. Photosynthesis as the primary C influx pathway
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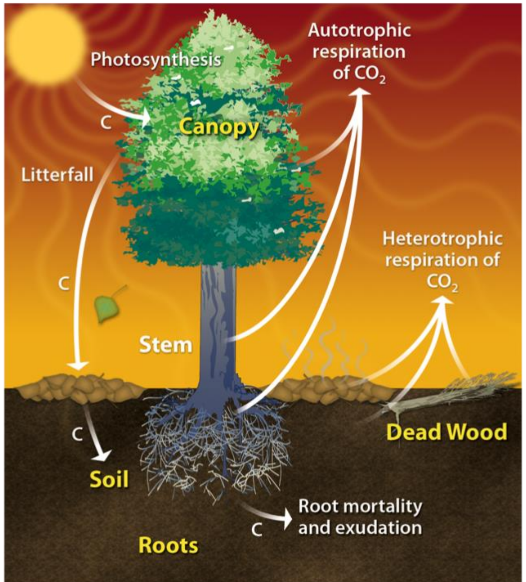
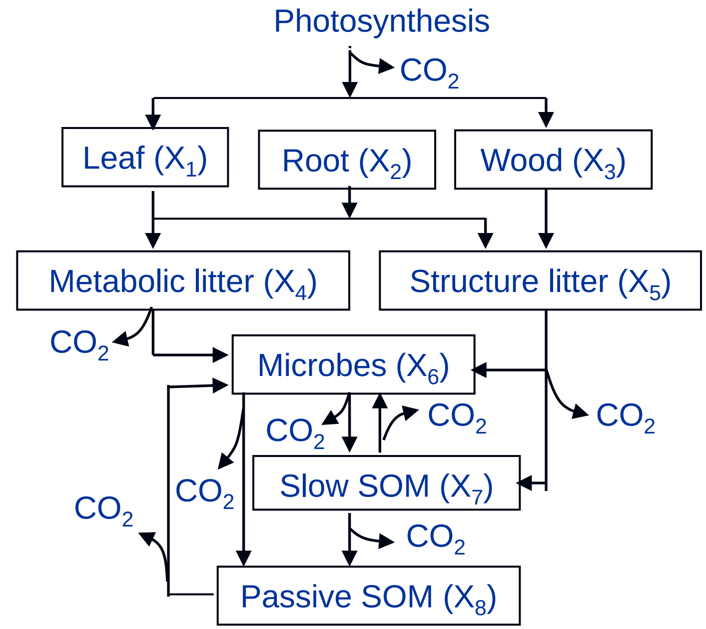
Luo and Weng 2011 TREE



A: Basic processes

Model development



B: Shared model structure

Encoding

C: Similar algorithm

$$
\text{Plant}\begin{cases}
dX_1(t)/dt = b_1U(t) - \xi c_1X_1(t) \\
dX_2(t)/dt = b_2U(t) - \xi c_2X_2(t) \\
dX_3(t)/dt = b_3U(t) - \xi c_3X_3(t)
\end{cases}
$$

$$
\text{Litter}\begin{cases}
dX_4(t)/dt = \xi[c_1a_{41}x_1(t) + c_3a_{43}x_3(t) - c_4X_4(t)] \\
dX_5(t)/dt = \xi[c_1a_{51}x_1(t) + c_2x_2(t) + c_3a_{53}x_3(t) - c_5X_5(t)]
\end{cases}
$$

$$
\text{SOM}\begin{cases}
dX_6(t)/dt = \xi[c_4a_{64}x_4(t) + c_5a_{65}x_5(t) + c_7a_{67}x_7(t) + c_8a_{68}x_8(t) - c_6X_6(t)] \\
dX_7(t)/dt = \xi[c_5a_{75}x_5(t) + c_6a_{76}x_6(t) - c_7X_7(t)] \\
dX_8(t)/dt = \xi[c_6a_{86}x_6(t) + c_7a_{87}x_7(t) - c_8X_8(t)]
\end{cases}
$$

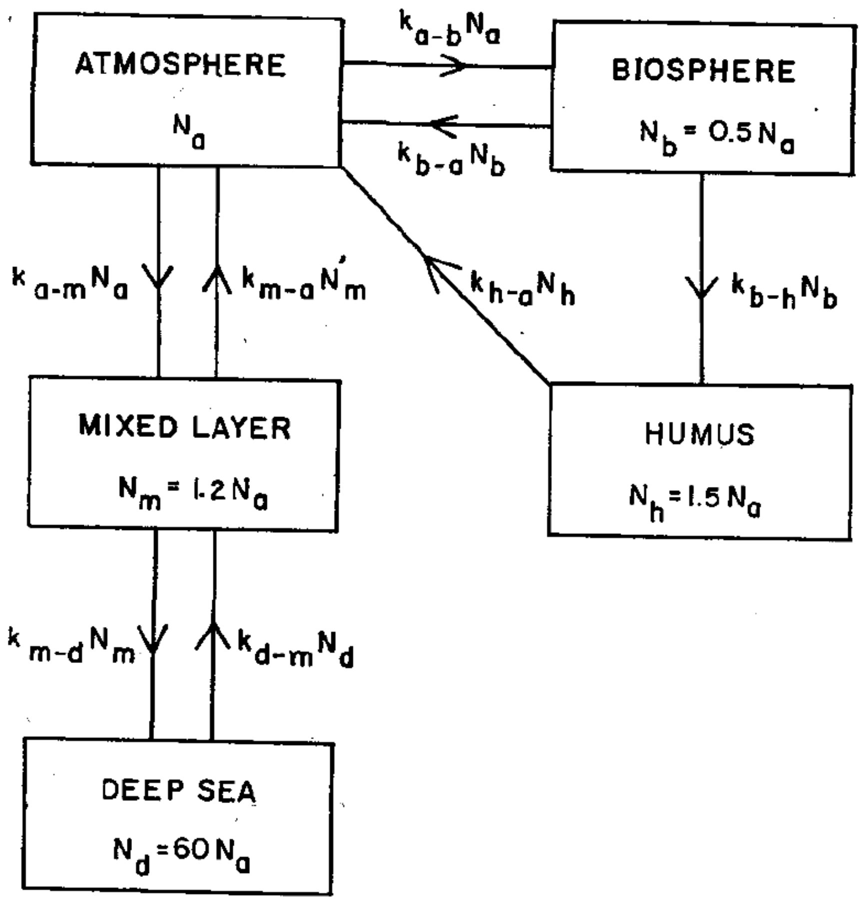
Generalization

D: General model

$$
\begin{cases}
\dfrac{dX(t)}{dt} = A\xi(t)CX(t) + BU(t) \\
X(t=0) = X_0
\end{cases}
$$

Luo et al. 2001 Ecol. Monog.
Luo et al. 2003 GBC
Luo and Weng 2011 TREE
Luo et al. 2015 GCB
Luo et al. under review

A long history of using matrix equations



Bolin & Eriksson, 1958;
Emanuel et al., 1981

Major issue

$$\begin{cases} \frac{dX(t)}{dt} = Ax(t)CX(t) + BU(t) \\ X(t=0) = X_0 \end{cases}$$

If the carbon cycle mathematically is an extremely simple system,

- Why is the natural phenomenon so complex?

Investigative Workshop

Jim Cushing: Nonautonomous system

Nonautonomous system

A dynamical system with its input and parameters being time dependent

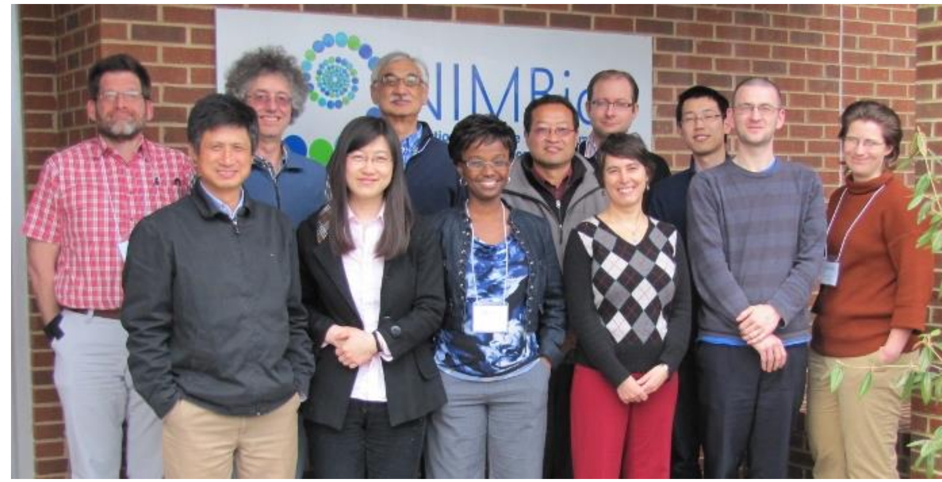
$$\begin{cases} \dfrac{dX(t)}{dt} = Ax(t)CX(t) + BU(t) \\ X(t=0) = X_0 \end{cases}$$

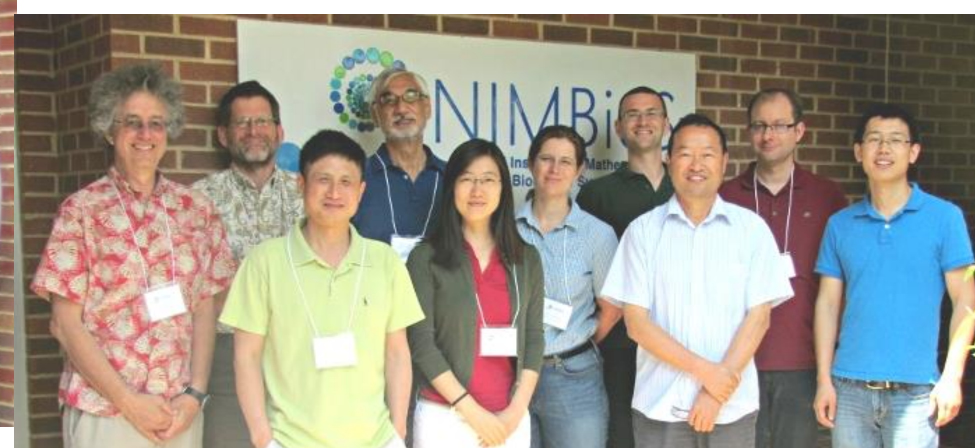
$U(t)$ is input, which is time dependent

Parameters $x(t)$ and $B(t)$ are time dependent

NIMBioS
National Institute for Mathematical
and Biological Synthesis

Working group





External vs. internal components of carbon cycle dynamics

$$X'(t) = Ax(t)CX(t) + BU(t)$$

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

Instantaneous responses to external forcing

Internal capacity of equilibribration

Three advances

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

Advance 1: Emulator

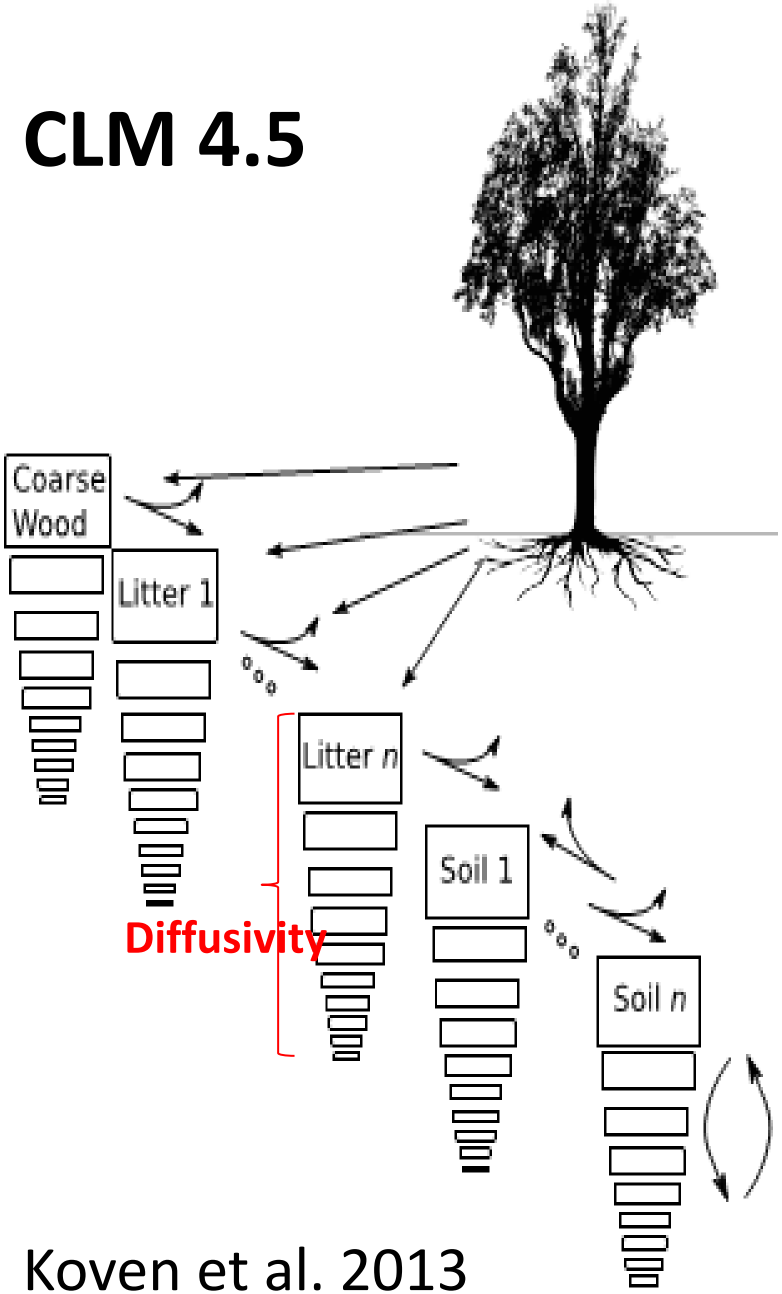
Input: GPP, temperature and precipitation

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

Exactly reproduce simulation output of original models

CLM 4.5

$$\frac{\partial C_i(z)}{\partial t} = R_i(z) + \sum_{j \neq i} (1 - r_j) T_{ji} k_j(z) C_j(z) - k_i(z) C_i(z) + \frac{\partial}{\partial z}\left(D(z)\frac{\partial C_i}{\partial z}\right)$$



Emulator

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

Shi et al. *in progress*

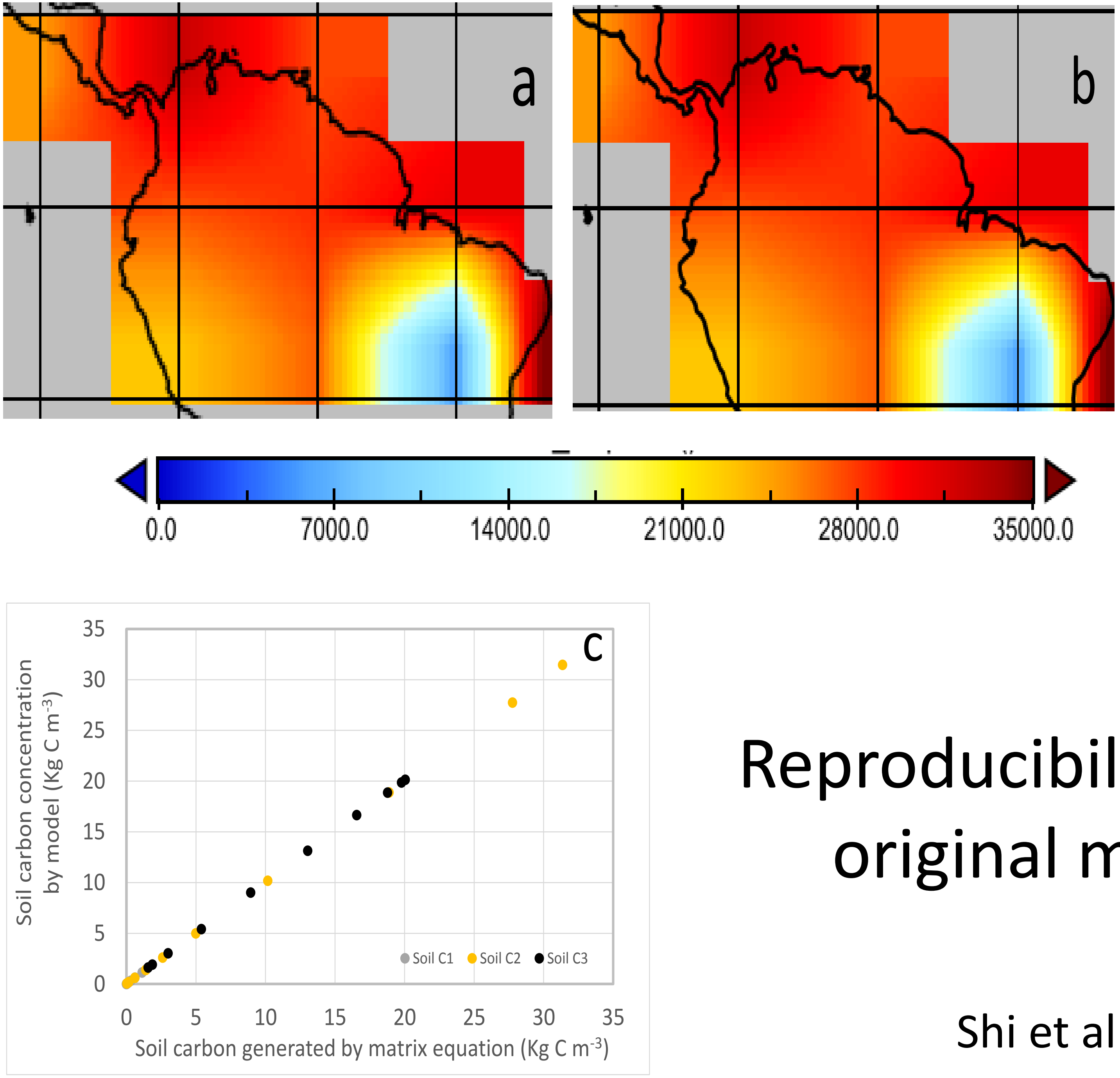
Koven et al. 2013
Oleson et al. 2013

A is a block diagonal transfer matrix with dimension 70 by 70 (7 C pools per soil layer for 10 layers).

$$A_{70\times70} = \begin{bmatrix} A_1 & & & & \\ & \cdots & & & \\ & & A_L & & \\ & & & \cdots & \\ & & & & A_{10} \end{bmatrix}, \text{ where } A_L = \begin{bmatrix} -1 & & & & & & \\ & -1 & & & & & \\ a_{3,1} & & -1 & & & & \\ a_{4,1} & & & -1 & & & \\ & a_{5,2} & a_{5,3} & & -1 & a_{5,6} & a_{4,7} \\ & & & a_{6,4} & a_{6,5} & -1 & \\ & & & & a_{7,5} & a_{7,6} & -1 \end{bmatrix}$$

A_L is a block matrix with L being the soil layers taking value from 1 to 10. $a_{i,j}$, is C transfer from i^{th} receiving pool from j^{th} donating pool

Shi et al. Unpublished

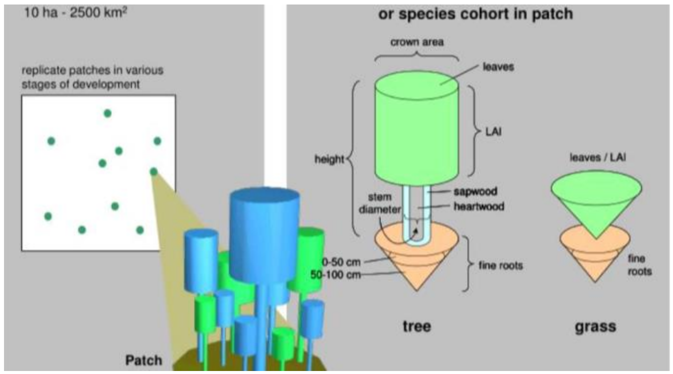


Reproducibility of the original models

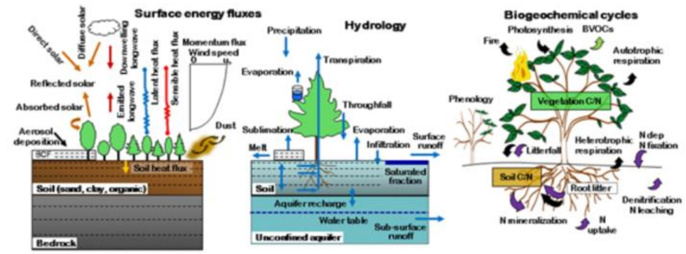
Shi et al. Unpublished

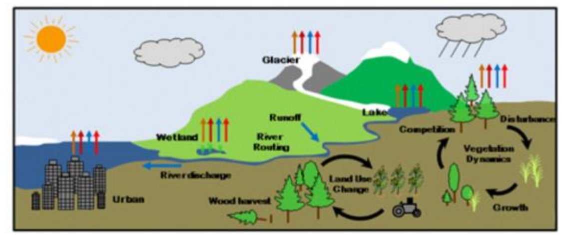
Emulators

LPJ-GUESS

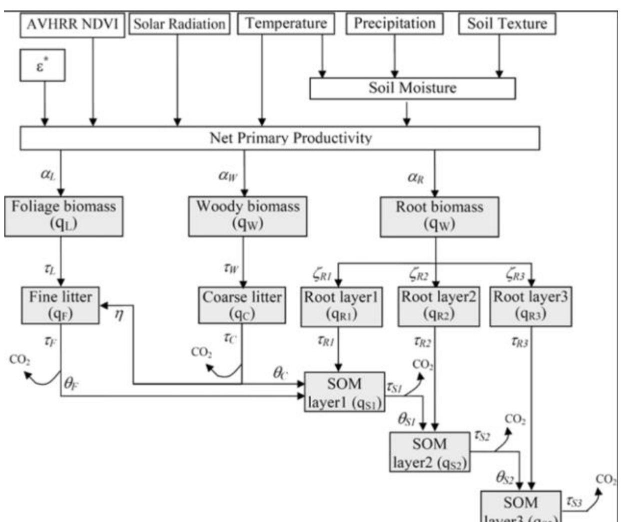


CLM 3.5, 4.0, 4.5

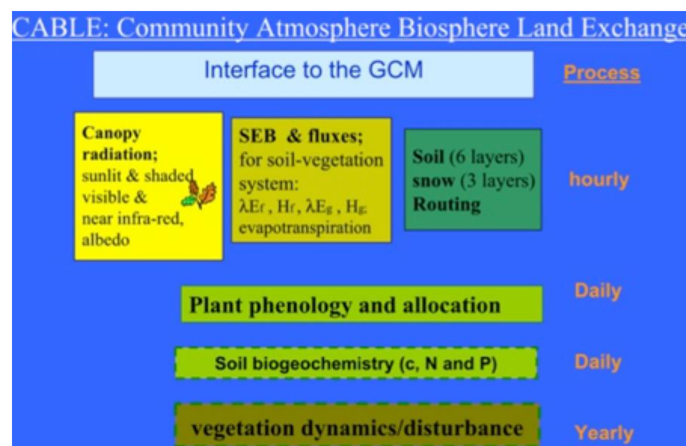




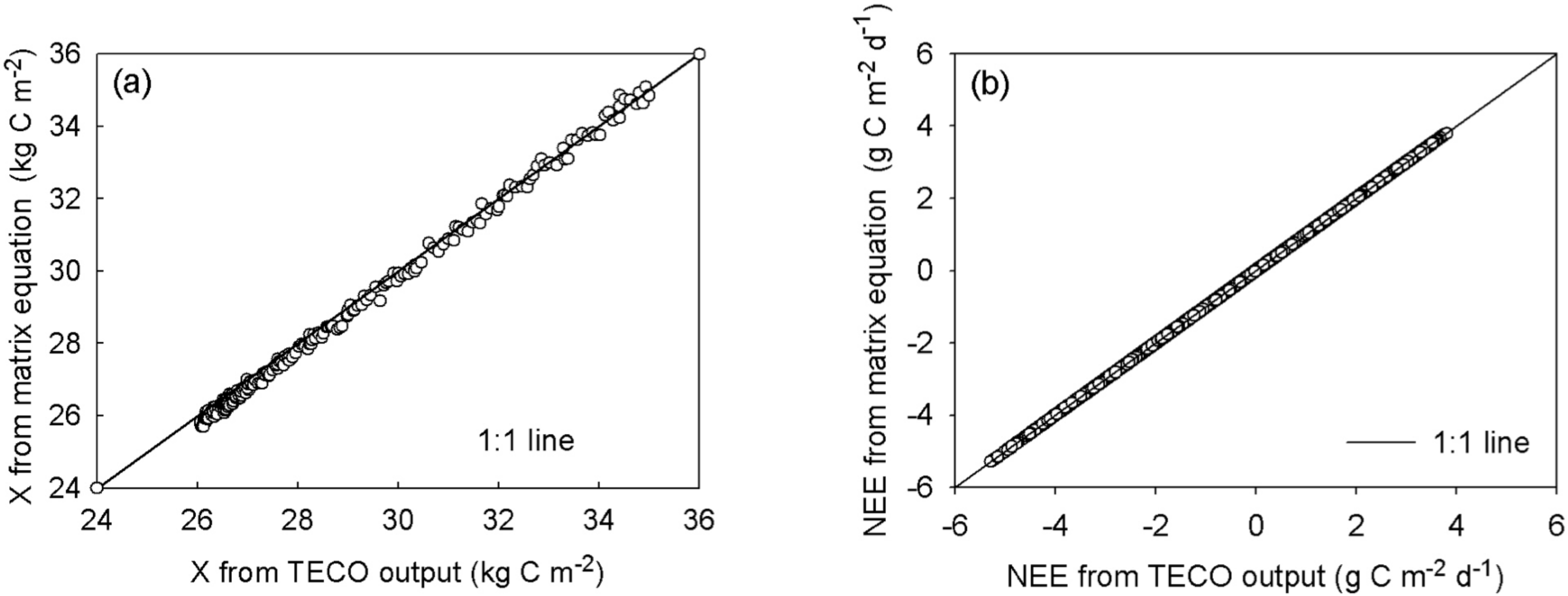
TECO



CABLE



100% reproducibility of the original models



Luo et al. under review

Advance 2: Nature of the terrestrial carbon cycle

External forcing	Terrestrial carbon cycle	Response
Periodic climate (e.g., seasonal)		Periodicity
Disturbance event (e.g. fire and land use)		Pulse-recovery
Climate change (e.g., rising CO_2)	$\begin{cases} \dfrac{dX(t)}{dt} = x(t)AX(t) + bU(t) \\ X(0) = X_0 \end{cases}$	Gradual change
Disturbance regime		disequilibrium
Ecosystem state change (e.g., tipping point)		Abrupt change

Complex phenomena of carbon cycle dynamics result from multiple environmental forcing variables interacting with relatively simple internal carbon cycle processes

Luo, Smith, and Keenan, 2015, GCB

Advance 3: The targeted quantity

- Carbon cycle research
- Government negotiation on carbon credicts
- Carbon trading

Transient dynamics = Capacity - Potential

$$X(t) = t_E(t)NPP(t) - X_p(t)$$

Two applications

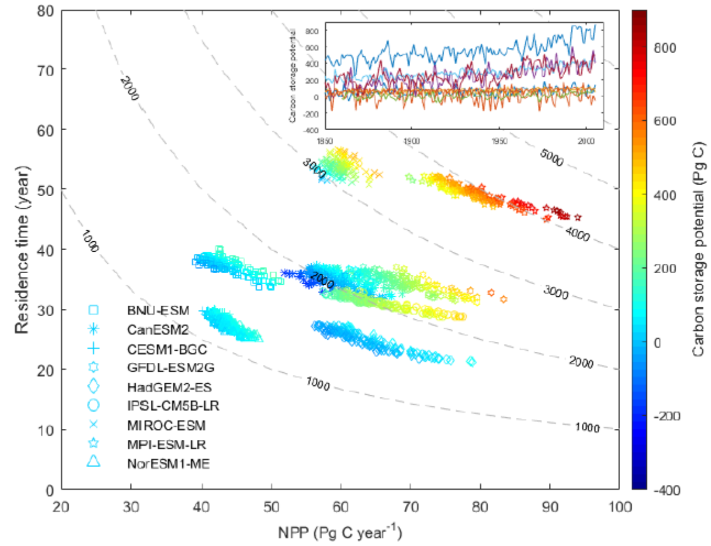
- Model evaluation
- Model improvement

3D parameter space

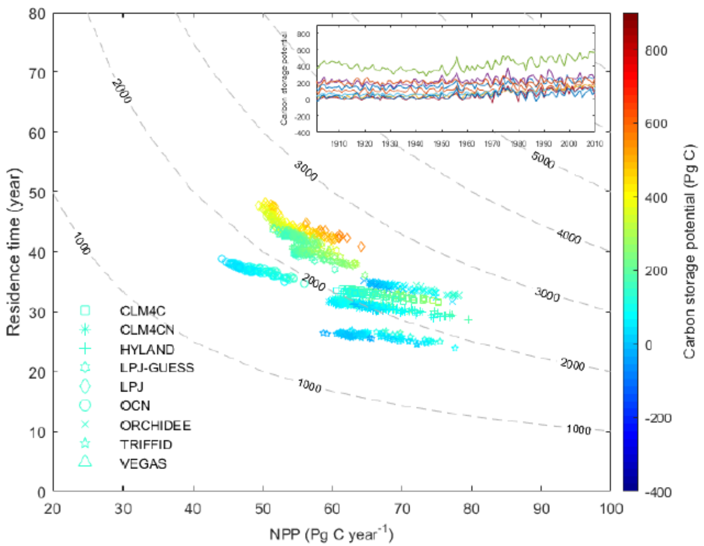
C storage dynamics = Capacity — Potential

$$X(t) = \tau_E(t)NPP(t) - X_p(t)$$

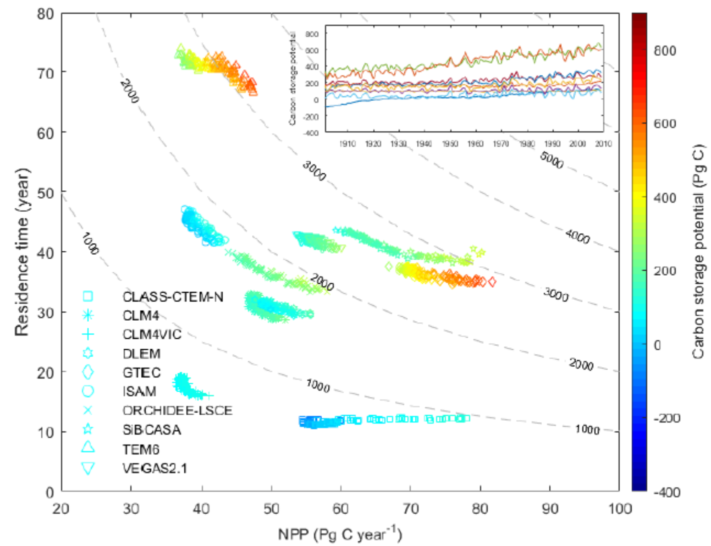
Residence time   C input



CMIP5



TRENDY



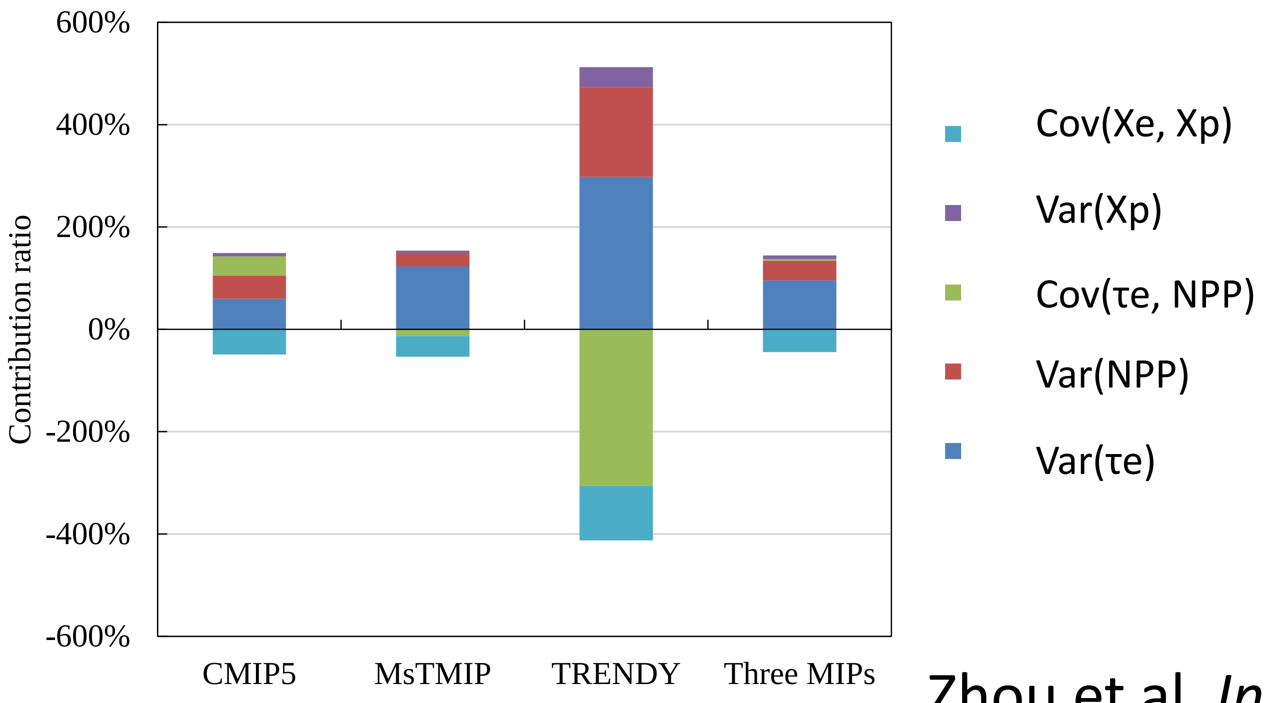
MsTMIP

Zhou et al. *In prep.*

Variance decomposition

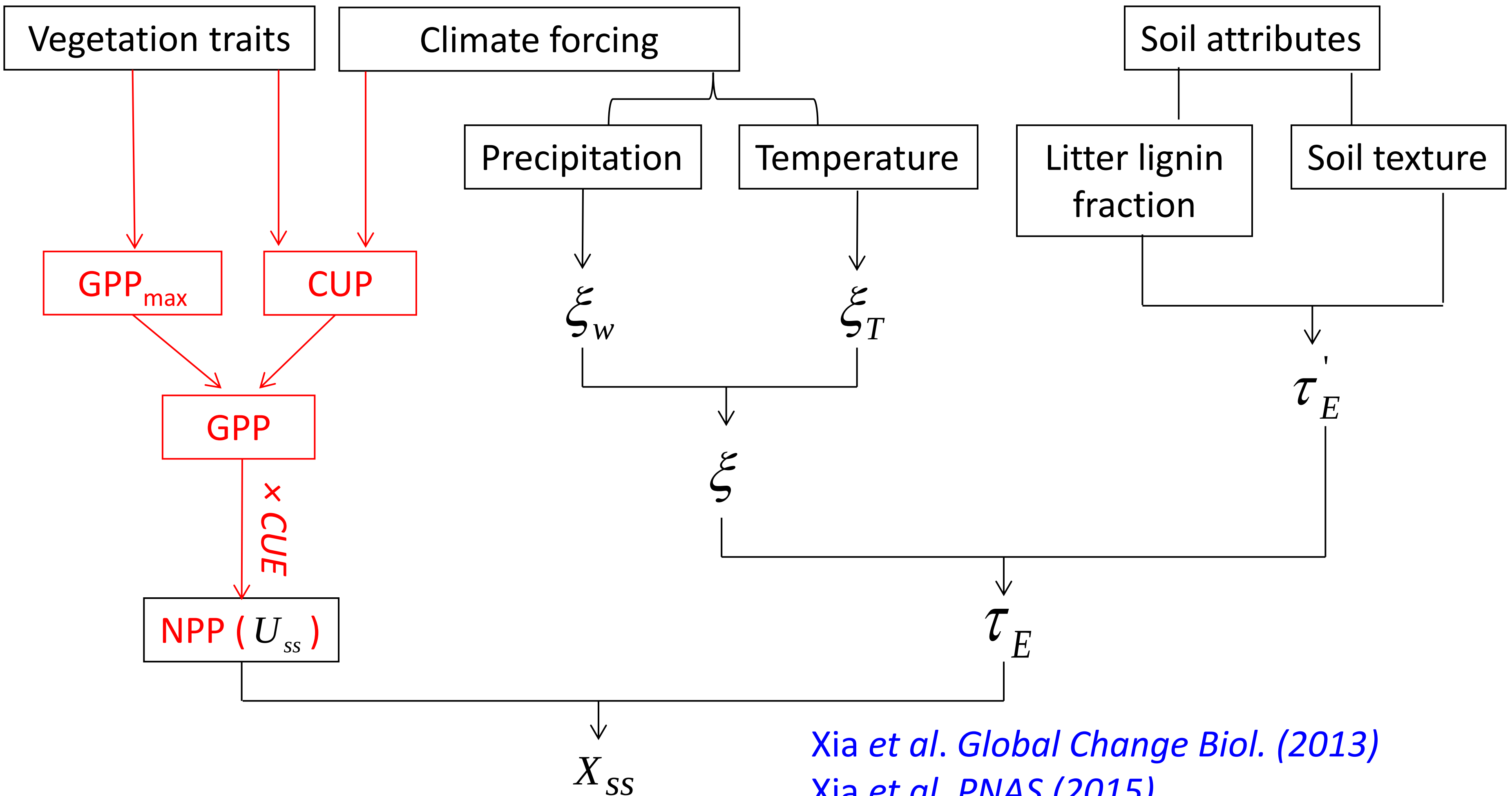
$$X = X_E - X_p; X_E = \tau_E * NPP$$

$$\sigma_X{}^2 = \widehat{\sigma_{\tau_E}}^2 + \widehat{\sigma_{NPP}}^2 + 2\widehat{\sigma_{\tau_E,NPP}} + \sigma_{X_p}{}^2 - 2\sigma_{X_E,X_p}$$



Zhou et al. *In prep.*

A traceability framework for terrestrial C cycle



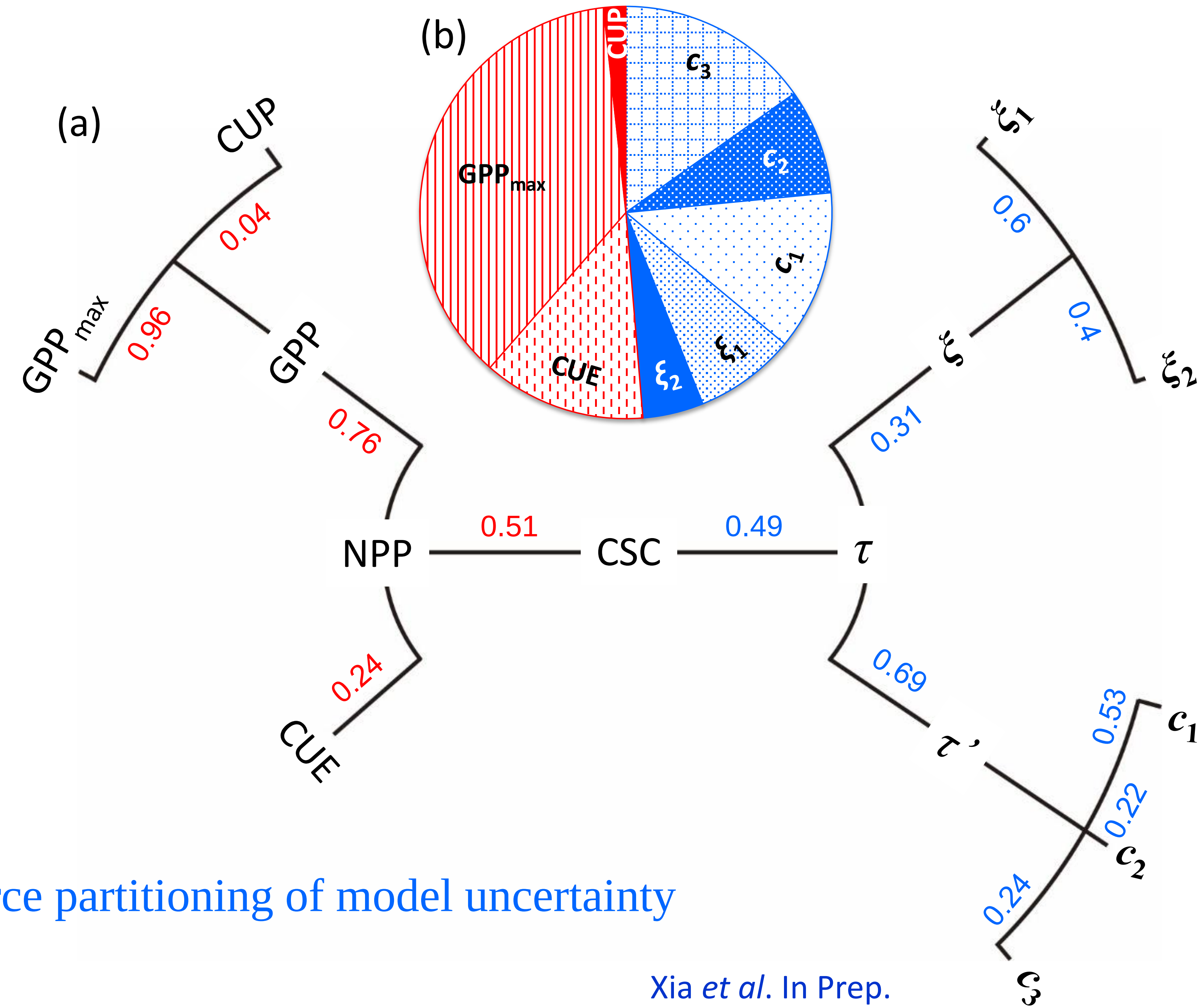
Xia *et al. Global Change Biol. (2013)*
Xia *et al. PNAS (2015)*
Luo *et al. Global Biogeochem. Cy.* (2016)

$\boldsymbol{\xi}$ – Environmental scalar on C decay rates

$\boldsymbol{\tau_E}$ – Ecosystem C residence time

$\boldsymbol{X_{ss}}$ – Ecosystem C storage capacity

CUE – C use efficiency as NPP/GPP



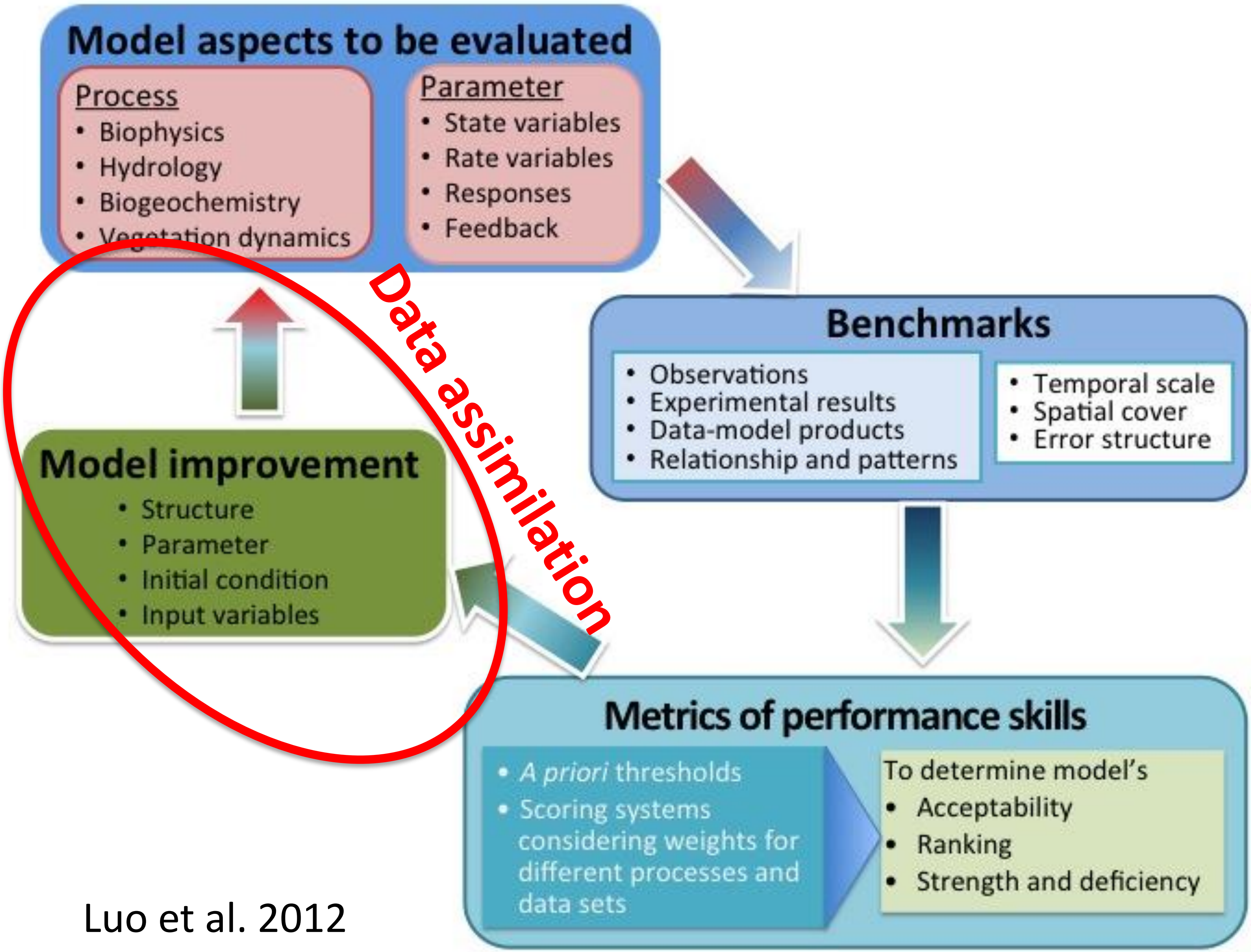
Source partitioning of model uncertainty

Xia *et al*. In Prep.

Model evaluations

- ***Minimal level*** Model outputs: GPP and residence time (τ_E) to estimate the equilibrium storage capacity (X_E) and the potential (X_p)
- ***Medium level*** Developing an emulator of your model to enable traceability analysis, parameter space, variance decomposition
- ***Ideal level*** Establishing a library of emulators of multiple models to allow various analyses

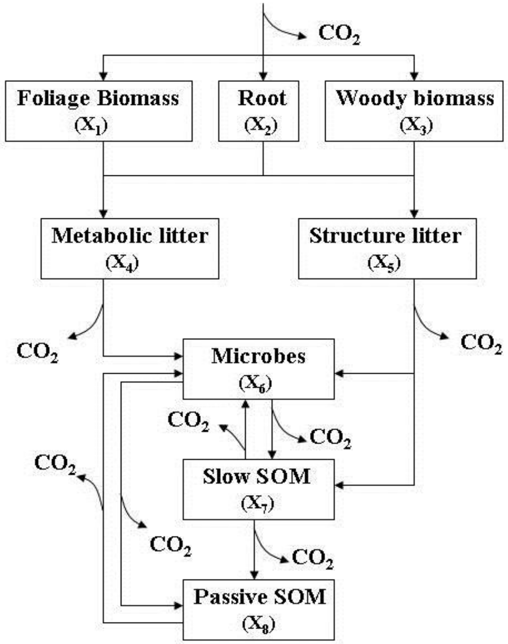
Application 2: Model improvement



Luo et al. 2012

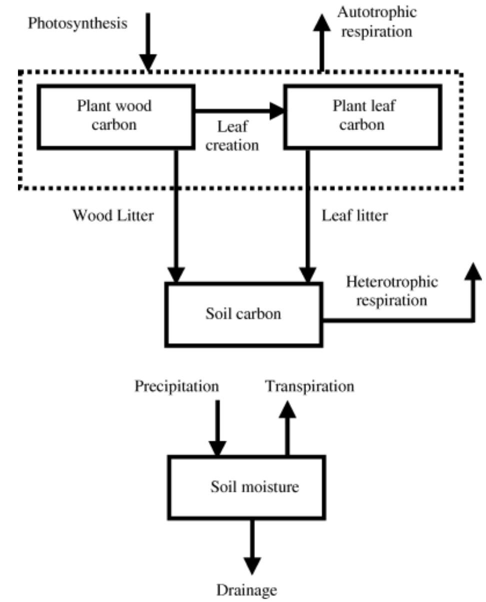
Simple but pool-based models

TECO

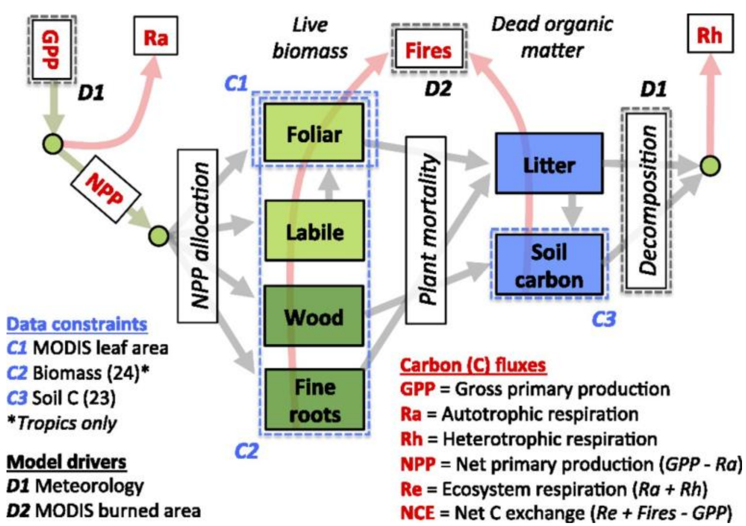


Luo lab

SIPNET

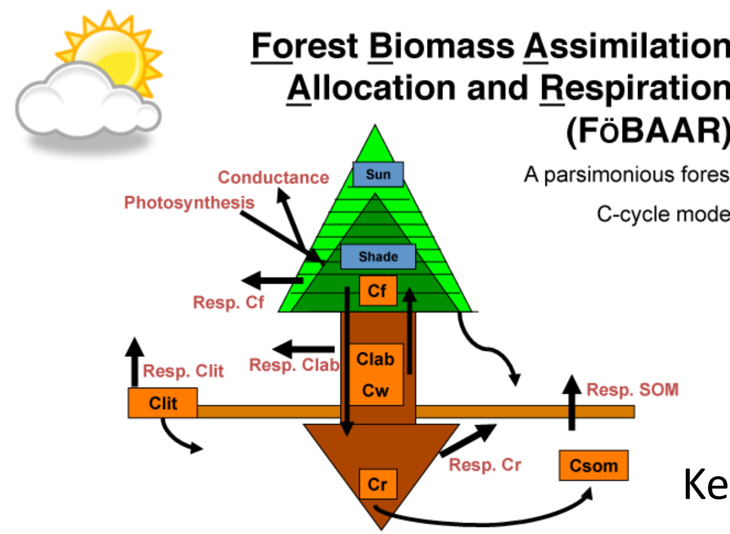


Rob Braswell



DELAC

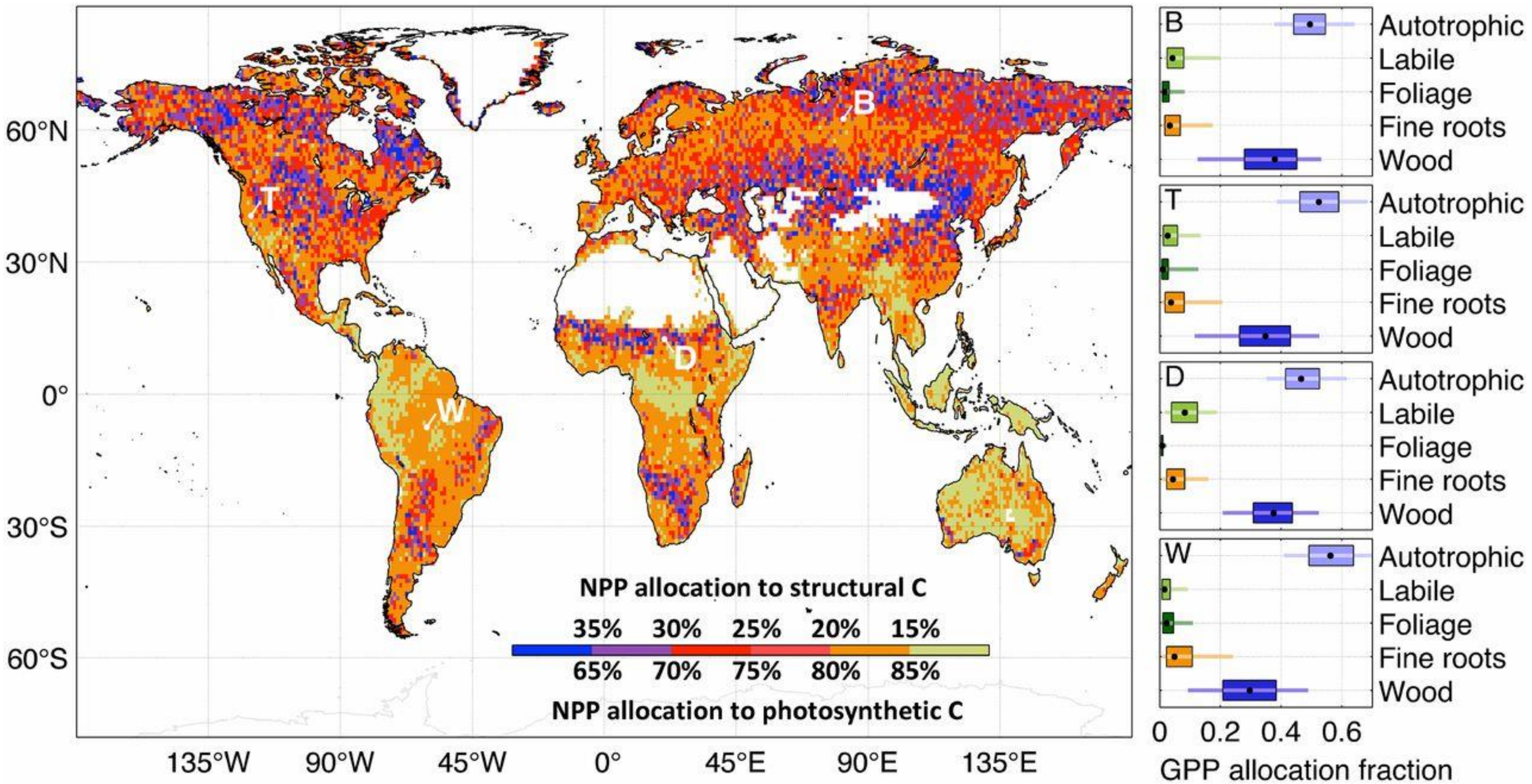
Williams lab



6 Pools, 29 Parameters, 3 dataset harmonization parameters = 38 p's optimized

Kenan

Retrievals of NPP allocation to structural (wood and fine roots) and photosynthetic (labile and foliage) C pools.



A. Anthony Bloom et al. PNAS 2016;113:1285-1290

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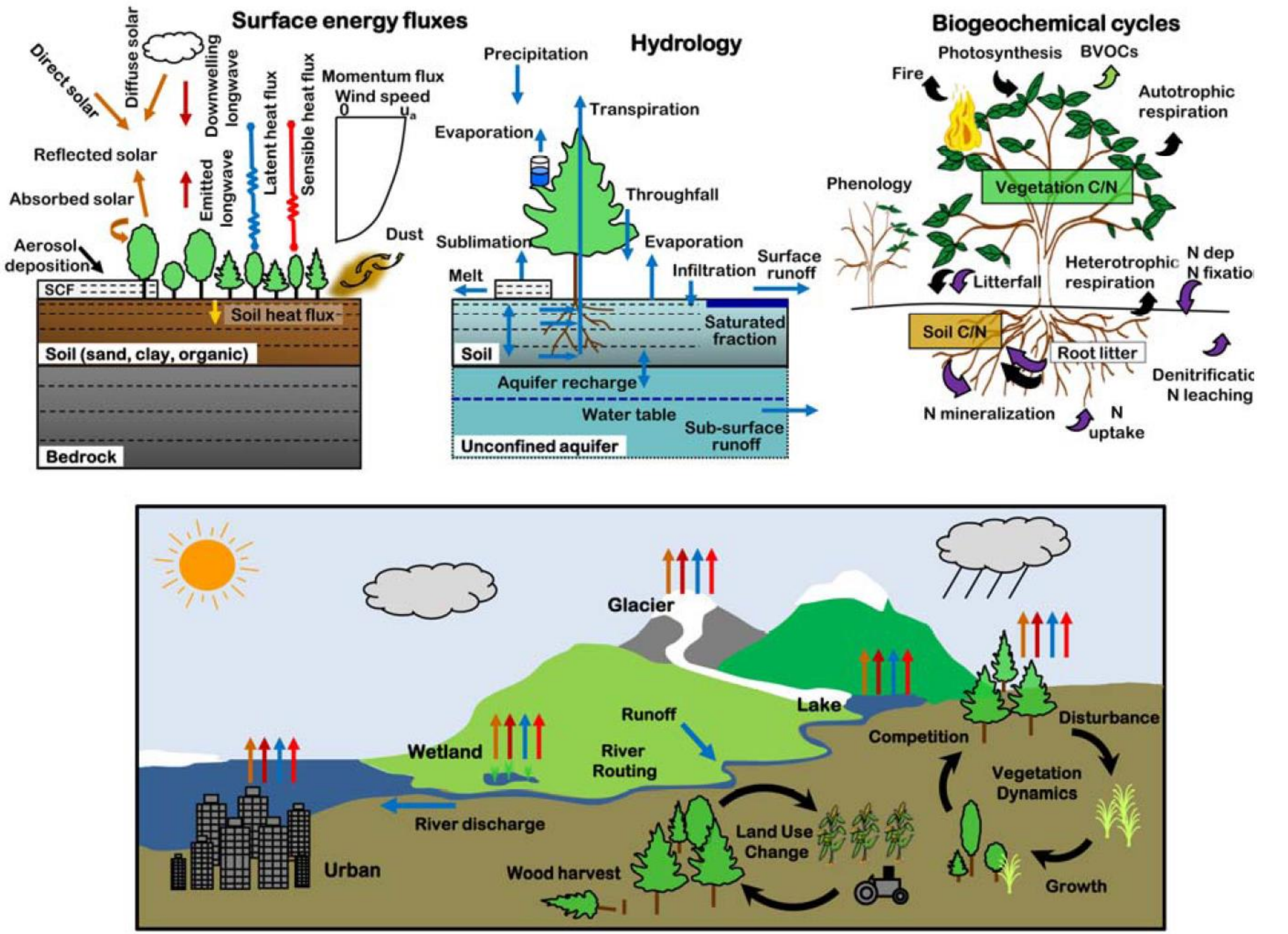
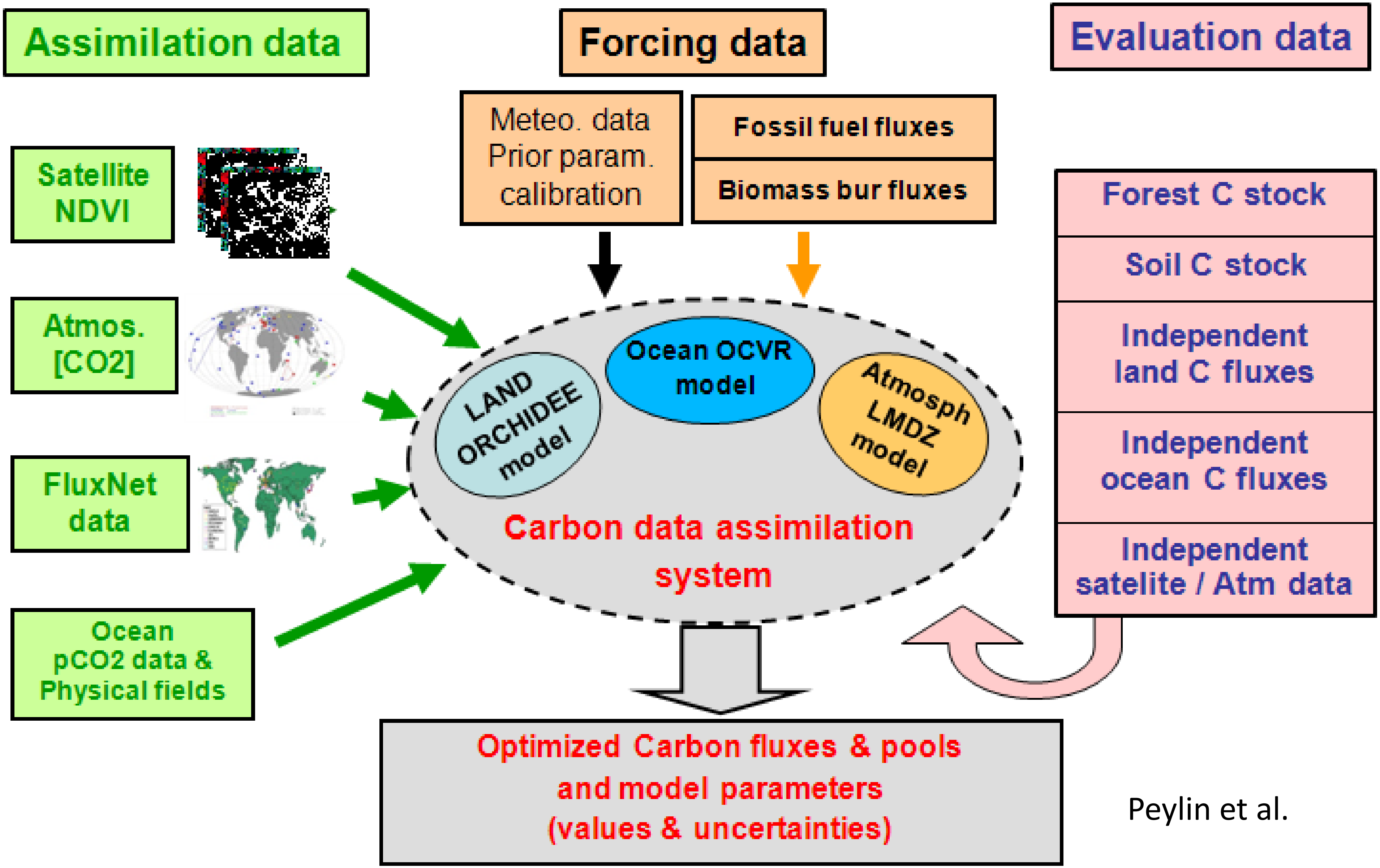
Community Land Model (CLM)

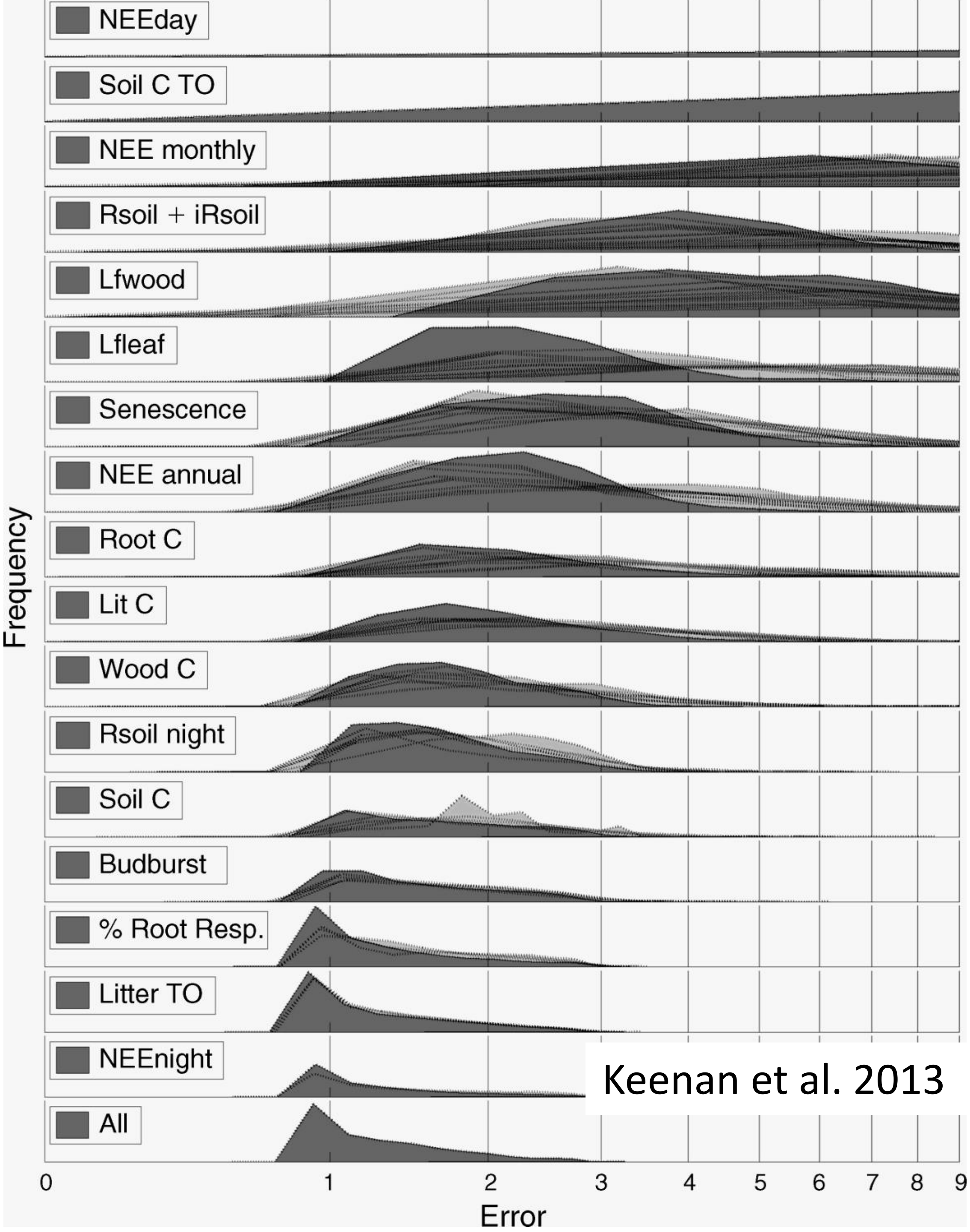


Lawrence et al. 2010

Carbon Cycle Data Assimilation System (CCDAS)



Peylin et al.

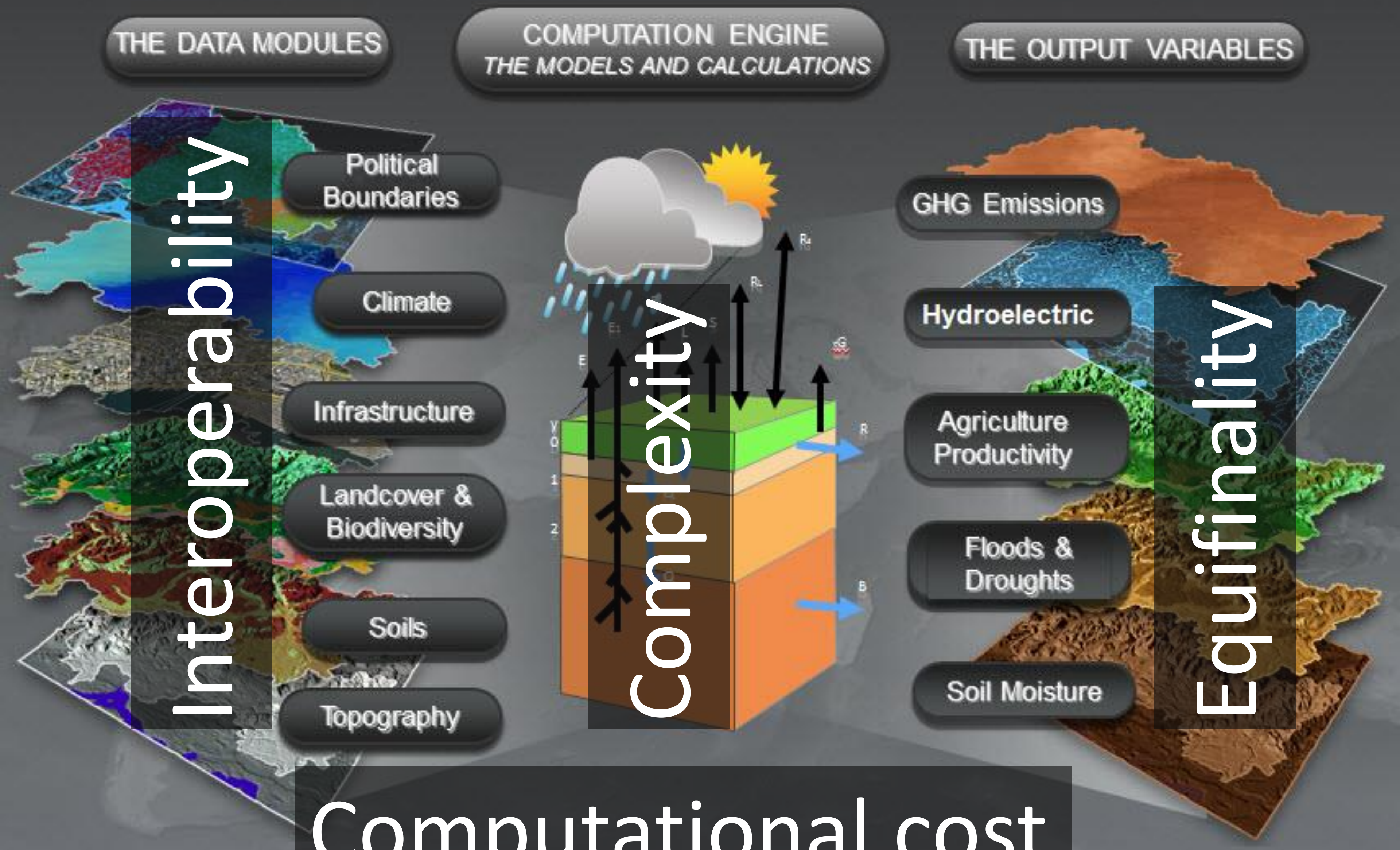


Flux data alone can not constrain turnover rates

When turnover rates are unconstrained, the models have low predictive skills.

Both pool- and flux-based data are needed to constrain global land models to improve their predictive skills.

Earth system modeling



Computational cost

BDBM challenges

Issue	Challenge	Innovation
Model complexity	Low tractability	
Global optimization	Computational cost	
Numerous parameters	Equifinality	
Heterogeneous datasets	Interoperatbility	

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

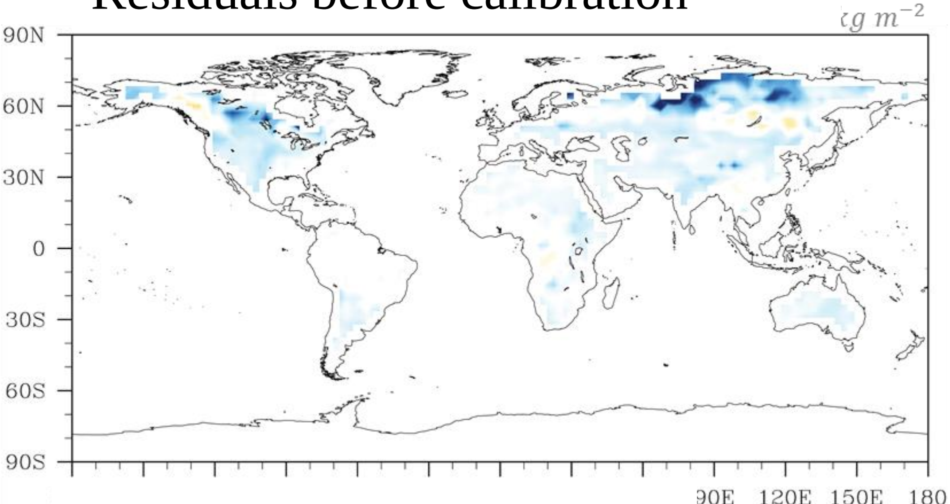
Our approaches to BDBM challenges

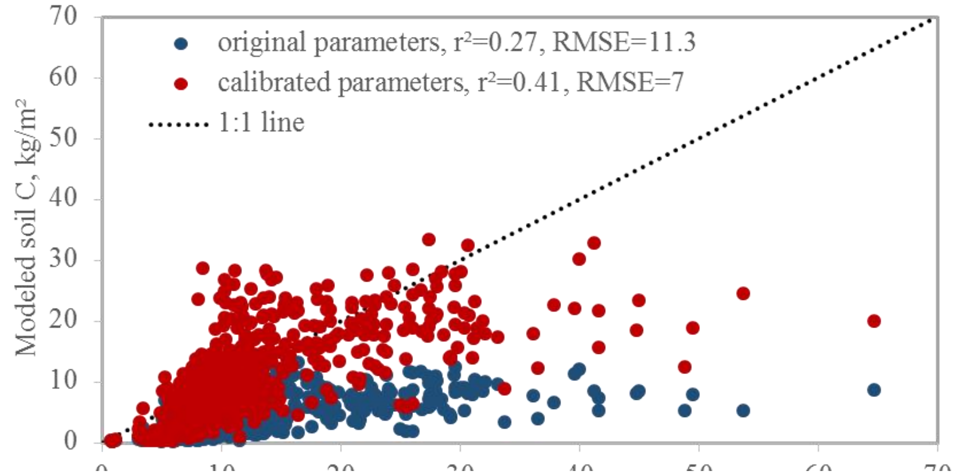
Issue	Challenge	Innovation
Model complexity	Low tractability	Traceability
Global optimization	Computational cost	High-fidelity emulator
Numerous parameters	Equifinality	Many datasets
Heterogeneous datasets	Interoperatbility	Various data assimilation strategies

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

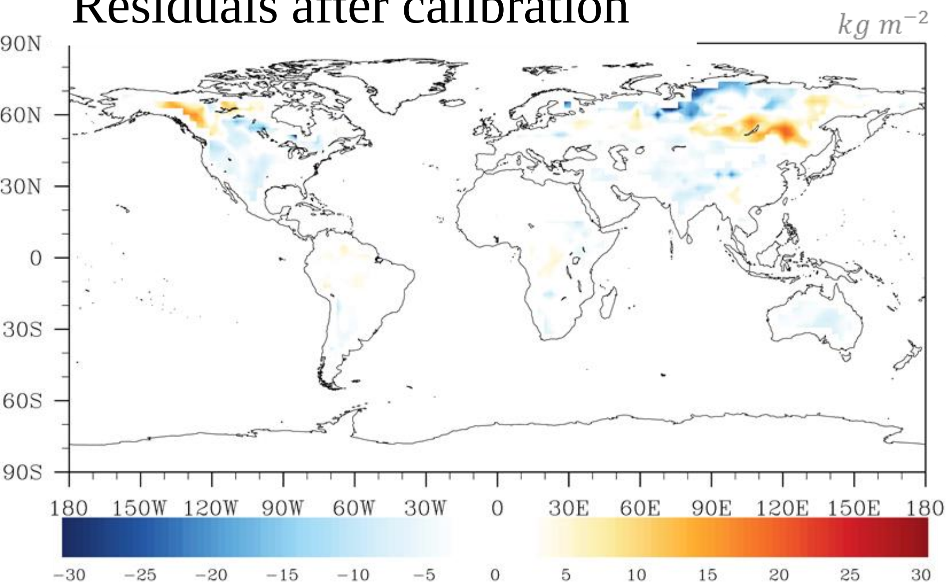
Improvement of soil C modeling

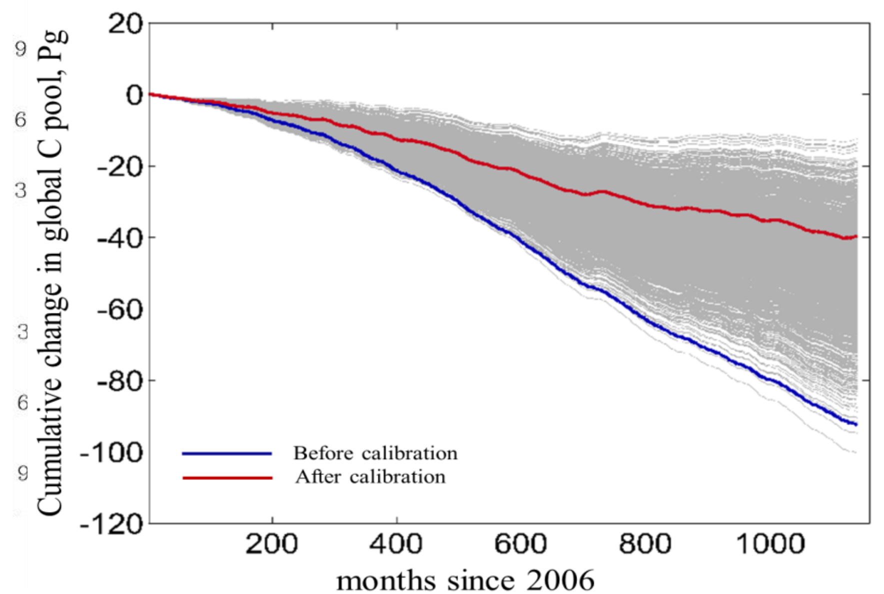
Residuals before calibration





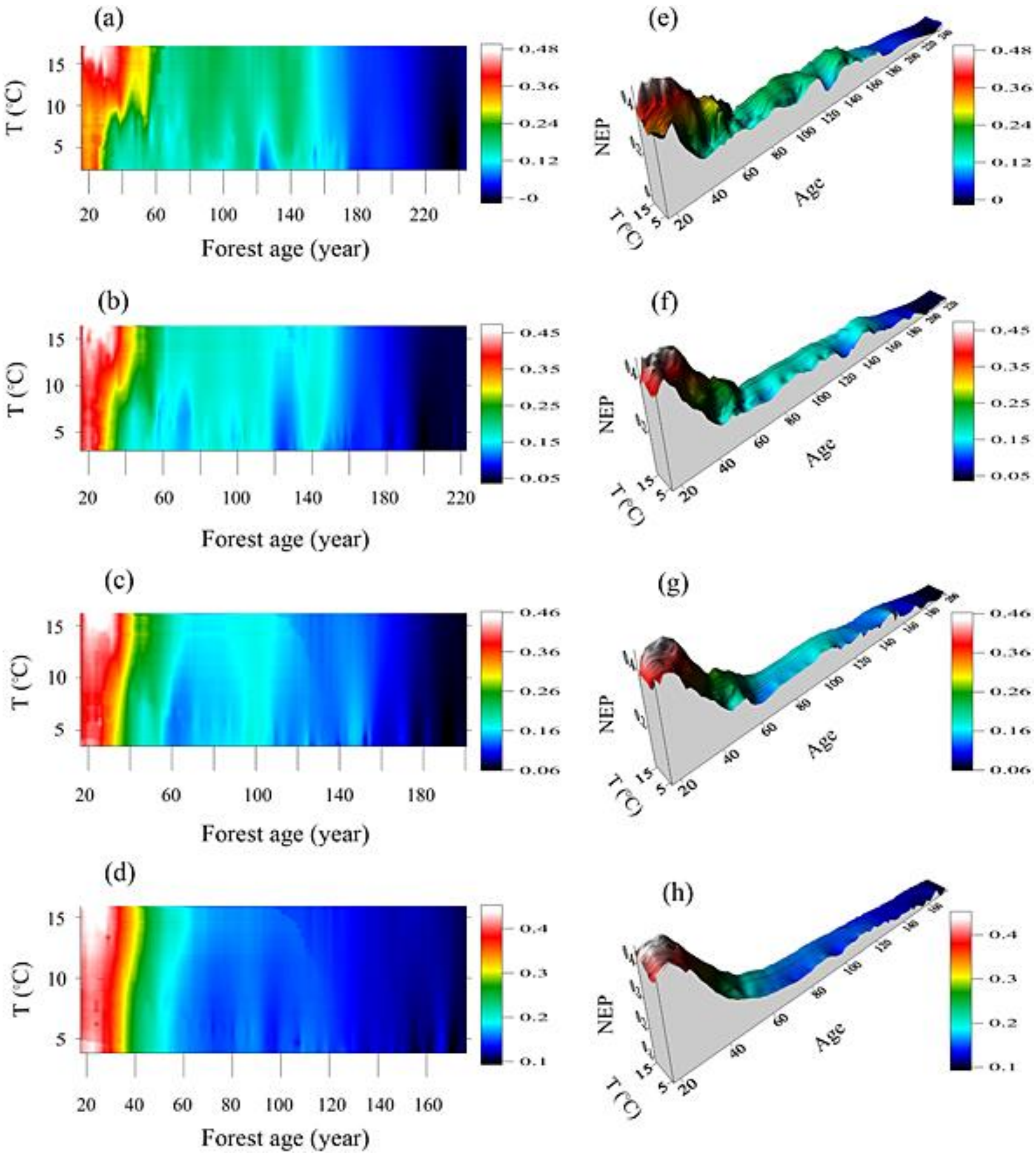
Residuals after calibration





RESIDUALS DECREASED, SPATIAL REPRESENTATION IMPROVED

HARARUK ET AL., 2014, *JGR*



Age-dependent forest carbon sink

Zhou et al. 2015 JGR-Biogeosciences

Summary

- A theoretical framework of carbon storage

  $$X(t) = Xe(t) - Xp(t)$$

- High-fidelity emulators of carbon cycle models
  - Model evaluation via 3D parameter space, traceability framework, variance decomposition
  - Model improvement via semi-analytic spin-up and data assimilation
  - Model development via component evaluation

Recommendations

- ***Tier 1*** Model outputs: GPP, τ_E, X_E, X_p to allow analytic model evaluation
- ***Tier 2*** Developing an emulator for your model to enable analytic spin-up, traceability, parameter space, variance decomposition, and data assimilation
- ***Tier 3*** Establishing a library (farm, zoo) of emulators to allow various analyses

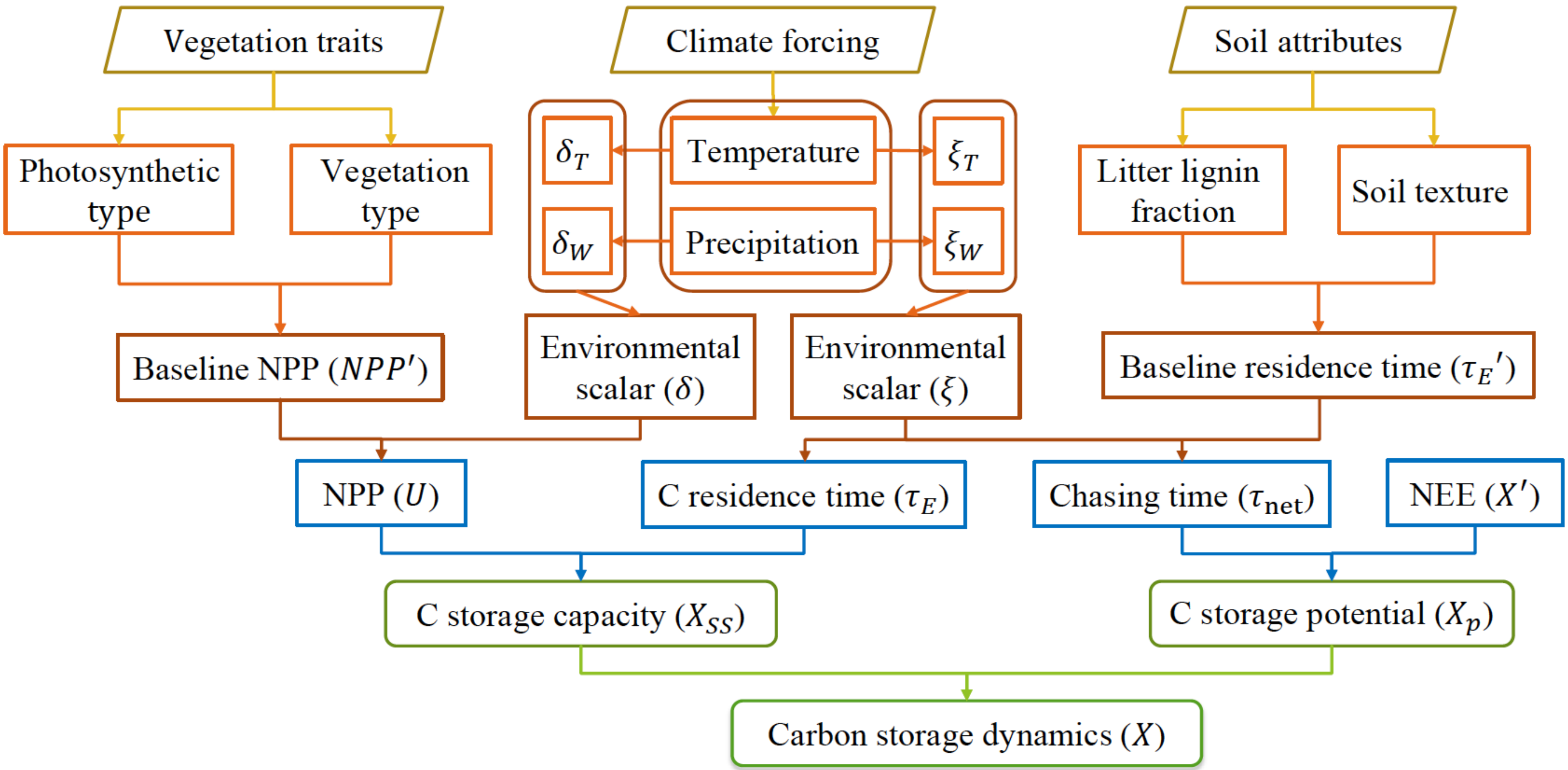
Matrix equation

$$X(t) = X_E(t) - X_p(t)$$

$$X(t) = t_E(t)NPP(t) - X_p(t)$$

$$X(t) = (A\xi(t)K)^{-1}Bu(t) - (A\xi(t)K)^{-1}X'(t)$$

The traceability framework



Lu et al. *In prep.*
Zhou et al. *In prep.*