Linking Plant Functional Traits and Carbon Processes to Evaluate Terrestrial Biosphere Models Based on A Traceability Framework

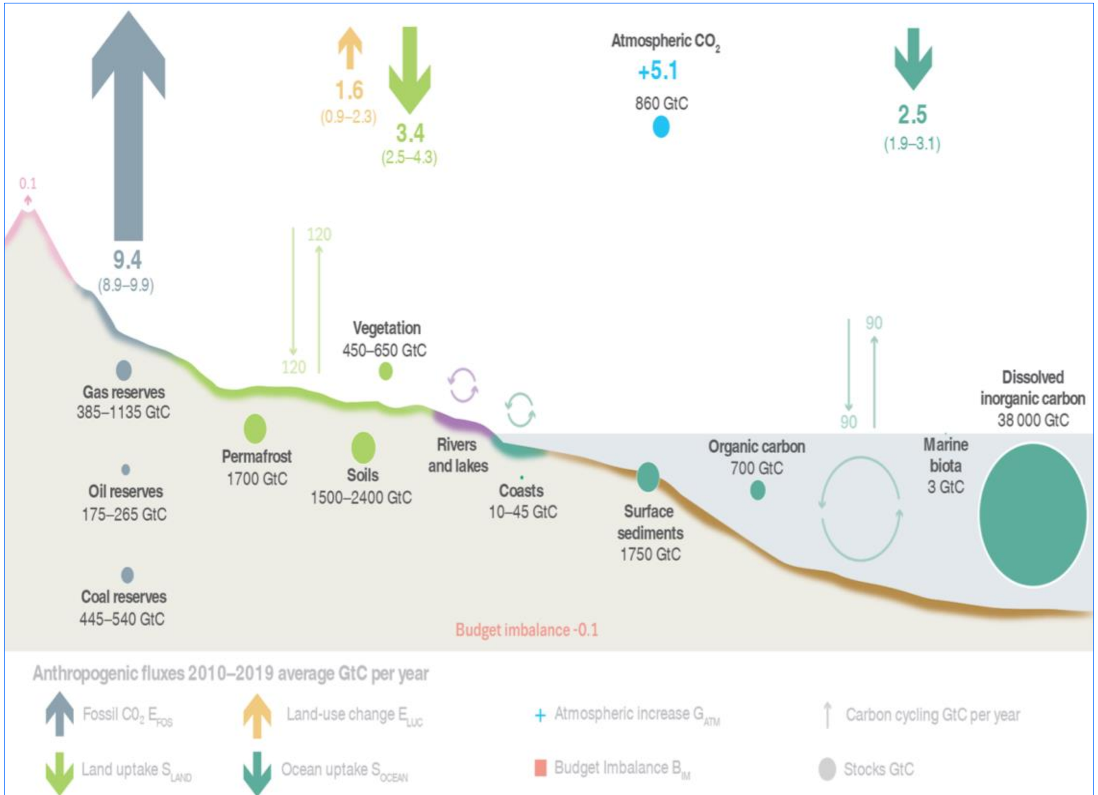
Jianyang Xia[1], Erqian Cui[1], Jian Zhou[1], Chengyu Bian[1], Ning Wei[1], Ying-ping Wang[2], Yiqi Luo[3], MsTMIP & CMIP modelers

[1] School of Ecological and Environmental Sciences, East China Normal University (Shanghai, CN)
[2] CSIRO Oceans and Atmosphere (Victoria, AU)
[3] Center for Ecosystem Science and Society, Northern Arizona University (Flagstaff, US)

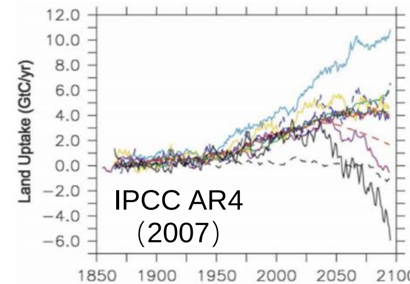
August 20, 2021

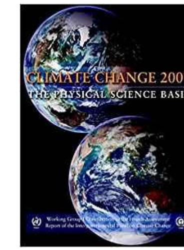
Challenge:

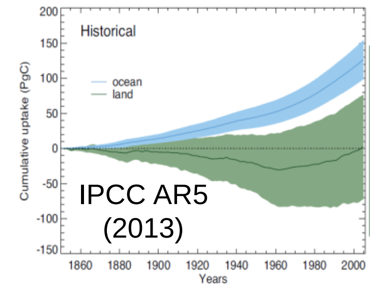
Large uncertainty of land C cycle in Earth system models

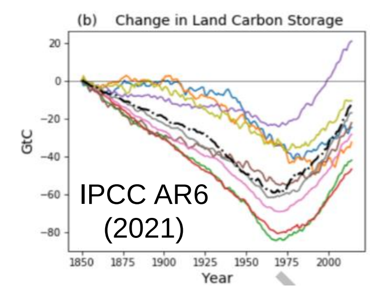


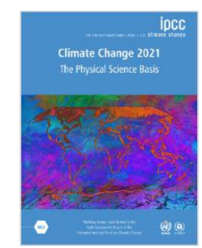
Friedlingstein *et al.*, 2020 *ESD*











ILAMB in IPCC AR6:

Improved model performance on land C cycle from CMIP5 to CMIP6

(a) Land Benchmarking Results	CMIP5 ESMs									CMIP6 ESMs										
	bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	NorESM1-ME	HadGEM2-ES	BCC-CSM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL	Mean CMIP5	Mean CMIP6
Land Ecosystem & Carbon Cycle	-0.72	-0.93	-1.55	-1.51	-0.13	0.60	-0.43	-1.31	0.19	-0.43	0.66	0.48	-1.09	0.22	0.60	-0.07	1.00	0.49	1.63	2.30
Biomass	0.20	-0.45	-1.52	-0.40	-1.26	-0.26	-1.07	-1.77	0.92	1.39	0.74	-0.20	-0.54	0.16	0.93	-0.96	-0.01	1.04	1.23	1.82
Burned Area			-0.87				0.10	-0.83				1.60								
Leaf Area Index	-0.20	-0.64	-1.30	-2.53	-0.01	0.30	0.01	-1.85	-0.16	0.27	0.08	0.34	-0.70	1.19	0.82	0.46	0.37	0.69	1.04	1.81
Soil Carbon	0.27	1.26	-1.46	0.07	0.75	0.47	-0.03	-1.14	0.07	0.23	1.35	-0.99	-2.04	-1.55	0.90	-0.75	-0.17	0.24	1.01	1.48
Gross Primary Productivity	0.59	-1.23	0.01	-1.81	-1.40	0.29	-0.53	-0.24	-1.04	0.77	0.04	0.59	-0.38	1.17	-1.02	-0.37	0.73	0.09	1.51	2.22
Net Ecosystem Exchange	-0.42	-1.81	-0.21	-0.65	1.10	-0.24	0.80	0.02	-1.03	-1.02	-1.19	0.59	1.69	-0.42	0.63	-0.21	1.08	-1.43	1.28	1.43
Ecosystem Respiration	0.90	-0.56	-0.86	-0.24	-1.35	0.99	-0.01	-0.94	-1.54	0.81	0.59	0.51	-0.79	0.90	-0.21	-1.24	0.43	-0.94	1.34	2.21
Carbon Dioxide		-1.54	-0.36	-2.92	-0.74	1.53	-0.00	0.37	0.85		0.42	0.26	0.39	0.59	1.10	-0.87	0.21	0.69	0.09	-0.07
Global Net Carbon Balance		-1.64	-0.88	-1.13	0.17	-0.31	-0.38	-0.50	0.24		-0.23	1.34	-1.70	0.17	-0.74	1.45	1.56	0.26	0.92	1.40

Model-Data difference:
Small improvements in net land C exchange

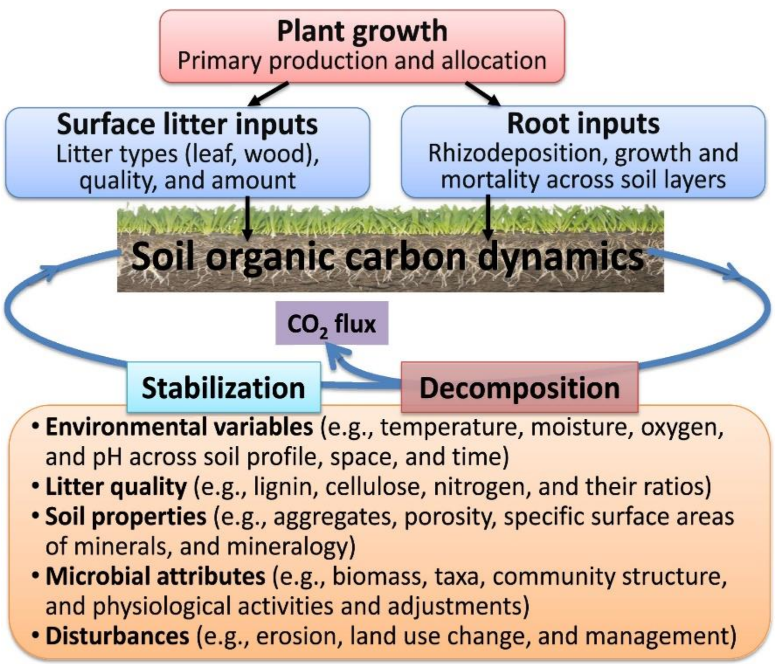
Inter-model difference:
Still large

IPCC AR6, 2021 *(Page 5-200)*

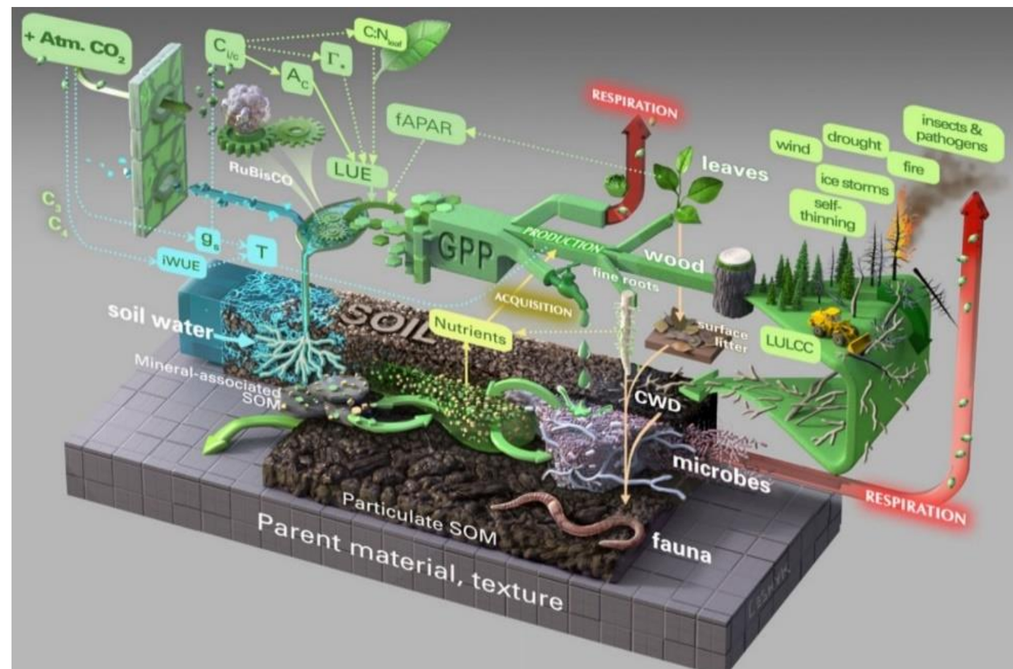
Further model improvements:

A better parameterization of carbon cycle processes

Plant functional traits are fundamental parameters in current global carbon-cycle models



Luo & Schuur. 2020 *GCB*



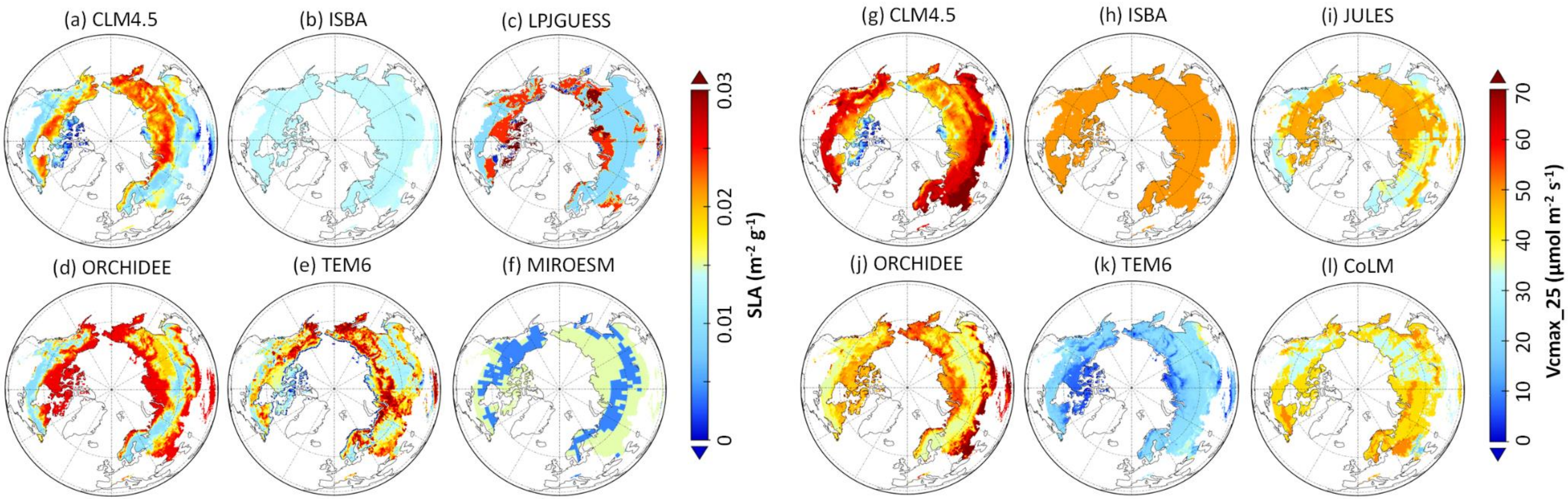
Walker *et al*. 2021 *New Phytologist*

Further model improvements:

A better parameterization of carbon cycle processes

↓

Key Question: Can we reduce the model uncertainty on land C cycle by an improved parameterization of plant functional traits?



Xia *et al*. 2017 *JGR Biogeosciences*

Further model improvements:

A better parameterization of carbon cycle processes

Key Question: Can we reduce the model uncertainty on land C cycle by an improved parameterization of plant functional traits?

Question 1

Can we link plant functional traits and land carbon cycle for model evaluation?

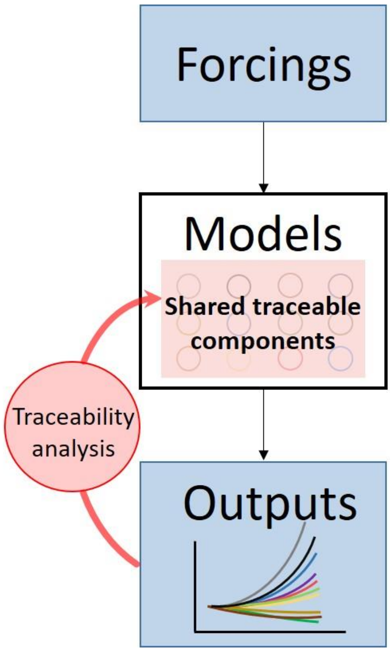
Question 2

How to improve model parameterization of plant functional traits based on data?

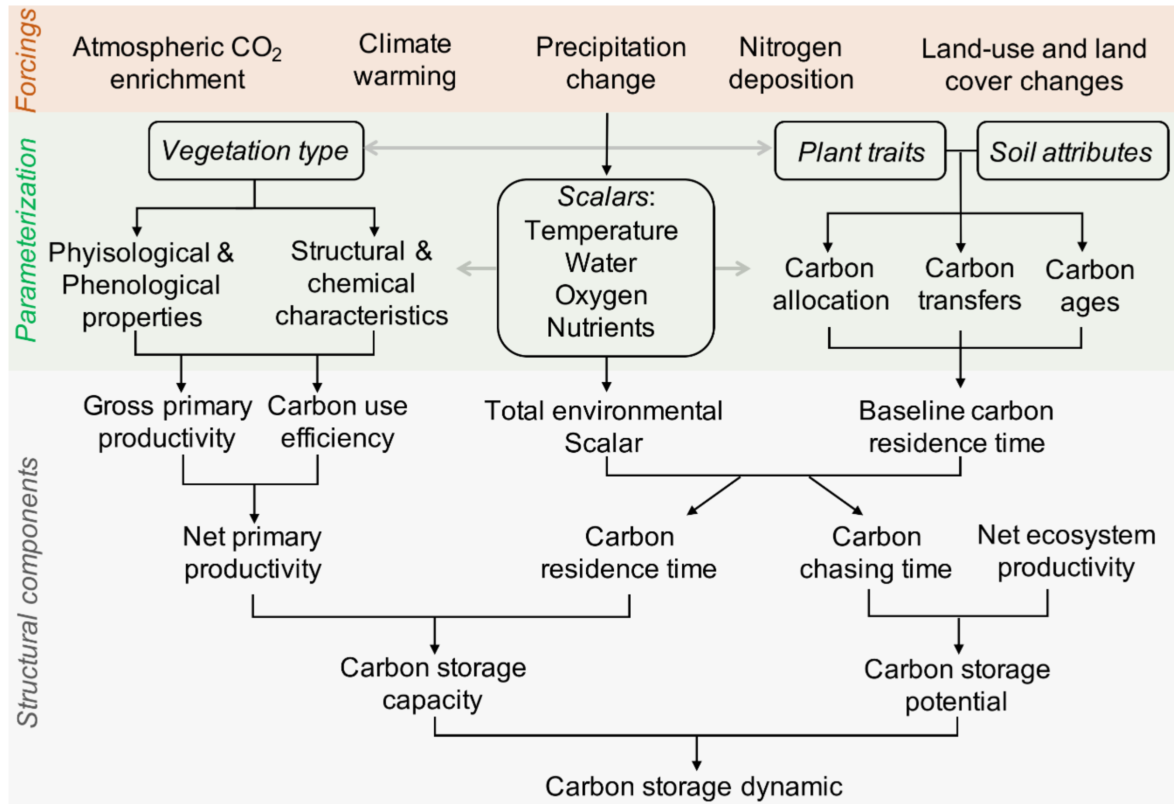
Question 1: Can we link the key plant functional traits to land carbon processes?

Tool: Traceability Analysis for Model Evaluation (TraceME)

$$\frac{d\mathbf{X}(t)}{dt} = u(t)\mathbf{B} - \boldsymbol{\xi}(t)\mathbf{ACX}(t)$$



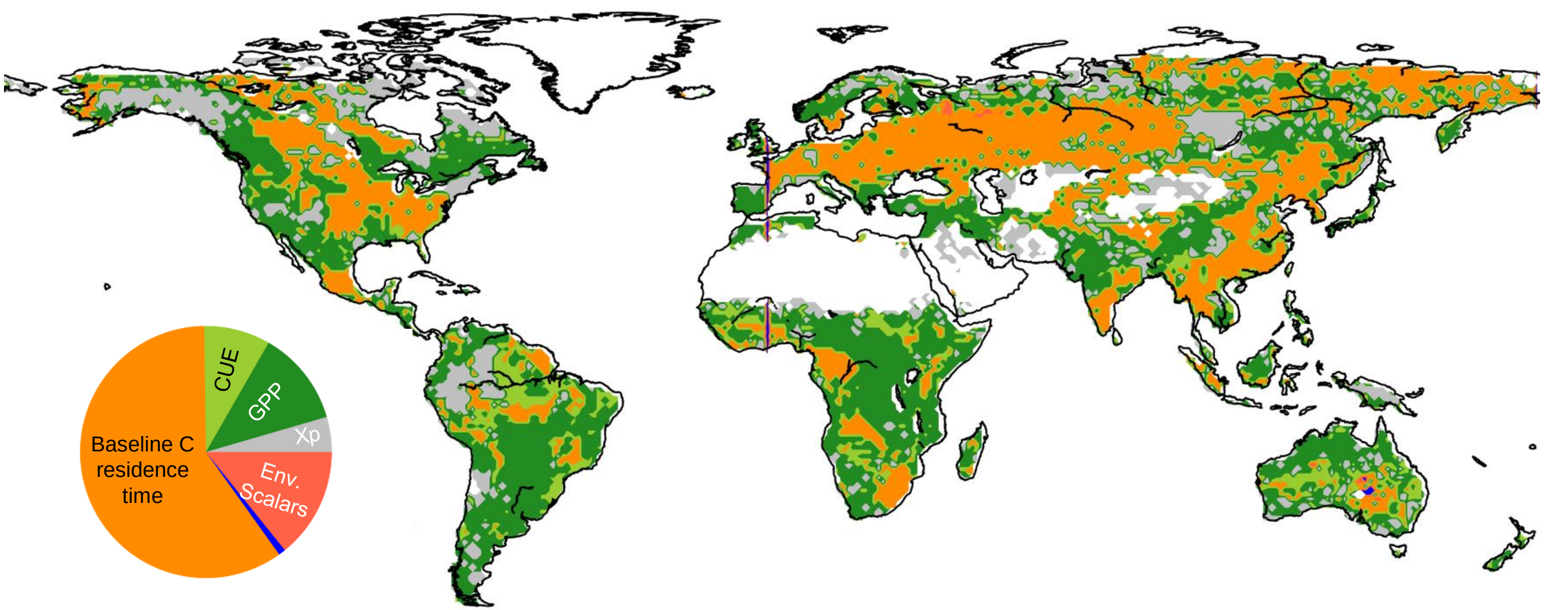
Luo & Weng, 2011 TREE
Xia *et al.*, 2013 GCB
Luo *et al.*, 2017 BG
Xia *et al.* 2020 GCB



Application of TraceME to CMIP6 models:

Baseline C residence time is a major uncertainty source in CMIP6 models

(Historical runs: 1850-2014)

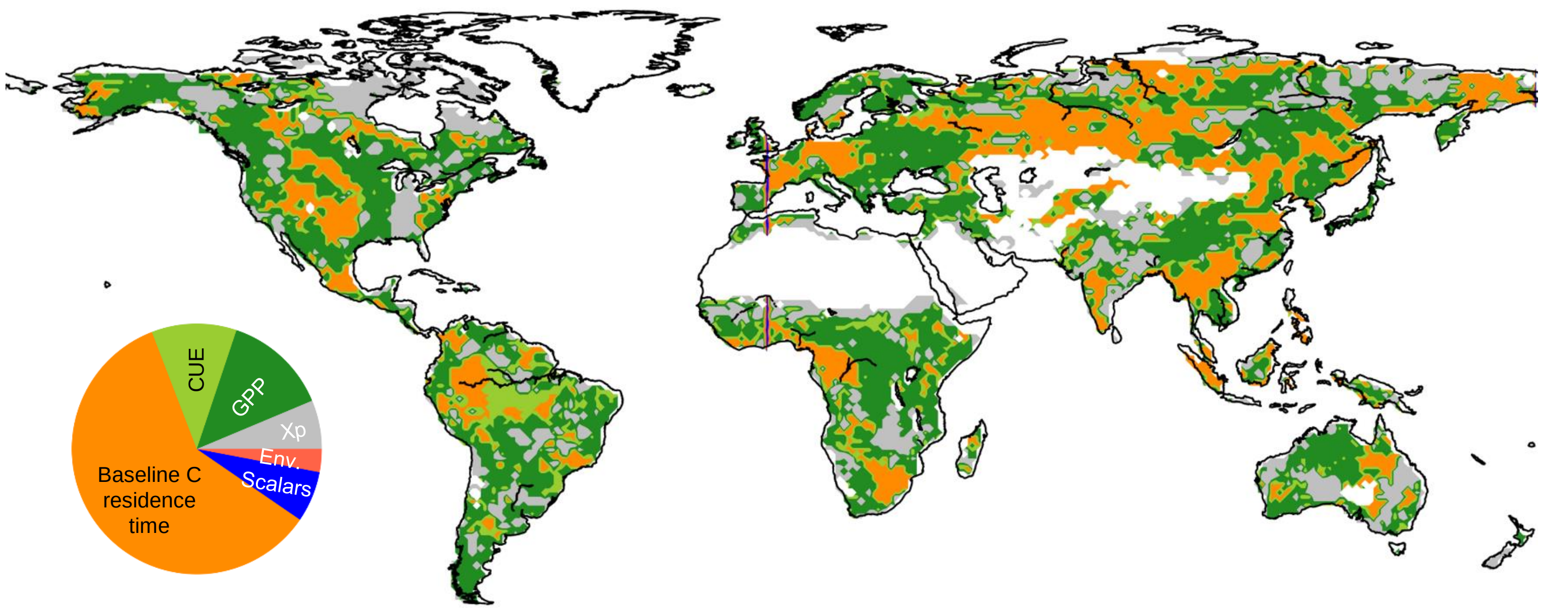


Zhou *et al*. 2021 Ecological Processes

Application of TraceME to CMIP6 models:

Baseline C residence time is a major uncertainty source in CMIP6 models

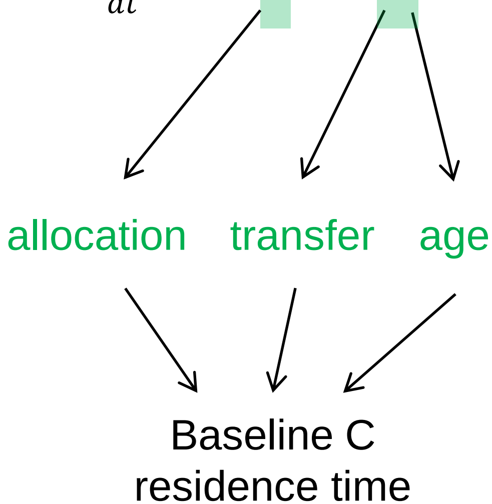
(Initial state: 1850)



- More parameter information of plant functional traits is useful for evaluating and understanding land C cycle uncertainty in CMIP6 models.

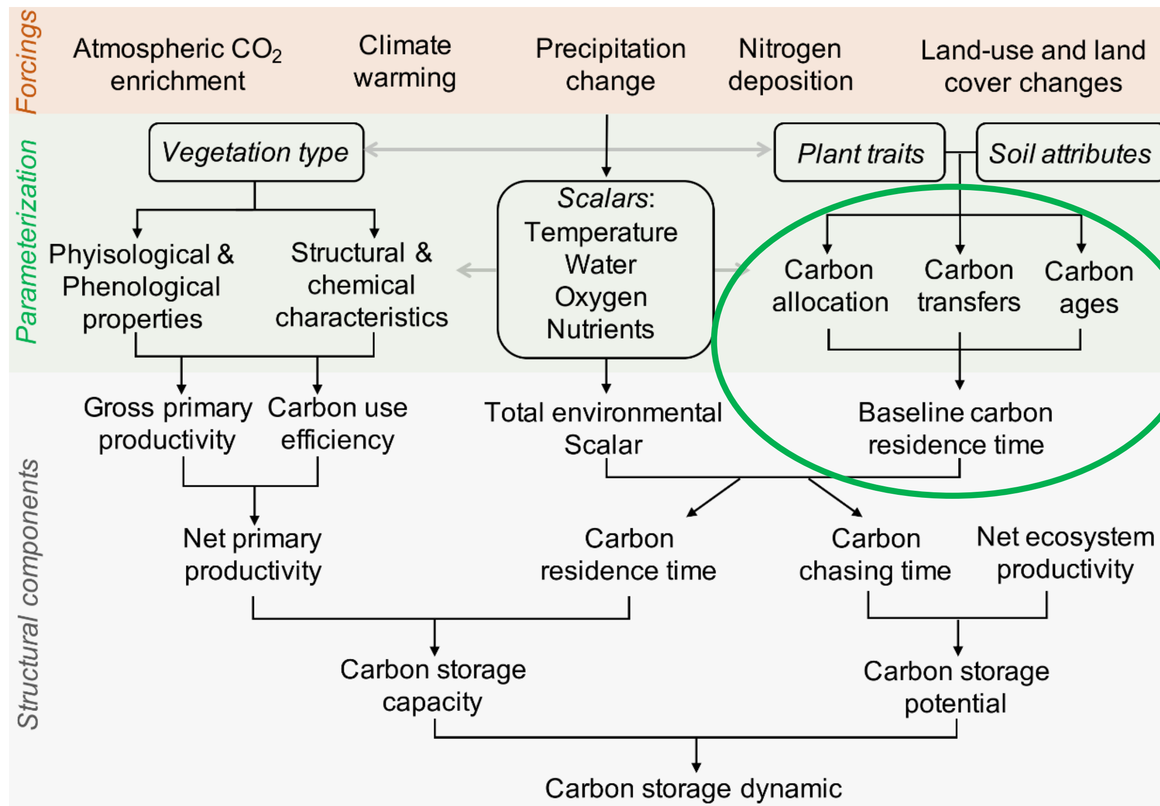
Plant functional traits and baseline C residence time

$$\frac{d\mathbf{X}(t)}{dt} = u(t)\mathbf{B} - \boldsymbol{\xi}(t)\mathbf{ACX}(t)$$



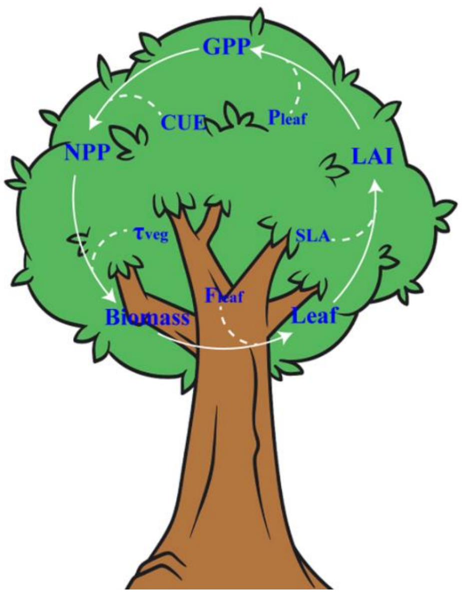
$$\tau'_{\mathrm{E}} = (\mathbf{AC})^{-1}\mathbf{B}$$

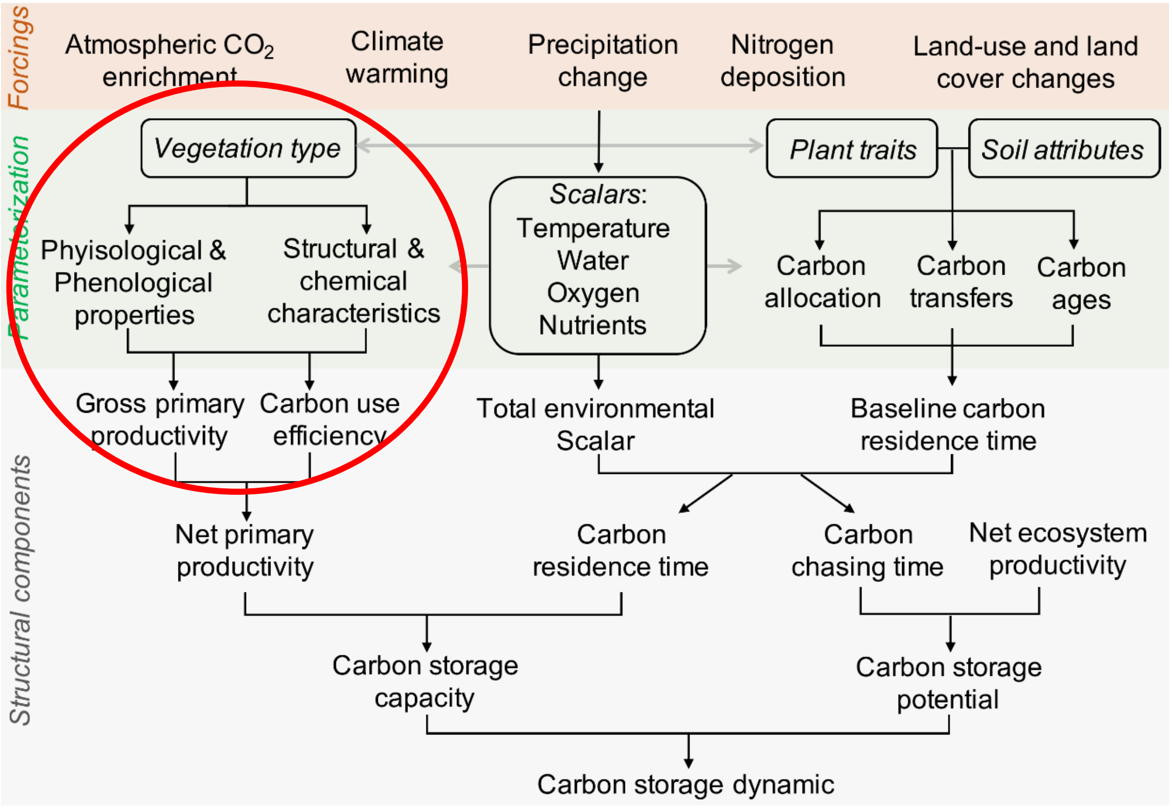
Luo & Weng, 2011 TREE
Xia *et al*., 2013 GCB
Luo *et al*., 2017 BG
Xia *et al*. 2020 GCB



Do plant functional traits contribute to the model uncertainty on ecosystem C uptake?

$$\frac{d\mathbf{X}(t)}{dt} = u(t)\mathbf{B} - \boldsymbol{\xi}(t)\mathbf{ACX}(t)$$



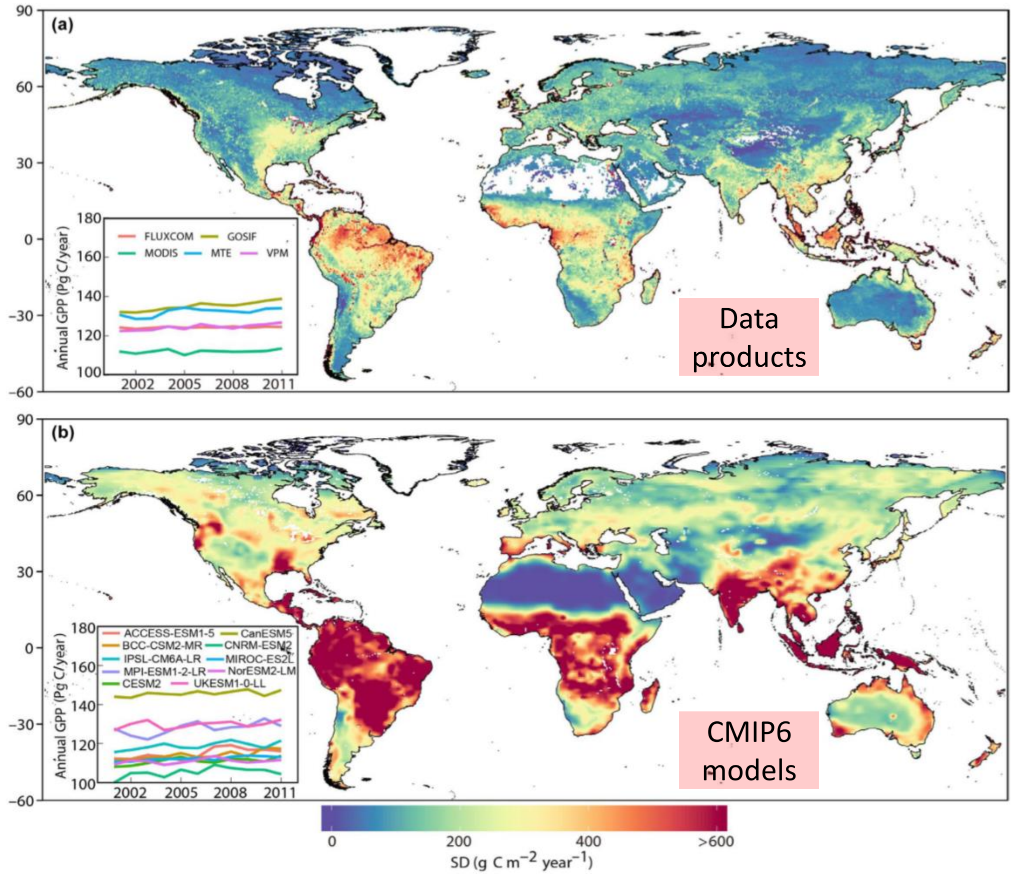


- Uncertainty propagates between plant traits and ecosystem C processes

Do plant functional traits contribute to the model uncertainty on ecosystem C uptake?

$$\frac{d\mathbf{X}(t)}{dt} = u(t)\mathbf{B} - \boldsymbol{\xi}(t)\mathbf{ACX}(t)$$

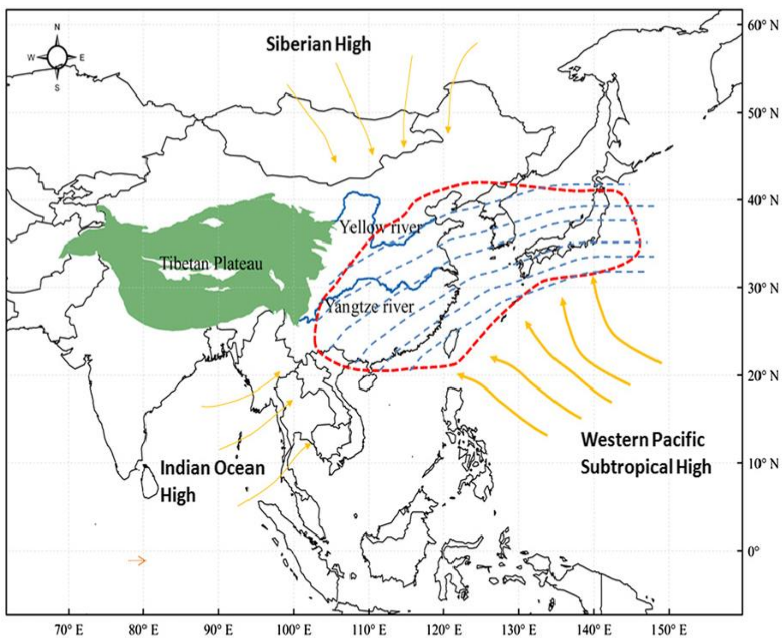
- Both data products and CMIP6 models have large uncertainty on terrestrial gross primary productivity (GPP).
- It is important to understand why GPP is differently simulated among the models.



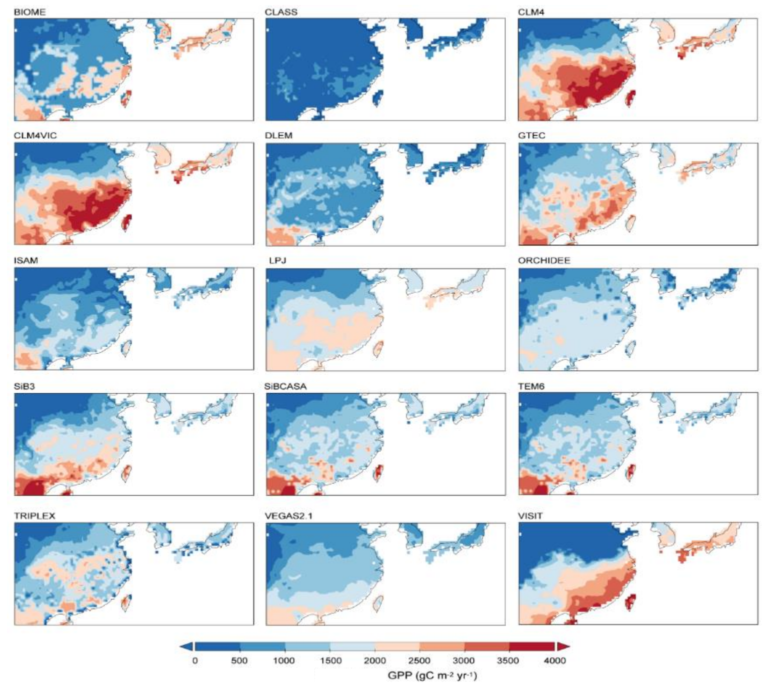
Xia *et al*. 2020 GCB

Modeling results: MsTMIP project

- East Asian Monsoon (EAM) region is a large C sink at middle to low latitudes .
- GPP uncertainty is large in current terrestrial biosphere models.



Yu *et al*. 2014 *PNAS*



Cui *et al*. 2019 *GBC*

MsTMIP project: experimental design

① **Baseline simulations** → **constant environmental drivers**

Order	Domain	Scenario	Climate	LULUC	Atm. CO_2	Nitrogen
1		RG1	Constant	Constant	Constant	Constant
2		SG1	Time-varying (CRU+NCEP)			
3		SG2		Time-varying (Hurtt)		
4		SG3			Time-varying	
5		BG1				Time-varying

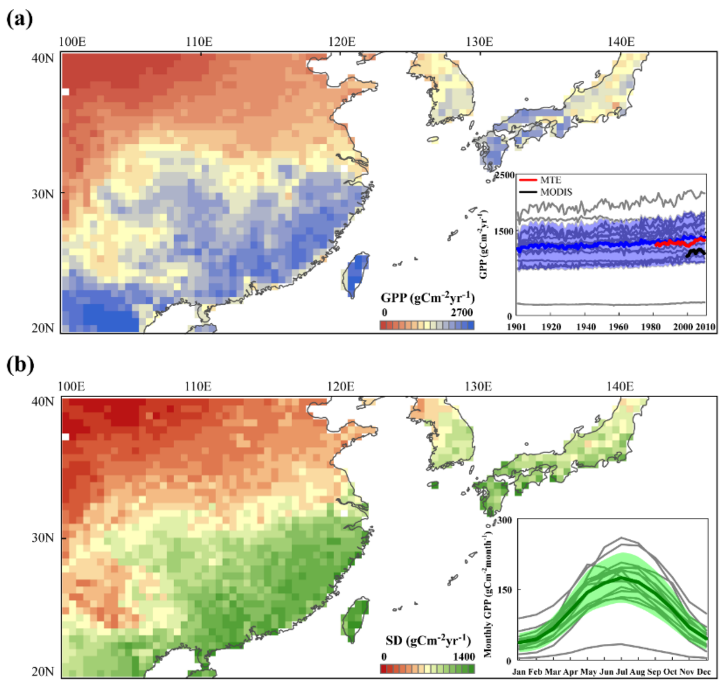
② **Environmental impacts** → **turn one environmental driver on at a time**

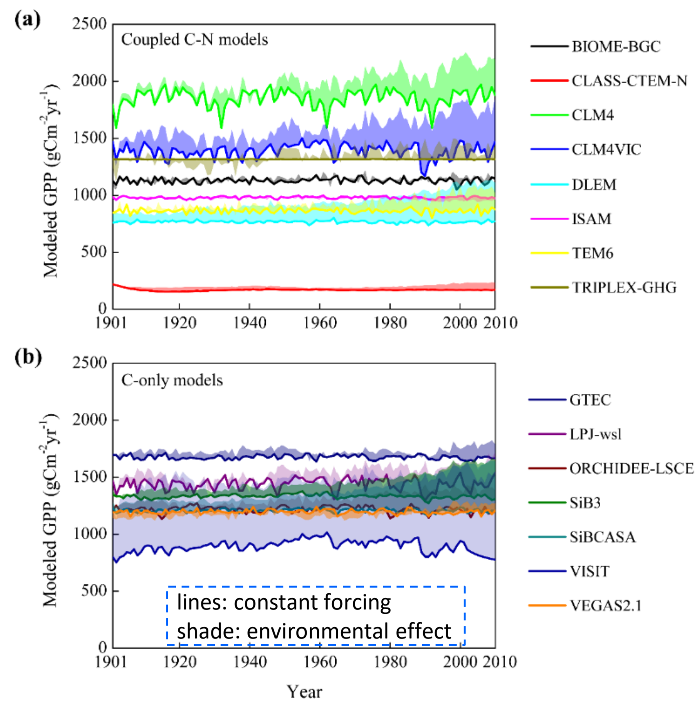
Factorial analyses on impacts of environmental drivers:

- **Climate (SG1 - RG1)** **Land-use land-cover change (SG2 - SG1)**
- **Atmospheric CO_2 concentrations (SG3 - SG2)** **Nitrogen deposition (BG1 - SG3)**

Modeling uncertainty in the East Asian Monsoon region

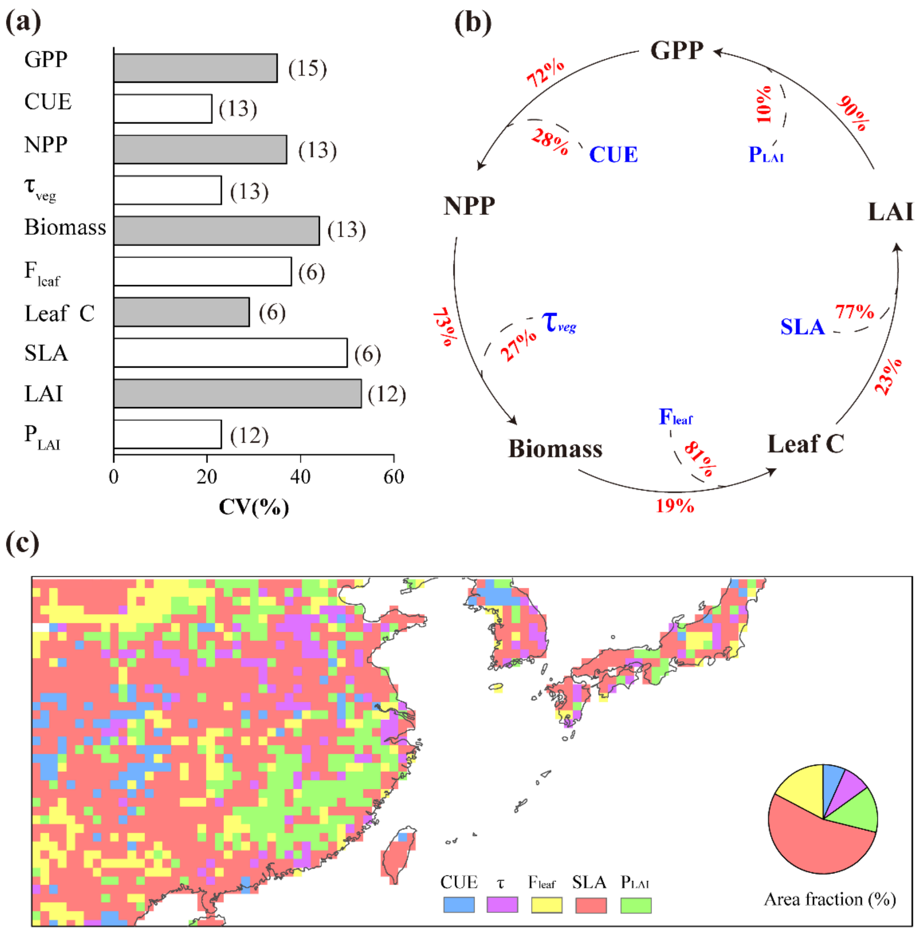
- The inter-model variation in GPP across the EAM region stems from the initial states.
- Model structure and parameterization of plant traits are important uncertainty sources





Cui *et al*. 2019 *GBC*

Plant functional traits are important model uncertainty sources



- Specific leaf area has a large contribution to GPP uncertainty in most area of the EAM region .
- It is important to use data to constrain plant trait parameters in the models.

SLA: Specific leaf area

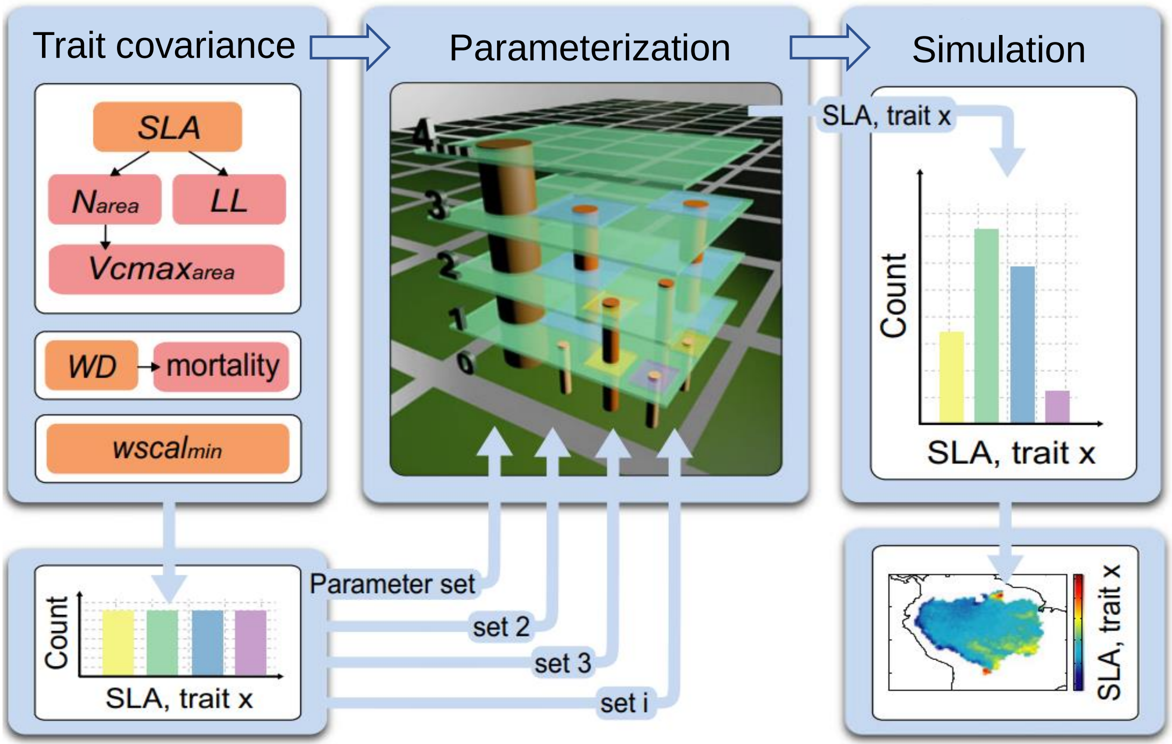
Fleaf: Fraction of leaf in vegetation biomass

P_{LAI}: Gross primary productivity per leaf area

Cui *et al*. 2019 *GBC*

Question 2: How to improve model parameterization of plant traits based on data?

Incorporation of trait acclimation and covariance to improve modeling of C processes



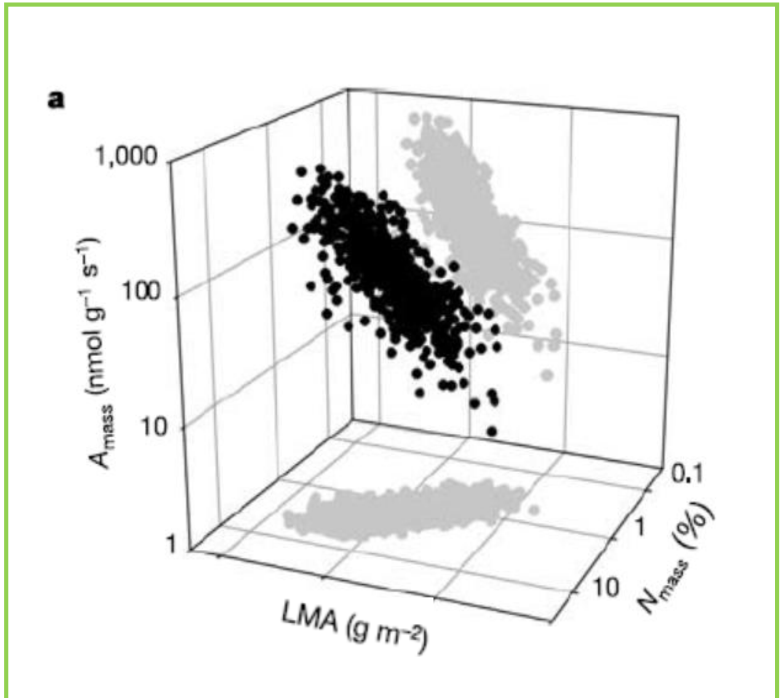
Two important types of plant traits for C cycle:

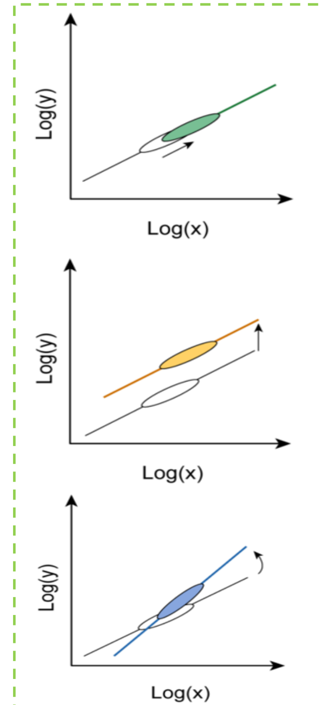
- **Photosynthesis**
  - Photosynthetic capacity
  - Leaf area
  - Leaf nitrogen content
  - Leaf life span
  - …
- **Mortality**
  - Tree mortality rate
  - Stem size
  - Wood density
  - …

Edited from Sakschewski *et al. Nature Climate Change* (2016)

Leaf photosynthetic traits

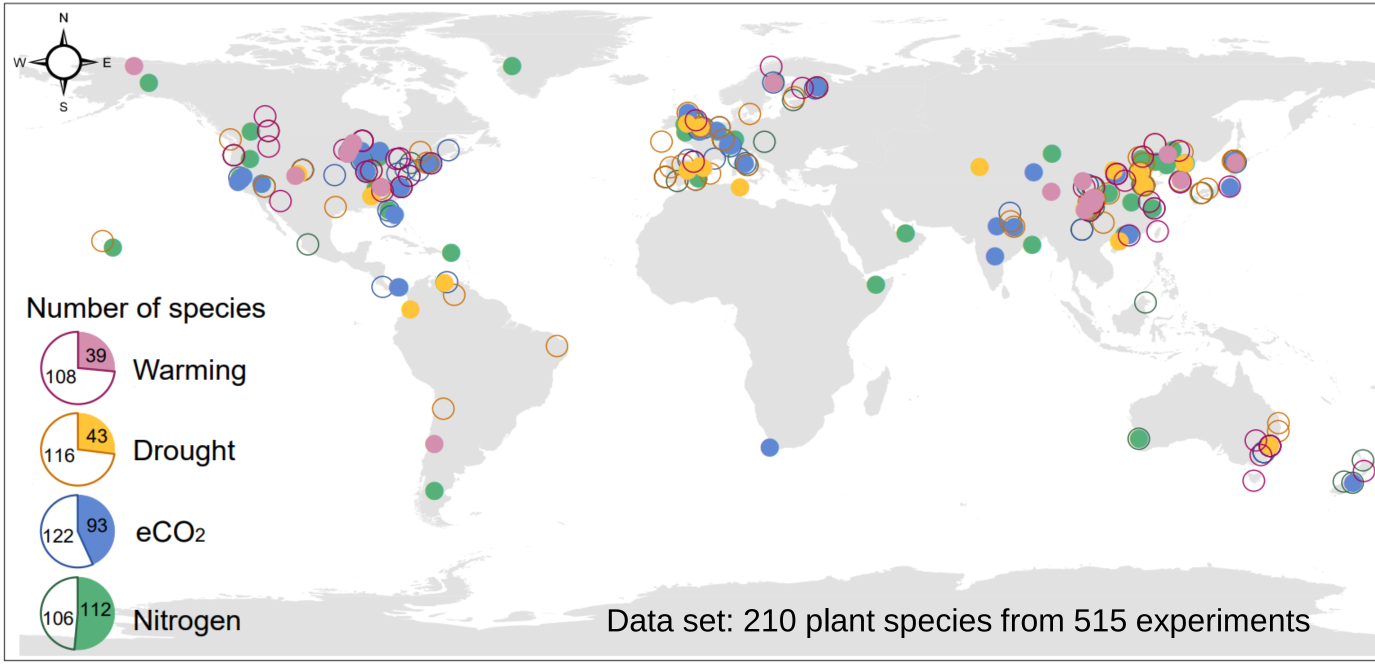
Whether and how global environmental changes affect plant traits and their covariance?





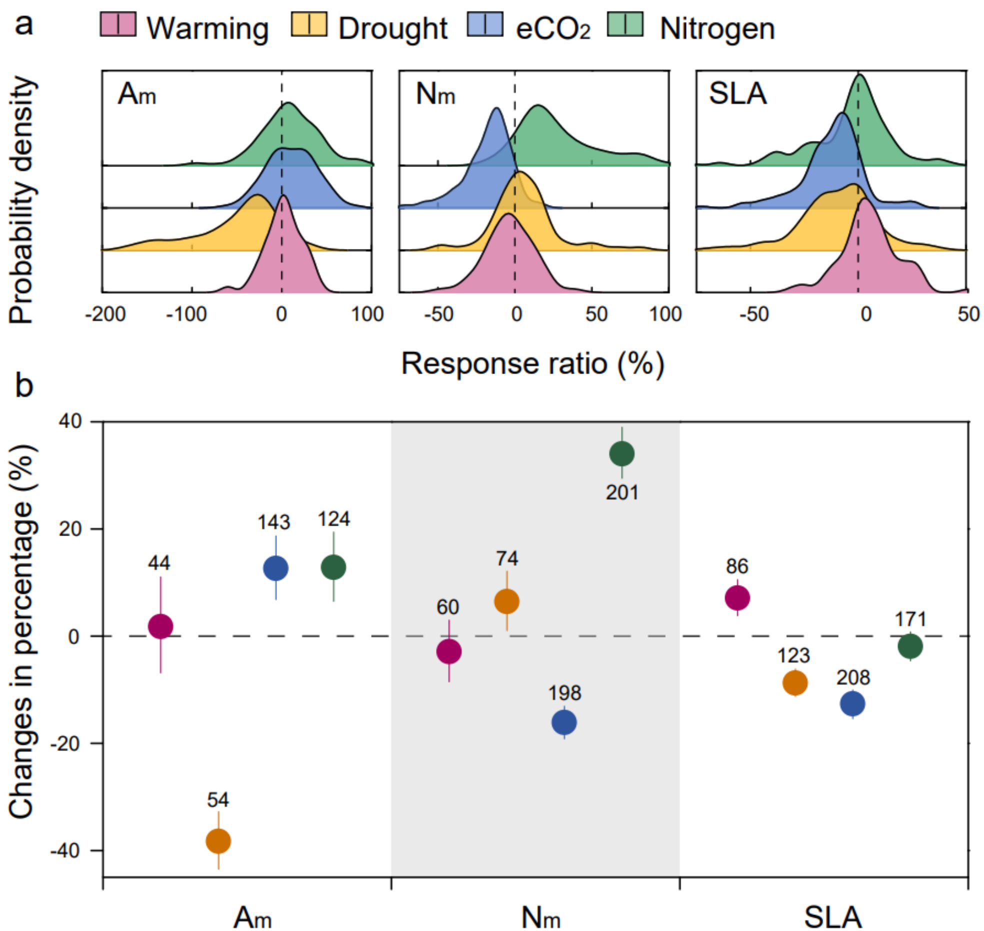
Reich *et al*., 1997; Wright *et al*., 2014

Meta-analysis: Data of trait acclimation and covariance in experiments



Cui *et al.*, 2020 *Nature Communications*

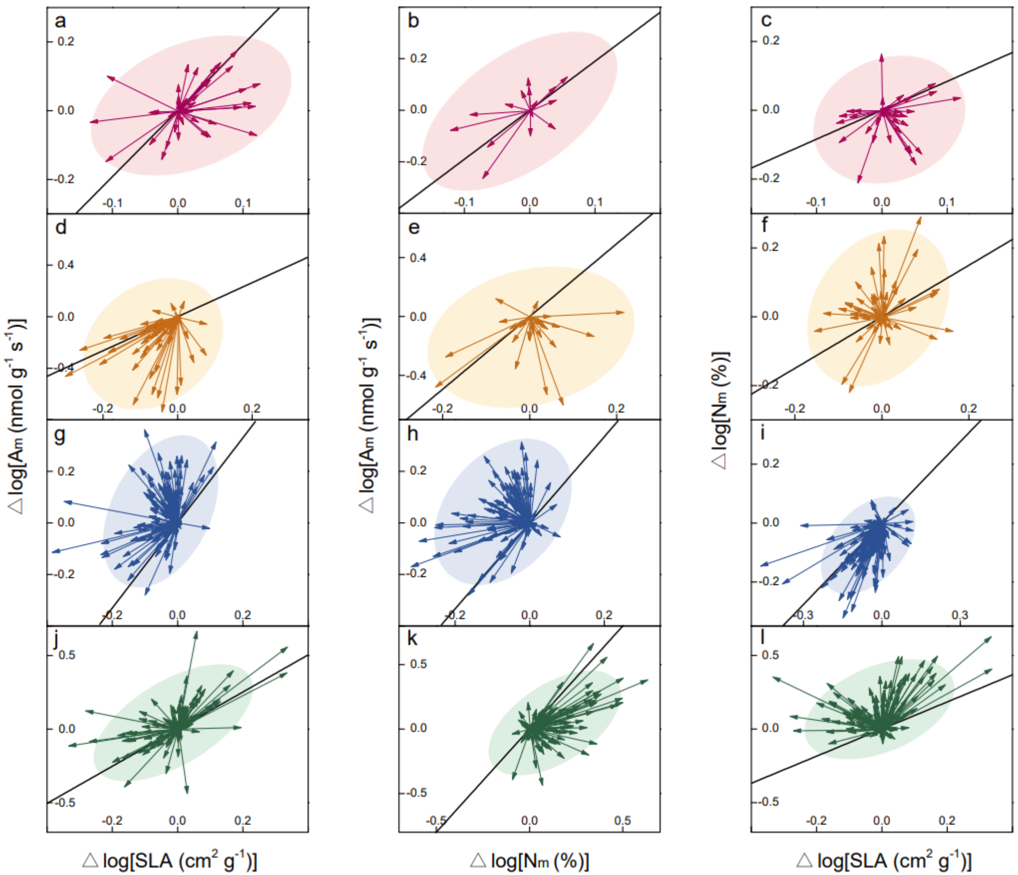
Trait acclimation under global changes



- Plant functional traits are sensitive to global changes
- Trait acclimation could be represented as probability distributions
- Different acclimation directions of plant trait among global change factors

Cui *et al.*, 2020 *Nature Communications*

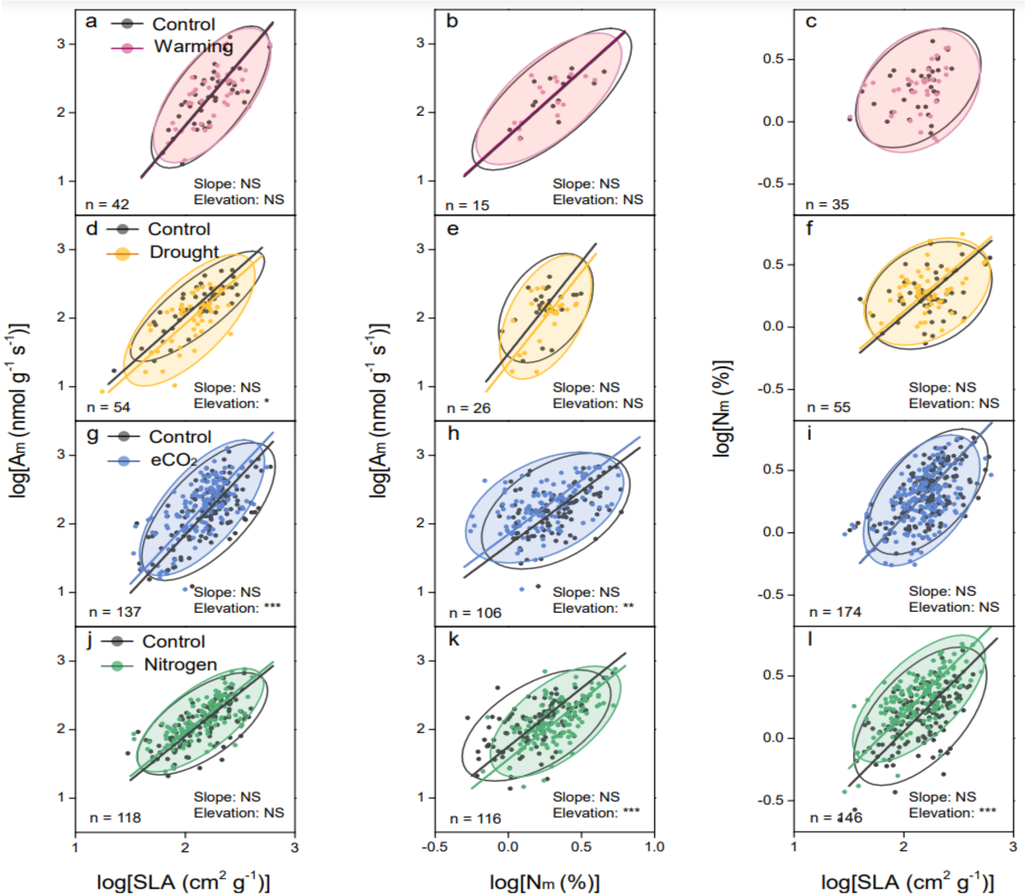
Various trait acclimation on the species level



- Plant functional traits are sensitive to global changes
- Trait acclimation could be represented as probability distributions
- Different acclimation directions of plant trait among global change factors
- Diverse directions of trait acclimation between species

Cui *et al.*, 2020 *Nature Communications*

Robust trait covariance over space under environmental changes



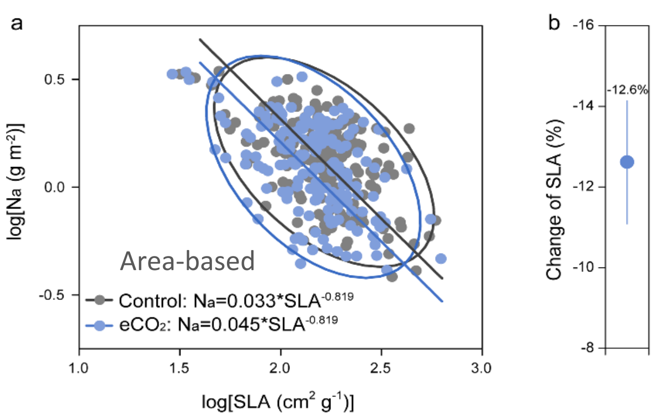
- Plant functional traits are sensitive to global changes
- Trait acclimation could be represented as probability distributions
- Different acclimation directions of plant trait among global change factors
- Diverse directions of trait acclimation between species
- A small change in trait covariance across species

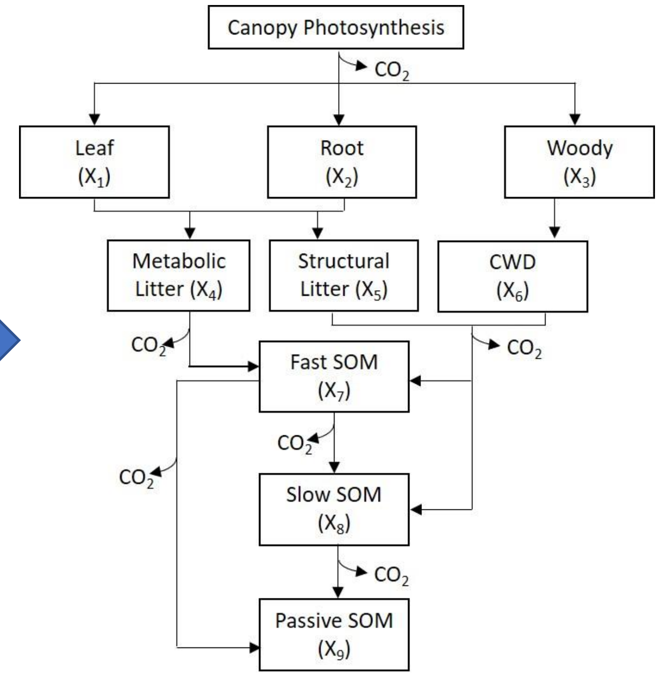
Cui *et al.*, 2020 *Nature Communications*

A modelling experiment:

Incorporating trait acclimation and covariance into a global process-based model

Simulation	[CO_2]	△*SLA*	*SLA*-N_a covariance	Description
Control	1×CO_2	/	N_a=0.033*$SLA^{-0.819}$	control
+CO_2	2×CO_2	/	N_a=0.033*$SLA^{-0.819}$	elevated CO_2
+CO2 +Acclimation	2×CO_2	-12.6%	N_a=0.033*$SLA^{-0.819}$	elevated CO_2 + SLA acclimation
+CO2 +Acclimation +Covariance	2×CO_2	-12.6%	N_a=0.045*$SLA^{-0.819}$	elevated CO_2 + SLA acclimation +N_a-SLA relationship acclimation

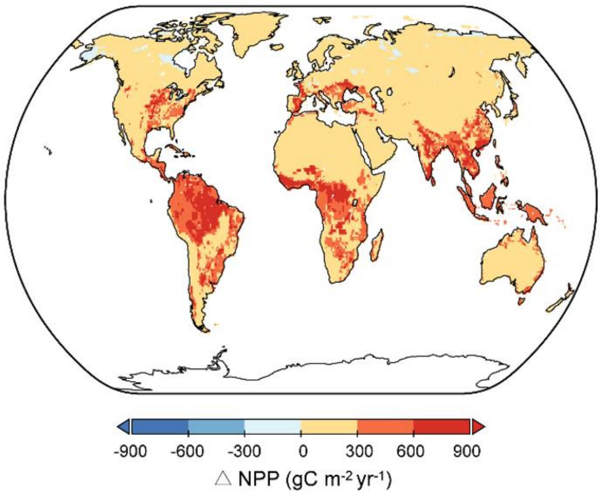




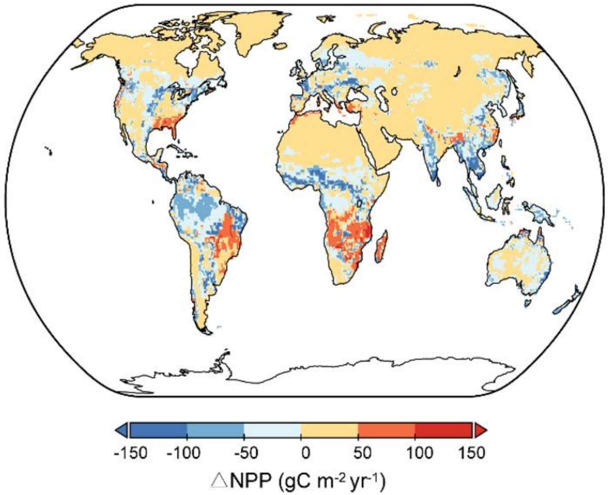
CABLE model

A modelling experiment:

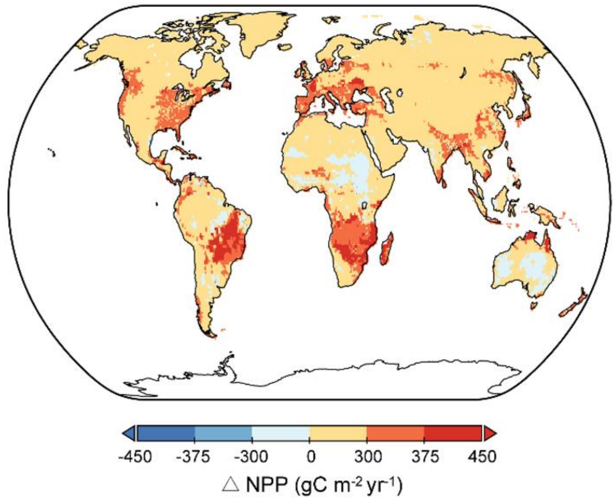
Incorporating trait acclimation and covariance can greatly change the modeled response of net primary productivity to CO_2 enrichment



+CO_2



+CO_2
+Acclimation



+CO_2
+Acclimation
+Covariance

Mortality traits

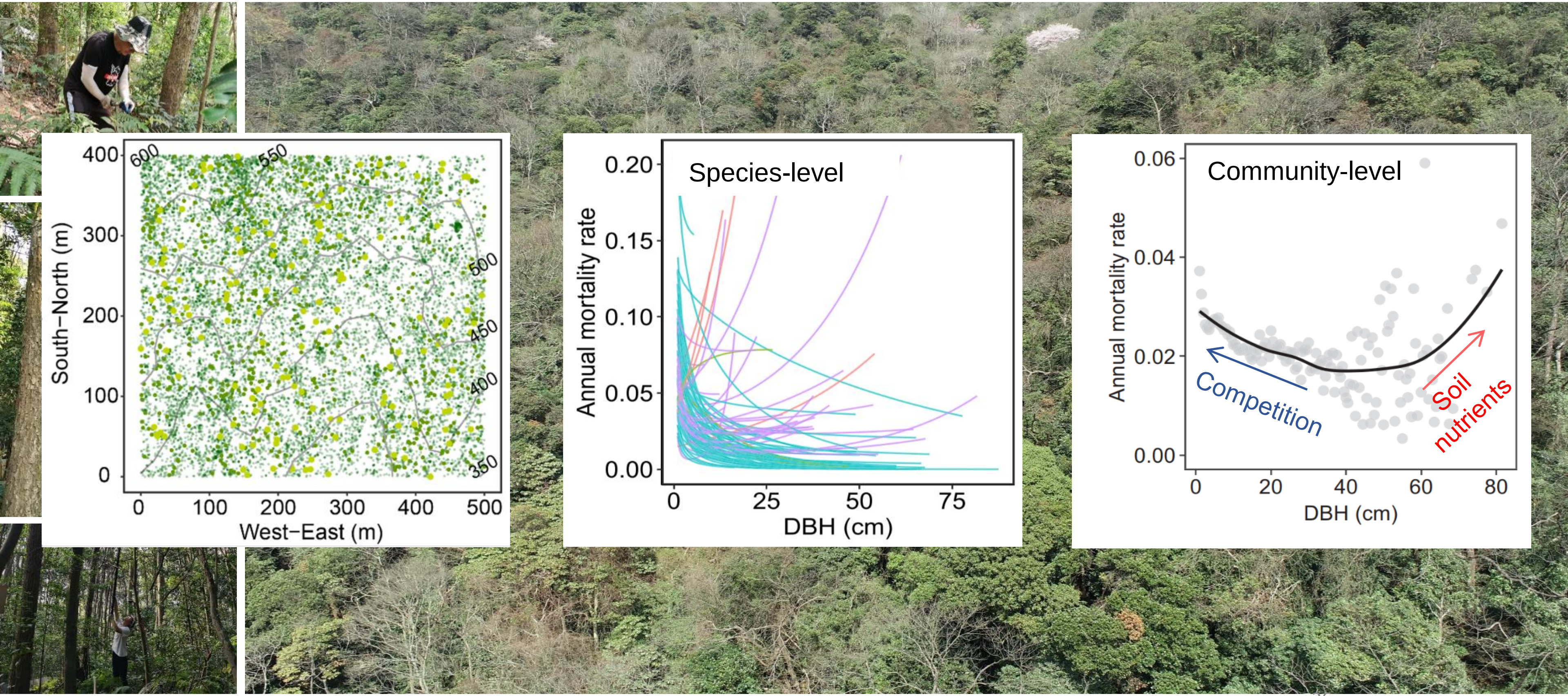
Covariance between stem size and tree mortality rate in a 20-ha subtropical monsoon evergreen forest




Lu *et al*., 2021 *Journal of Ecology*

Mortality traits

A U-shaped size-dependent mortality pattern in the species-rich forest



Lu *et al.*, 2021 *Journal of Ecology*

Dynamic vegetation models use different traits to simulate mortality rate

Plant mortality algorithms in models

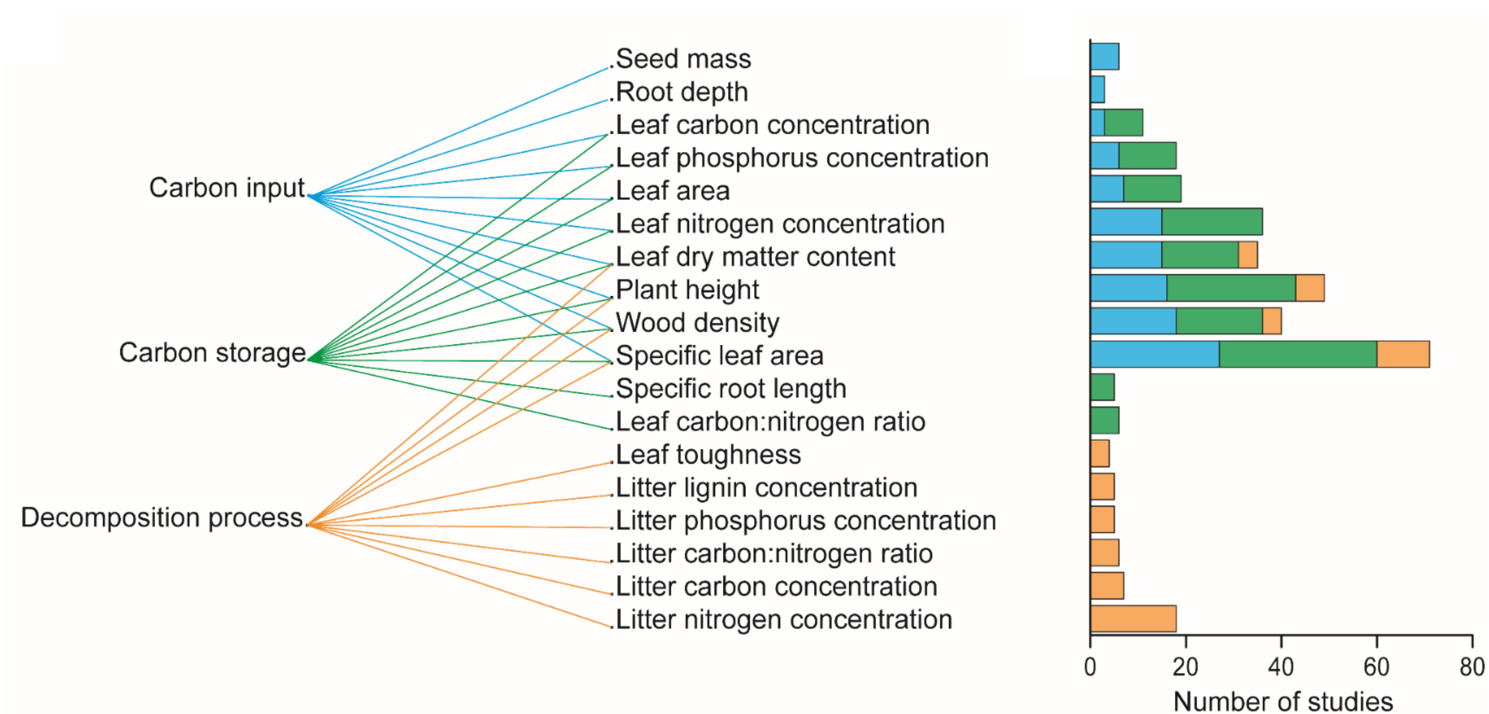
Mortality algorithms	Description	Model acronym
Productivity dependence	No explicit concept of mortality; biomass reduced via declining productivity	TRIFFID
Background rate	Mortality is set at a constant rate (approximately 1-2% yr^{-1}).	ORCHIDEE, BIOME-BGC, CLM, ED
	Mortality increases as wood density declines	ED
Age dependence	Death increases with age approaches the PFT-specific maximum	ForClim, CTEM, SDGVM
Size dependence	U-shaped mortality pattern for canopy trees	LM3-PPA
Growth efficiency threshold	Mortality occurs when biomass increment per unit leaf area falls below a quantitative threshold that varies between models.	SDGVM, LPJ-GUESS, CLM-DGVM, SEIB, ORCHIDEE, SDGVM, CLM 3.0
Shading/competition	Mortality increases as a function of canopy cover	ED, ED2, LPJ-GUESS, CLM-DGVM, SEIB, ORCHIDEE
Negative productivity	Death occurs if annual net productivity < 0.0 g	LPJ-GUESS, CLM-DGVM, SEIB, ORCHIDEE, CTEM
Carbon starvation	Mortality is a function of carbohydrate storage per unit leaf biomass	ED, CLM(ED), LM3-PPA
Climate tolerance	Death occurs if the average climate exceeds predefined monthly climatic tolerances	LPJ-GUESS, CLM-DGVM, SEIB, ORCHIDEE, CTEM
Heat stress threshold	Mortality is a function of the number of days per year in which the average temperature exceeds a threshold temperature, and the number of degrees by which this threshold is exceeded.	LPJ-GUESS, CLM-DGVM, SEIB, ORCHIDEE, CTEM, ED
Hydraulic failure	Mortality is a function of carbohydrate storage per unit leaf biomass	CLM(ED), LM3-PPA
Fire disturbance	Mortality is a function of fuel load, litter moisture	ED, SEIB, LPJ-GUESS, CLM(ED) , LM3-PPA

Edited from McDowell *et al*. (2011)

A literature survey on empirical trait-based studies

More studies are focusing on C uptake than decomposition processes

$$\frac{d\mathbf{X}(t)}{dt} = u(t)\mathbf{B} - \boldsymbol{\xi}(t)\mathbf{ACX}(t)$$



Summary

The model uncertainty on land C cycle can be further reduced by an improved parameterization of plant functional traits.

✓ Can we link plant functional traits and land carbon cycle for model evaluation?

- Yes, we can trace baseline C residence time and GPP to some key plant traits.
- Parameterization uncertainty can propagate between traits and to C processes.
- It is still challenging to evaluate CMIP models without details of trait parameters.

✓ How to improve model parameterization of plant functional traits based on data?

- Explore probability distributions of trait acclimations to environmental factors
- More data of community-level trait covariance on both of spatial and temporal scales
- Model outputs of plant functional traits associated with ecosystem processes

Thanks for your listening!