清華大學地球系统科学系
Department of Earth System Science, Tsinghua University

LEMONTREE
Land Ecosystem Models based On New Theory, obseRvations and ExperimEnts

Implementing the acclimation of photosynthesis and leaf respiration in the Noah-MP land surface model

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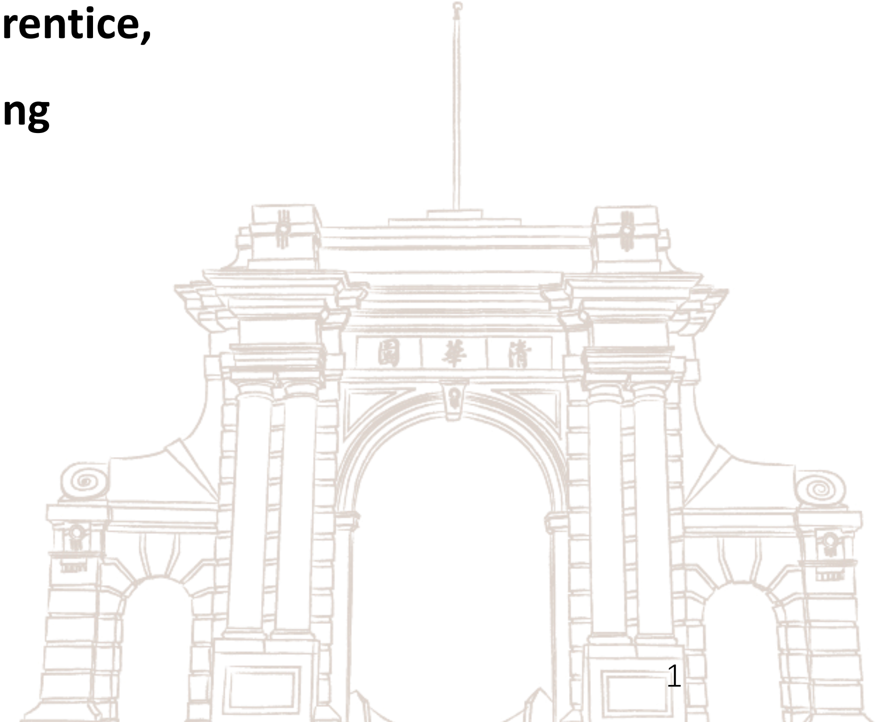

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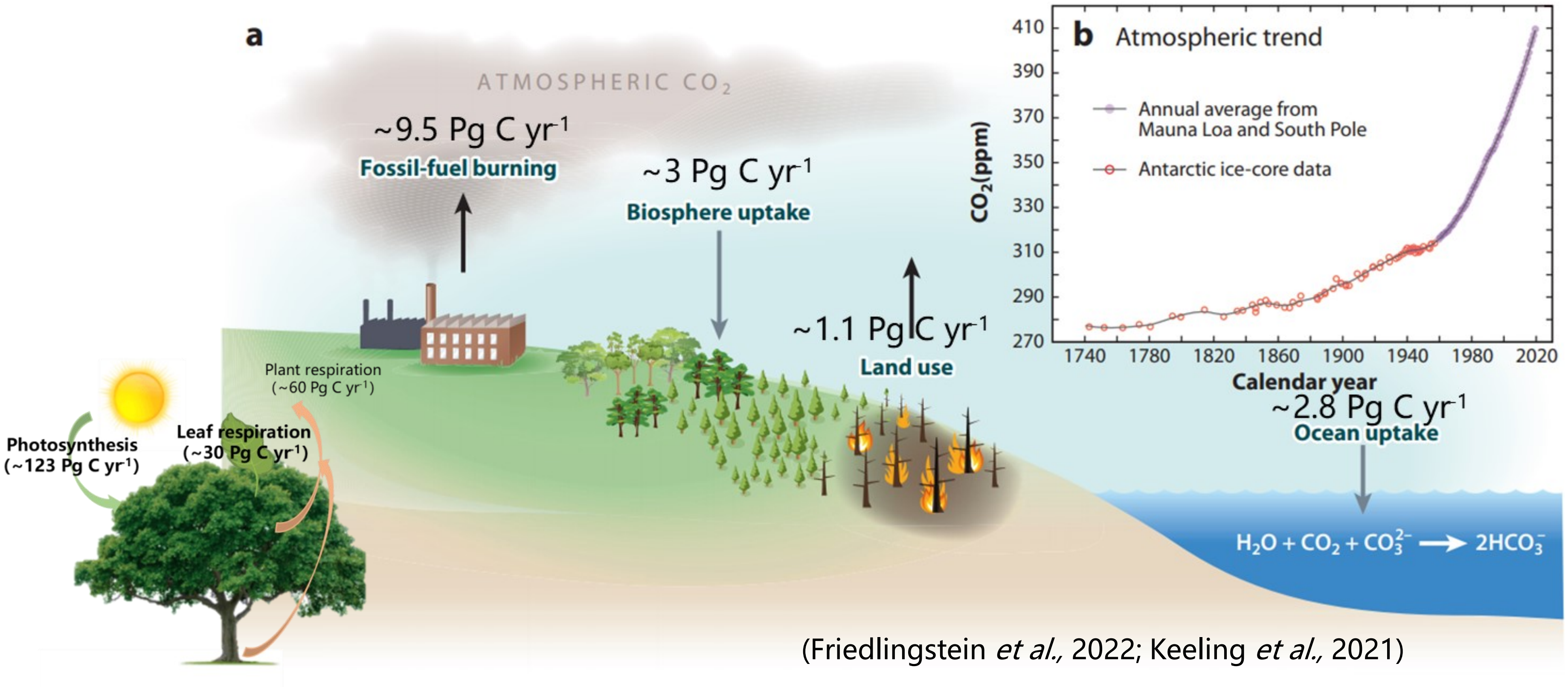
Background

Realistic simulation of leaf photosynthetic and respiratory processes is needed for accurate prediction of the global carbon cycle.

- Plant leaves absorb CO_2 through **photosynthesis** (123 PgC yr^{-1}, globally).
- About a quarter CO_2 absorption (30 PgC yr^{-1}) was released to the atmosphere by **leaf respiration.**
- Changes in leaf respiration and photosynthesis would significantly modify the **global carbon balance.**

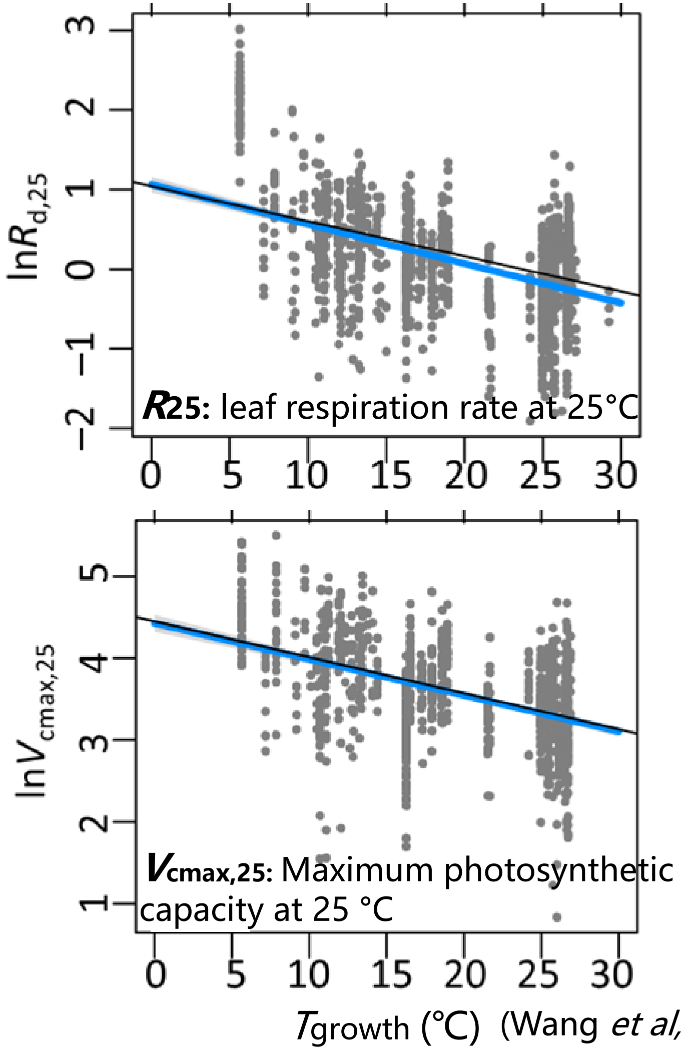


(Friedlingstein *et al.*, 2022; Keeling *et al.*, 2021)

Background

Plant photosynthesis and respiration acclimate to long-term environmental changes by adjusting photosynthetic and respiratory traits with increasingly well-understood principles.

☐ Evidence of acclimation

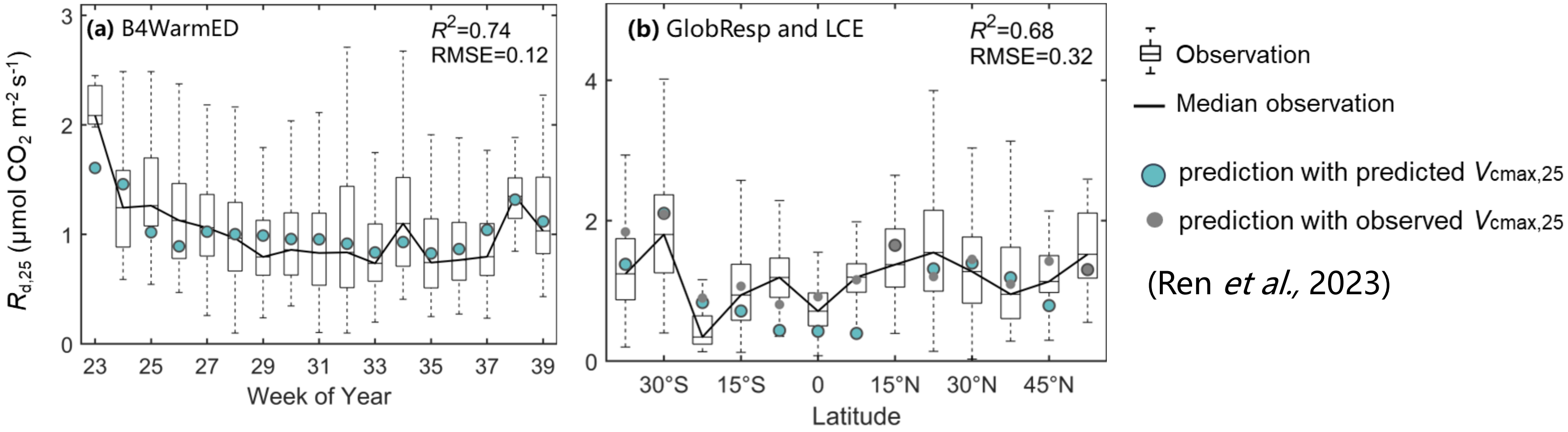


***R_{25}*: leaf respiration rate at 25°C**

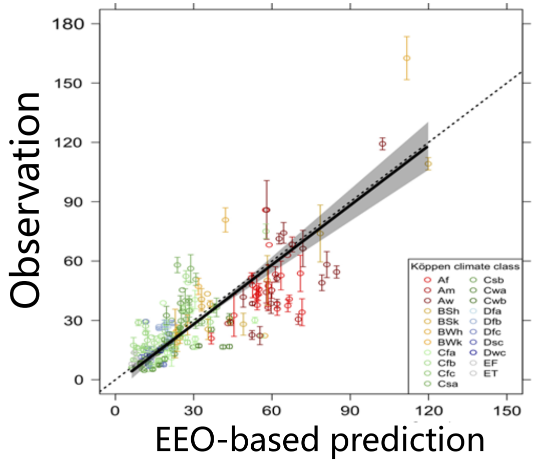
***$V_{cmax,25}$*: Maximum photosynthetic capacity at 25 °C**

(Wang *et al*. 2020)

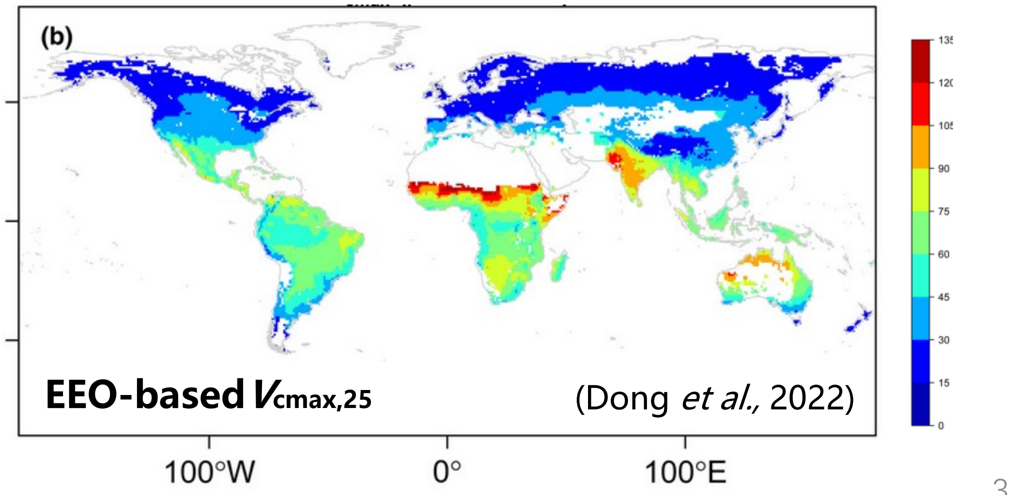
☐ Eco-Evolutionary Optimality-based predictions



(Ren *et al.*, 2023)



(Smith *et al.*, 2019)



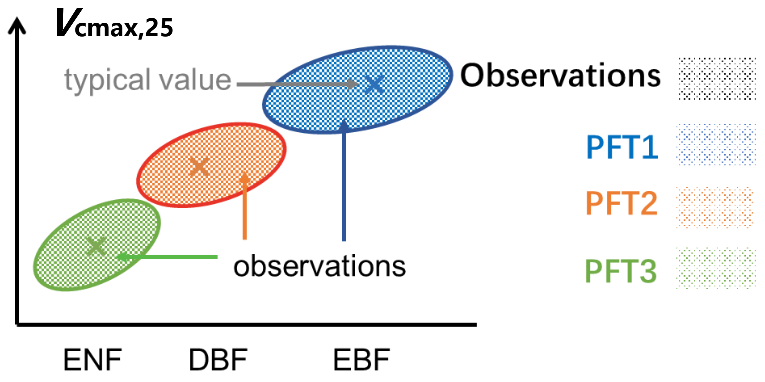
EEO-based $V_{cmax,25}$

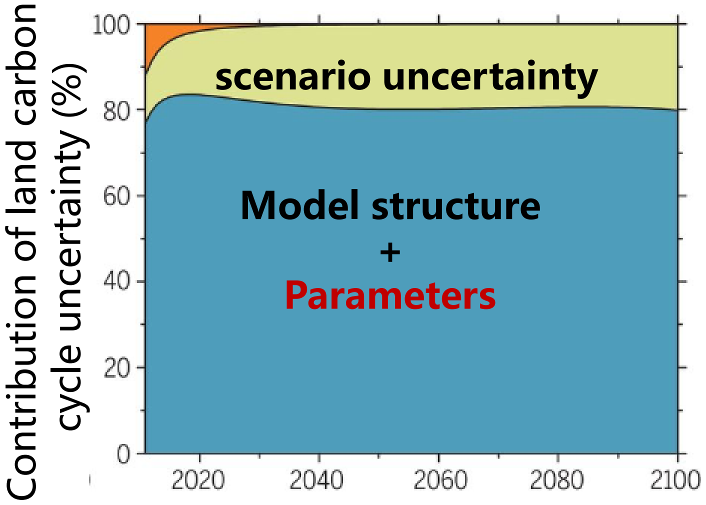
(Dong *et al.*, 2022)

Background

However, acclimation is still not routinely considered in land surface models (LSMs).

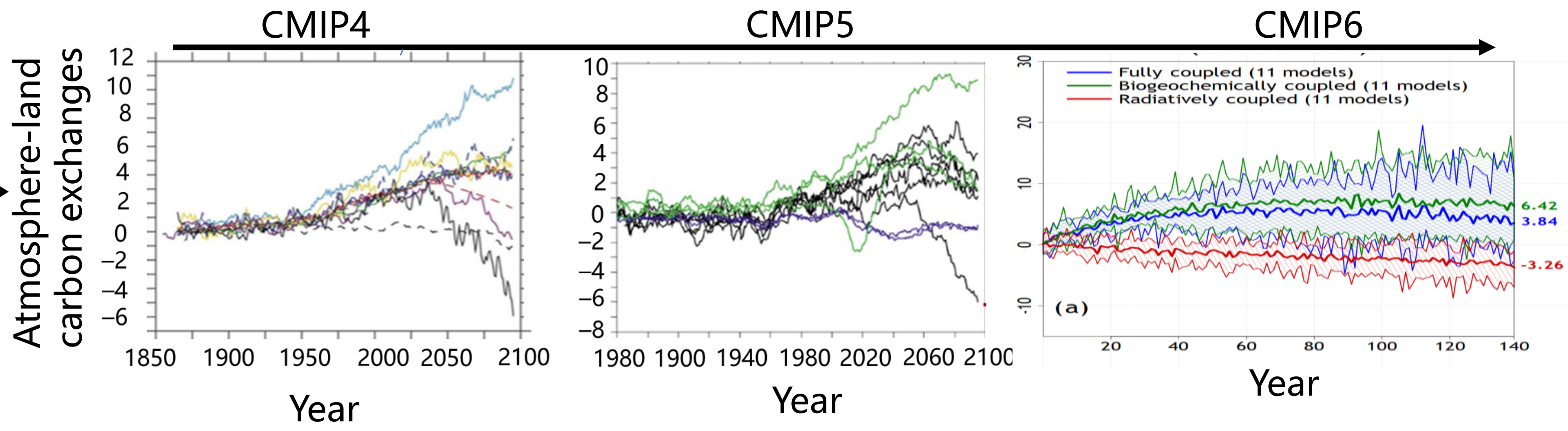
- LSMs conventionally assumed a **constant** R_{25} and $V_{cmax,25}$ by **plant functional types (PFTs)**.
- Calibration of PFT-dependent parameters together with model structures results in **disagreement among LSMs** in projections of the carbon cycle at regional or global scales.





(Bonan *et al.*, 2018)

Huge uncertainty!



(Friedlingstein *et al.,* 2006, 2014; Arora *et al.,* 2020)

Contents

This study implemented EEO-based schemes representing the acclimation of photosynthesis and leaf respiration in the Noah MP LSM.

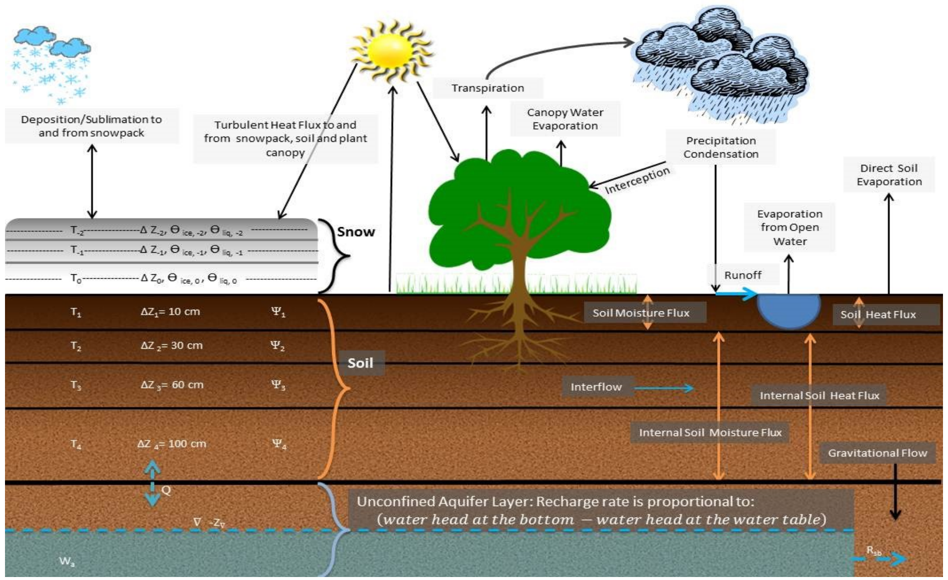
- **Model development:**

  model description, experimental design, the forcing and benchmark data
- **Evaluation:**

  traits variations, carbon flux variations

Model description

Land surface model: **Noah-MP**

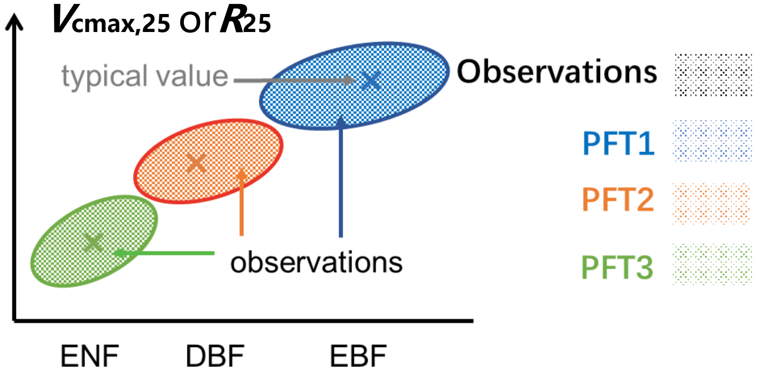


The framework of the land surface model Noah-MP

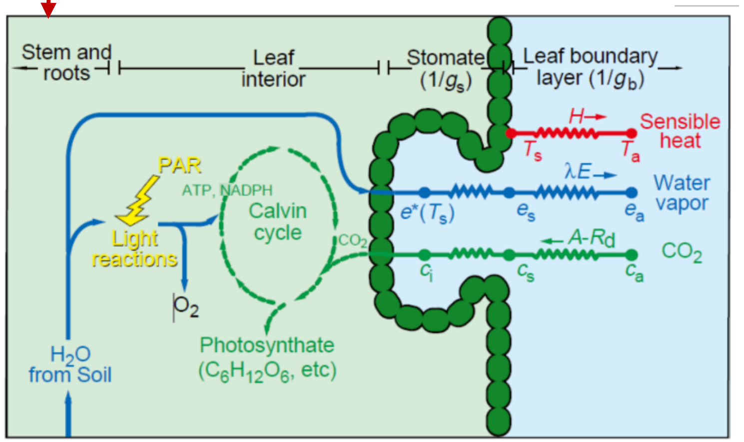
☐ $GPP=\min(A_C, A_J)$

$$A_C = \begin{cases} V_{cmax}\cdot\dfrac{c_i-\Gamma^*}{c_i+K}, & C3\ plant \\ V_{cmax}, & C4\ plant \end{cases}$$

$$A_J = \begin{cases} \dfrac{J}{4}\cdot\dfrac{c_i-\Gamma^*}{c_i+2\Gamma^*}, & C3\ plant \\ \dfrac{J}{4}, & C4\ plant \end{cases}$$



☐ $R_{canopy} = R_{25}\cdot f_r(T)\cdot LAI$



Numerical iteration via Ball-Berry model

Model description

☐ $GPP = \min(A_C, A_J)$

$$A_C = \begin{cases} V_{cmax} \cdot \dfrac{c_i - \Gamma^*}{c_i + K}, & C3\ plant \\ V_{cmax}, & C4\ plant \end{cases}$$

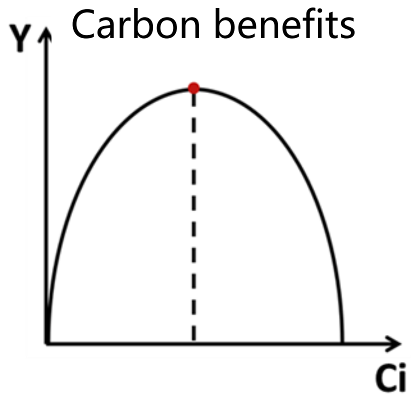
$$A_J = \begin{cases} \dfrac{J}{4} \cdot \dfrac{c_i - \Gamma^*}{c_i + 2\Gamma^*}, & C3\ plant \\ \dfrac{J}{4}, & C4\ plant \end{cases}$$

☐ $R_{canopy} = R_{25} \cdot f_r(T) \cdot LAI$

	Standard Noah-MP scheme	**EEO-based scheme**
c_i	Numerical iteration	Least-cost hypothesis
$V_{cmax,25}$	PFT parameters	Coordination hypothesis
$J_{max,25}$	Infinity	Coordination hypothesis
R_{25}	PFT parameters	R-Vcmax coupling

EEO-based scheme

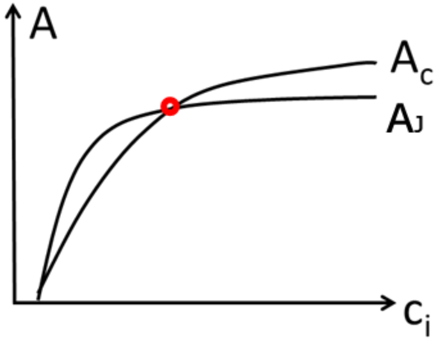
Least-cost hypothesis



$$c_i = \frac{\xi c_a + \Gamma^* \sqrt{VPD}}{\xi + \sqrt{VPD}}$$

$$\xi = \sqrt{\frac{\gamma (K + \Gamma^*)}{1.6\eta^*}}$$

Coordination： $A = A_J = A_C$

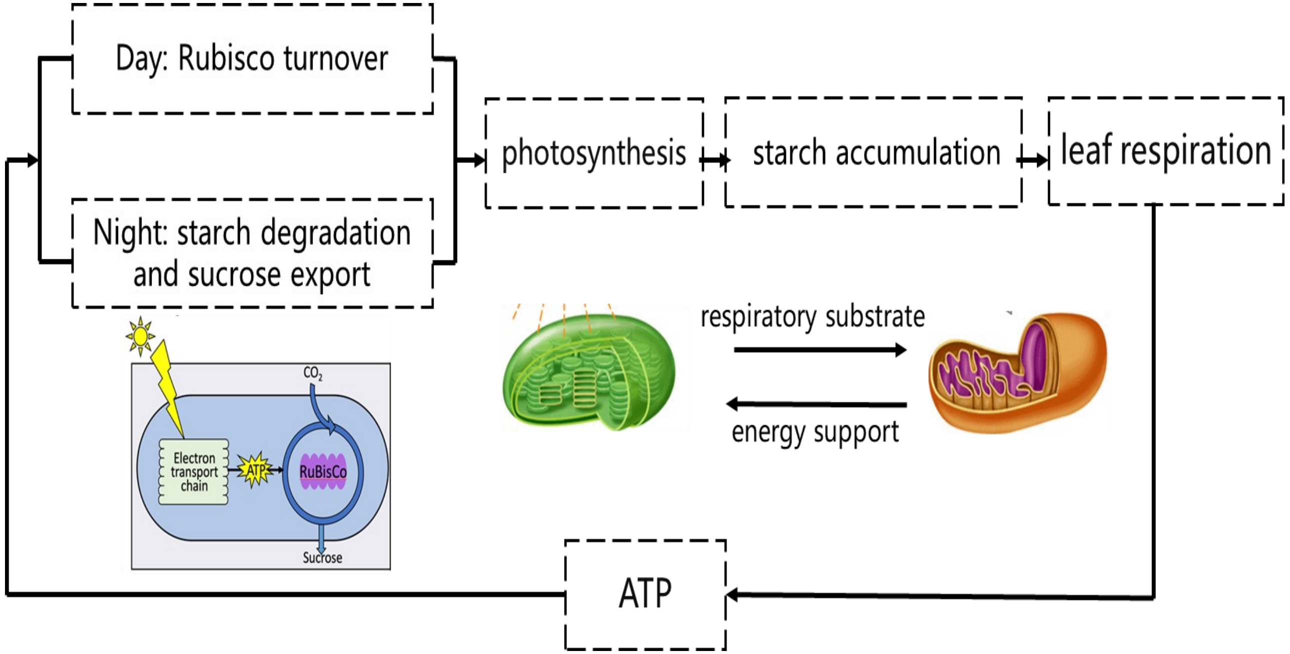


$$V_{cmax,opt} = \varphi_0 I_{abs}[(c_i + K)/(c_i + 2\Gamma^*)] \sqrt{\left\{1 - \left[c^* \frac{(c_i + 2\Gamma^*)}{(c_i - \Gamma^*)}\right]^{2/3}\right\}}$$

$$J_{max,opt} = 4\varphi_0 I_{abs}\beta \Big/ \sqrt{1 \Big/ \left\{1 - \left[c^* \frac{(c_i + 2\Gamma^*)}{(c_i - \Gamma^*)}\right]^{2/3}\right\} - 1}$$

Model description: New hypothesis of leaf respiration acclimation

R and carboxylation capacity (V_{cmax}) at 25˚C (R_{25}, $V_{cmax,25}$) are coordinated, so that R_{25} variations support $V_{cmax,25}$ at a level allowing full light use; with $V_{cmax,25}$ reflecting daytime conditions (for photosynthesis), and the ratio of R_{25} to $V_{cmax,25}$ reflecting night-time conditions (for starch degradation and sucrose export).



Day: Rubisco turnover

Night: starch degradation and sucrose export

photosynthesis

starch accumulation

leaf respiration

respiratory substrate

energy support

ATP

*R*d and *V*cmax are coordinated

$$b = \frac{R}{Vcmax} = \frac{R_{25}\cdot f\mathrm{r}(T\mathrm{night})}{Vcmax_{25}\cdot fv(Tmidday)}$$

$$\boldsymbol{R_{25} = b\frac{f_v(T_{midday})}{f_r(T_{night})}V_{cmax,25}}$$

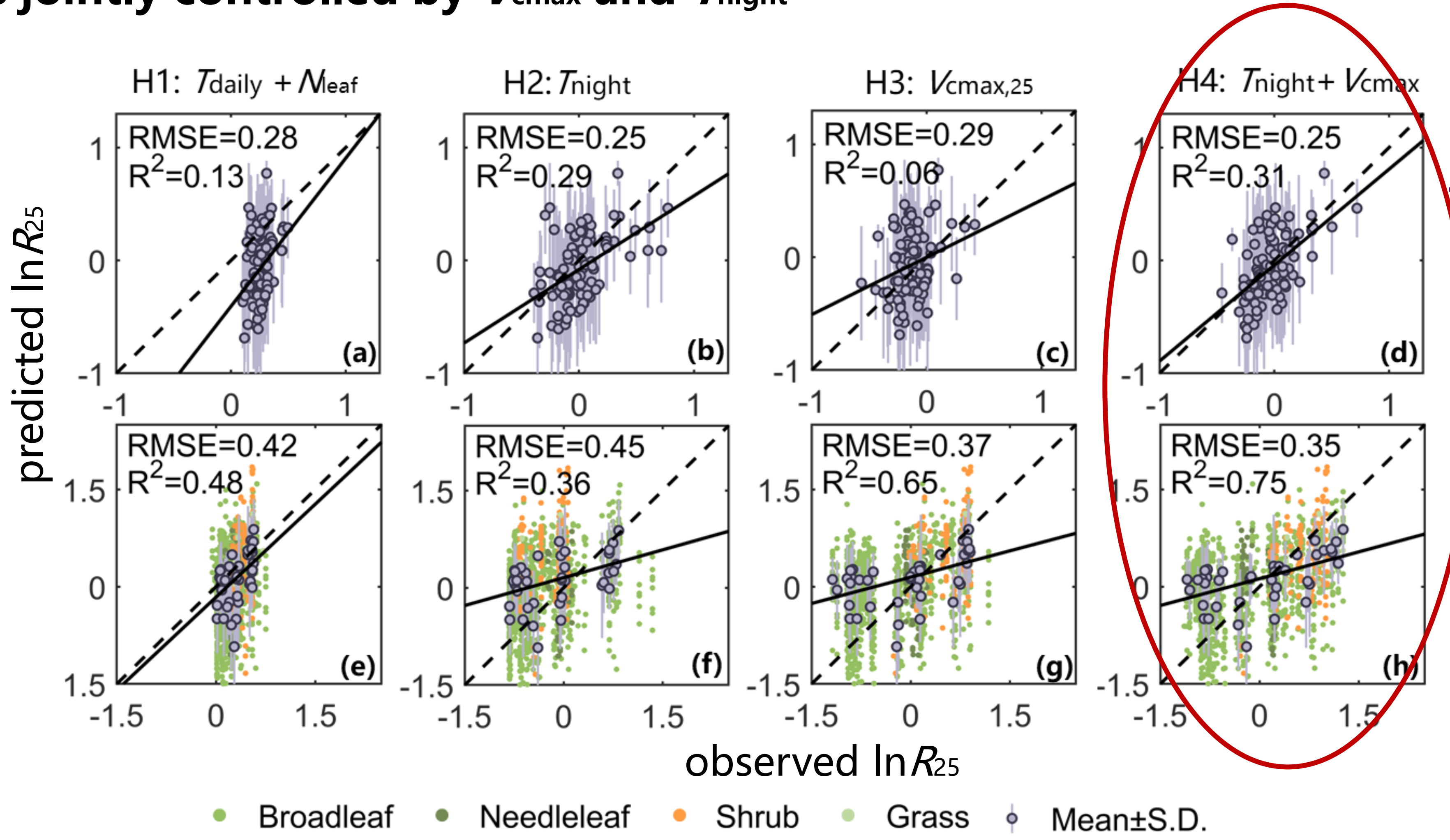
where $fv(Tmidday) = \exp\left[(\Delta Ha/R)\left(\frac{1}{298.15} - \frac{1}{T\mathrm{midday} + 273.15}\right)\right]$

$$f\mathrm{r}(T\mathrm{night}) = \exp(0.1012(T\mathrm{night} - 25) - 0.0005(T\mathrm{night}^2 - 25^2))$$

(Ren *et al.*, 2023, *New Phy*)

Model description: New hypothesis of leaf respiration acclimation

- ***R_{25}* is jointly controlled by *V_{cmax}* and *T_{night}***



Temporal changes

Spatial changes

Fig. Scatter plots of natural-log transformed *$R_{d,25}$* between observation and prediction at their highest R^2 by four hypotheses

(Ren *et al.*, 2023, *New Phy*)

Model description: New hypothesis of leaf respiration acclimation

- **The acclimation time scale of R_{25} is about 15 days (consistent with $V_{\mathrm{cmax,25}}$).**

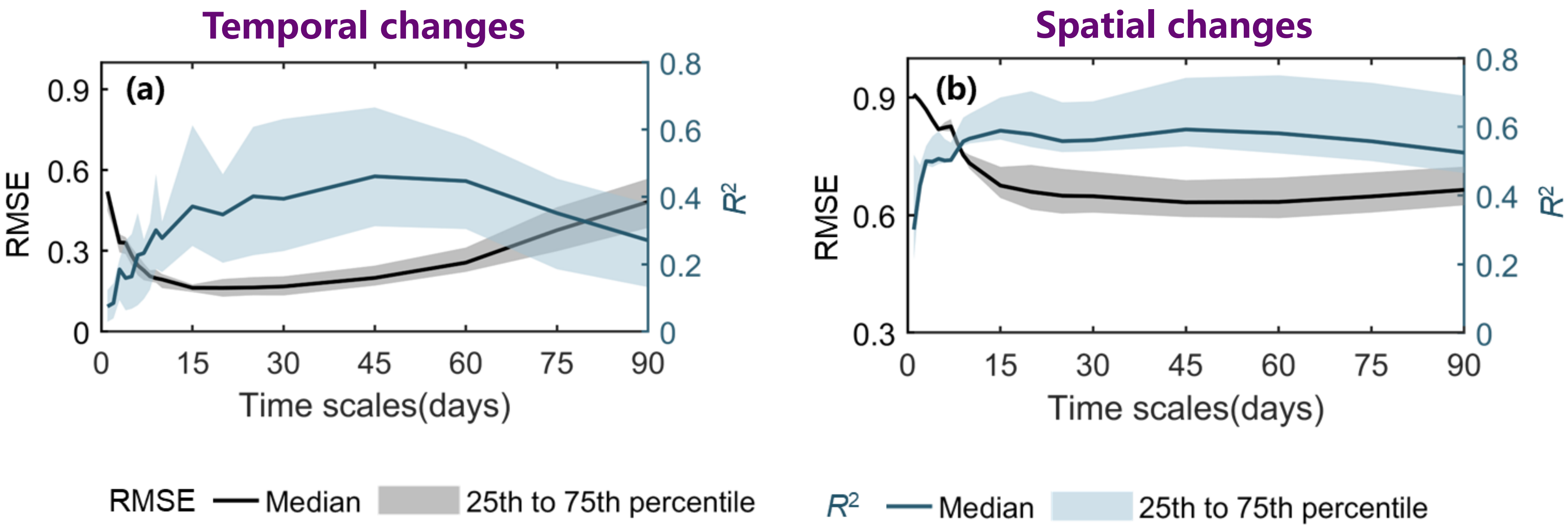


Fig. Estimating the acclimation time scale of leaf respiration (a-b)).

(Ren *et al.*, 2023, *New Phy*)

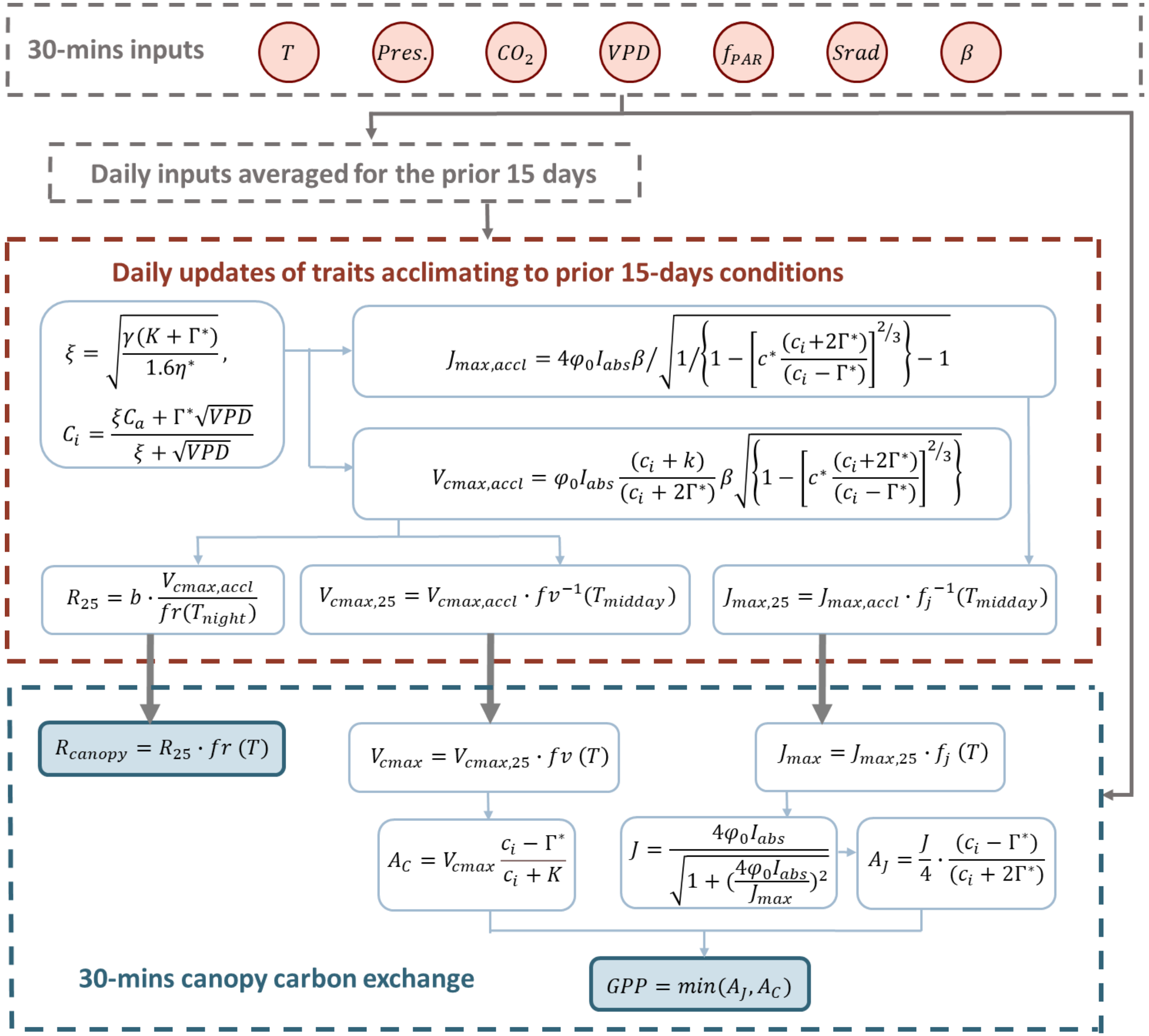
Model description

EEO-based scheme:

- ✓ less parameters (12 PFT-dependent → 3 PFT-independent)
- ✓ less computationally demanding (No numerical iteration)

	Standard Noah-MP scheme	EEO-based scheme
c_i	Numerical iteration	Least-cost hypothesis
$V_{cmax,25}$	PFT parameters	Coordination hypothesis
$J_{max,25}$	Infinity	Coordination hypothesis
R_{25}	PFT parameters	R-Vcmax coupling

Flowchart of the trait-acclimation scheme incorporated in Noah MP



30-mins inputs

T, $Pres.$, CO_2, VPD, f_{PAR}, $Srad$, β

Daily inputs averaged for the prior 15 days

Daily updates of traits acclimating to prior 15-days conditions

$$\xi = \sqrt{\frac{\gamma(K+\Gamma^*)}{1.6\eta^*}},$$

$$C_i = \frac{\xi C_a + \Gamma^*\sqrt{VPD}}{\xi + \sqrt{VPD}}$$

$$J_{max,accl} = 4\varphi_0 I_{abs}\beta / \sqrt{1/\left\{1-\left[c^*\frac{(c_i+2\Gamma^*)}{(c_i-\Gamma^*)}\right]^{2/3}\right\}-1}$$

$$V_{cmax,accl} = \varphi_0 I_{abs}\frac{(c_i+k)}{(c_i+2\Gamma^*)}\beta\sqrt{\left\{1-\left[c^*\frac{(c_i+2\Gamma^*)}{(c_i-\Gamma^*)}\right]^{2/3}\right\}}$$

$$R_{25} = b\cdot\frac{V_{cmax,accl}}{fr(T_{night})}$$

$$V_{cmax,25} = V_{cmax,accl}\cdot fv^{-1}(T_{midday})$$

$$J_{max,25} = J_{max,accl}\cdot f_j^{-1}(T_{midday})$$

$$R_{canopy} = R_{25}\cdot fr\,(T)$$

$$V_{cmax} = V_{cmax,25}\cdot fv\,(T)$$

$$J_{max} = J_{max,25}\cdot f_j\,(T)$$

$$A_C = V_{cmax}\frac{c_i-\Gamma^*}{c_i+K}$$

$$J = \frac{4\varphi_0 I_{abs}}{\sqrt{1+(\frac{4\varphi_0 I_{abs}}{J_{max}})^2}}$$

$$A_J = \frac{J}{4}\cdot\frac{(c_i-\Gamma^*)}{(c_i+2\Gamma^*)}$$

30-mins canopy carbon exchange

$$GPP = min(A_J, A_C)$$

(Mengoli et al., 2022, *JAMES*; Ren *et al.*, 2023, *New Phy*)

Experimental design

Two sets of model experiments:

a. The standard Noah MP scheme

b. The new EEO-based scheme

Simulation design:

- Time step: half hour
- Spin up: one loop
- Simulation sites:

  FLUXNET2015 sites; field trait-measurement sites
- Simulation periods: over 1200 site years
- Forcing: observed or WFDE5-based climate forcings

  + satellite LAI + observed atmospheric CO_2

Module options used in the two experiments

Modules	EEO scheme	Standard scheme
GPP and R_{canopy} (canopy carbon flux)	Trait acclimation	Static PFT-dependent (Ball-Berry module)
Dynamic vegetation	Use LAI input	
Soil moisture limitation	Noah	
Runoff and ground water	TOPMODEL with groundwater	
Surface layer drag coefficient	Monin-Obukhov similarity theory	
Supercooled liquid water	No iteration	
Frozen soil permeability	Linear effects	
Radiation transfer	Two-stream applied to vegetated fraction	
Ground snow surface albedo	CLASS	
Snow-rain partitioning	Jordan, 1991	
Lower boundary condition of soil temperature	TBOT at ZBOT (8m) read from a file	
Snow/soil temperature time scheme	Semi-implicit	
Surface resistance to evaporation/sublimation	Sakaguchi & Zeng, 2009	
Glacier	Phase change	
Defining soil properties	Use dominant soil texture input	

Benchmark data

Trait ($V_{\mathrm{cmax},25}$ and R_{25}):

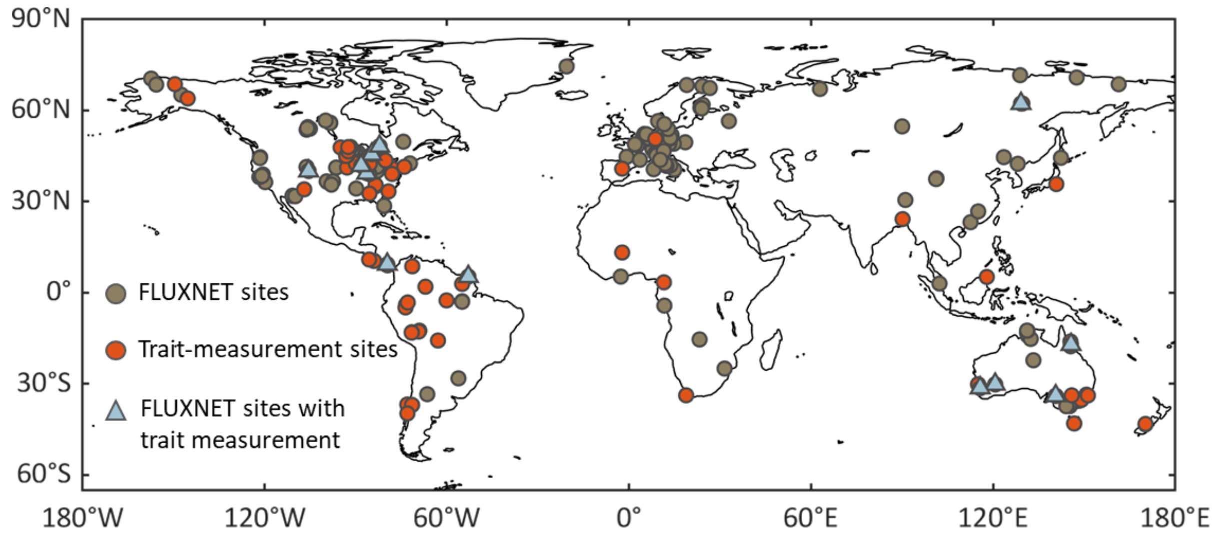
- extensive global field measurement

  (LCE: Smith & Dukes 2017; GlobResp: Atkin *et al.*, 2015)
- a five-year warming experiment

  (B4WarmED: Reich *et al.*, 2021)

more than 2000 paired measurements at 53 sites globally

Locations of the 53 trait-measurement sites and the 168 FLUXNET sites



Carbon flux:

- GPP: 168 FLUXNET sites covering 12 PFTs,

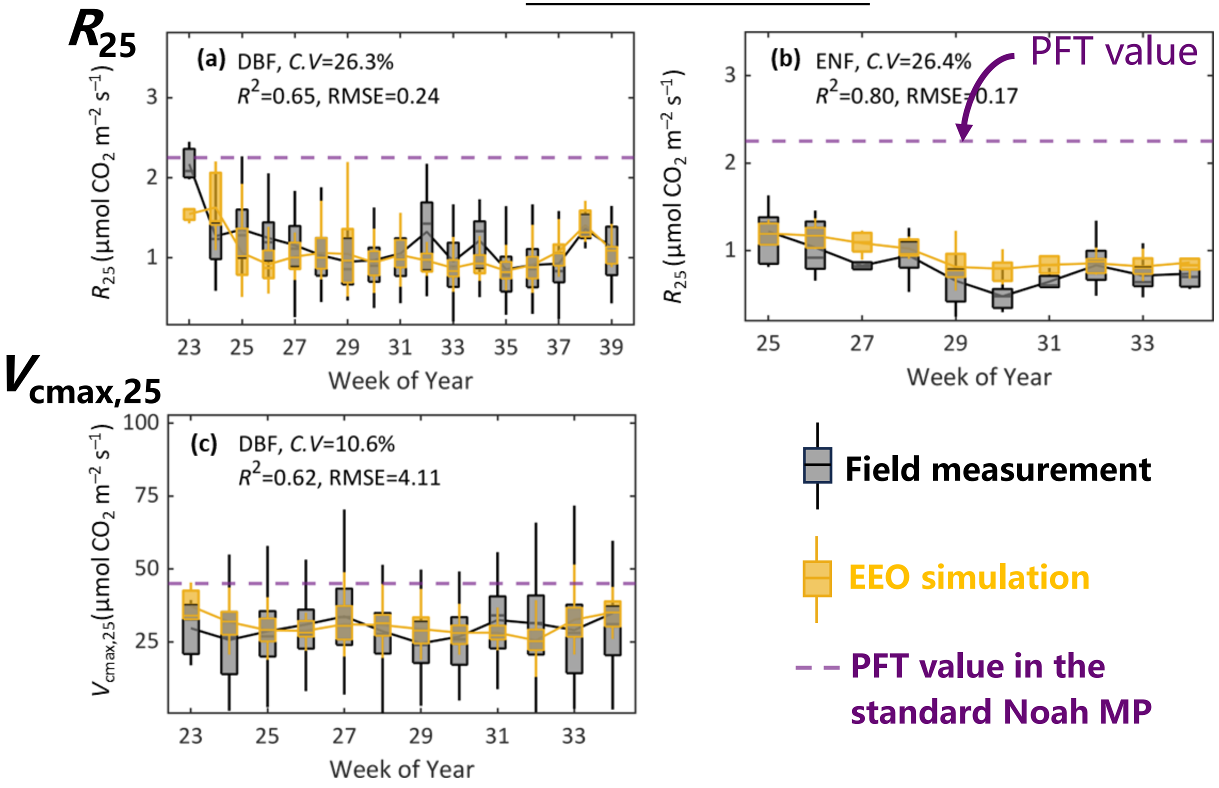
  1200 site-years observations
- R_{canopy}: upscaled from single leaf measurement of R_{25} to canopy level ($R_{\mathrm{canopy}}=\mathrm{LAI}\cdot R_{25}\cdot f_r(T)$)

Result 1: Simulation of Trait Variations

Observed $V_{cmax,25}$ and R_{25} displayed substantial variability temporally and spatially within each PFT.

- The standard scheme with constant parameter values cannot be expected to reproduce the observed seasonal variability
- The new EEO-based scheme reasonably well captured both seasonal and latitudinal variation (R^2 of 0.7 for R_{25} and 0.6 for $V_{cmax,25}$)

Seasonal variation



Spatial variation

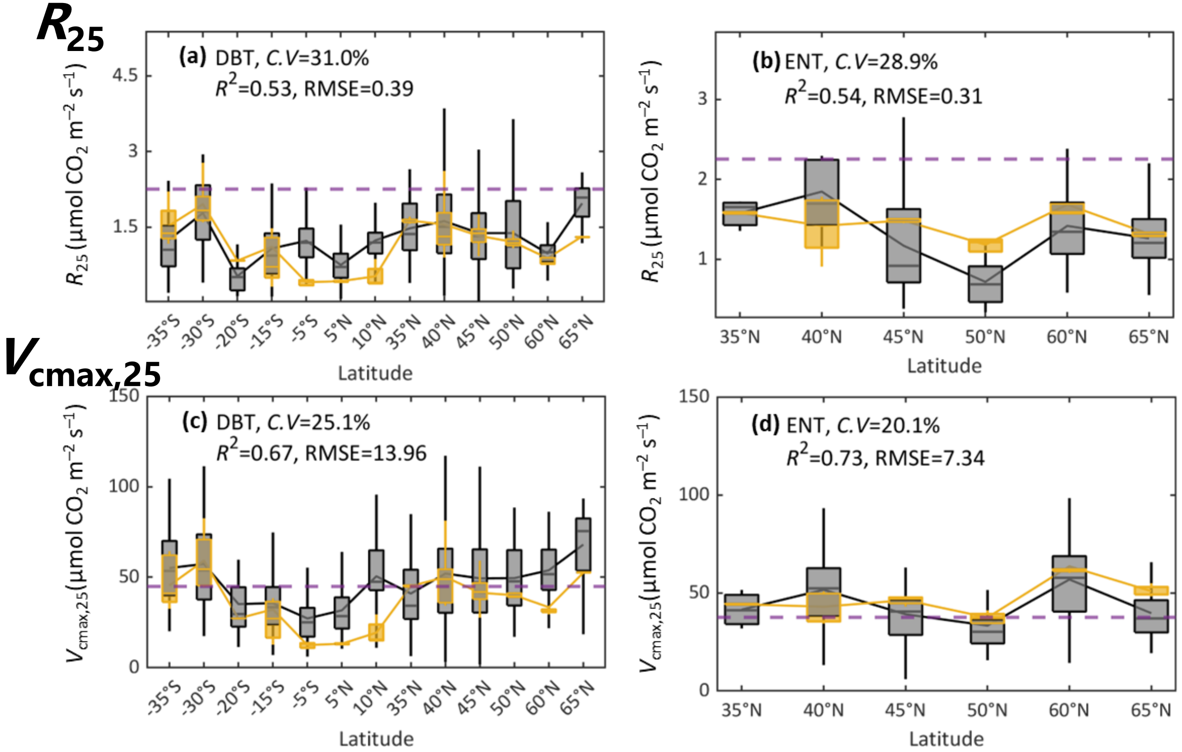


Figure Variations in R_{25} and $V_{cmax,25}$ for the specific PFT

Result 2: Evaluation of Carbon Flux Variations-GPP

- EEO-based scheme successfully reproduced the variations in half-hourly GPP at the 12 FLUXNET sites (higher median R^2: 0.86 (standard scheme) to 0.94 (EEO-based scheme); lower median RMSE: 3.6 to 2.4 μmol CO_2 m^{-2} s^{-1})

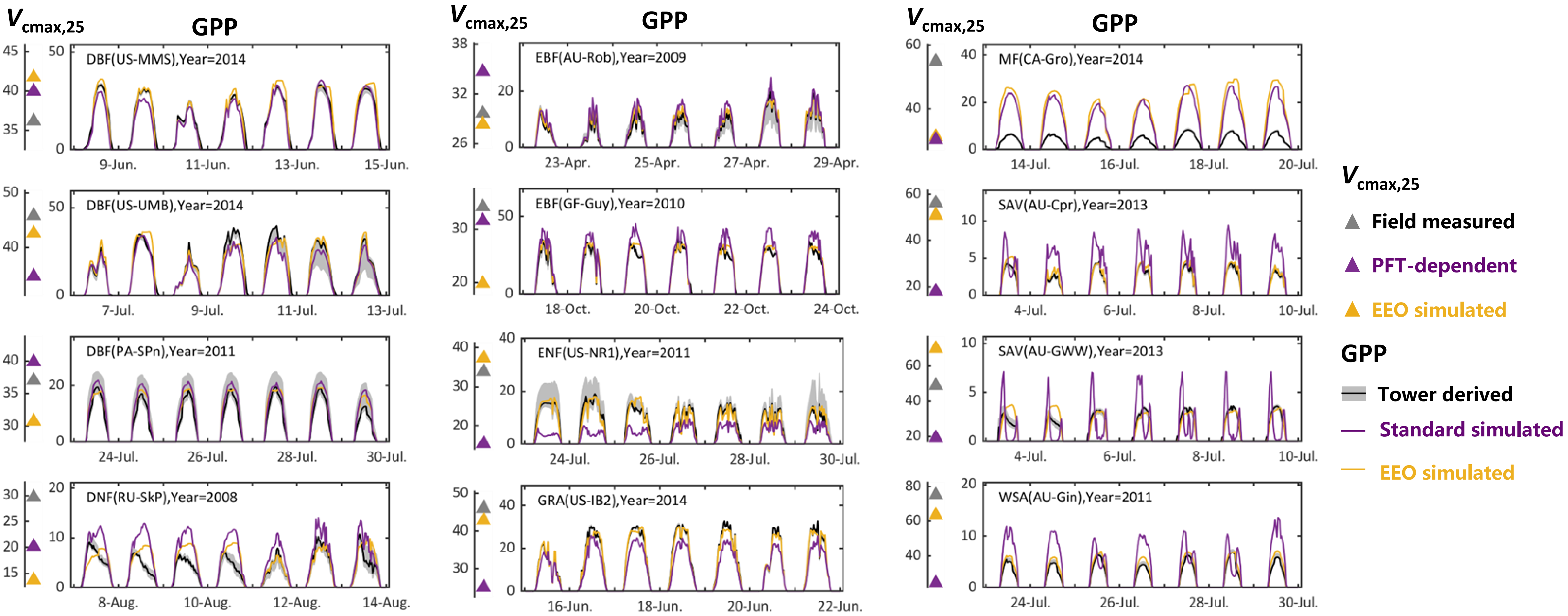


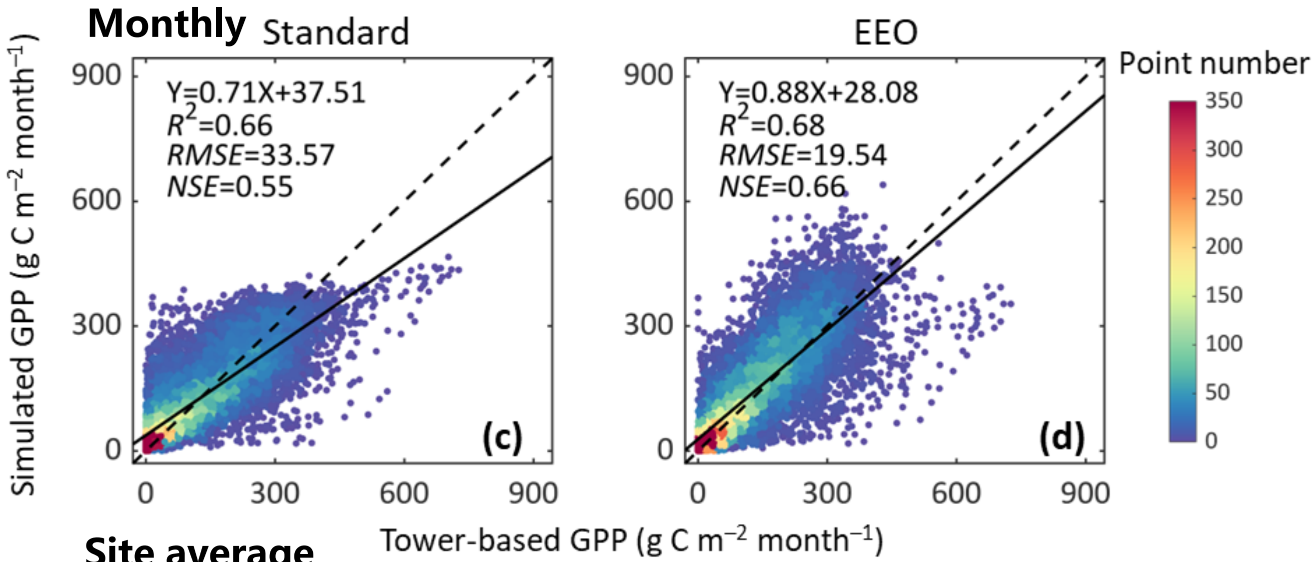
Figure Half-hourly GPP at 12 FLUXNET sites at which field trait were measured.

Result 2: Evaluation of Carbon Flux Variations-GPP

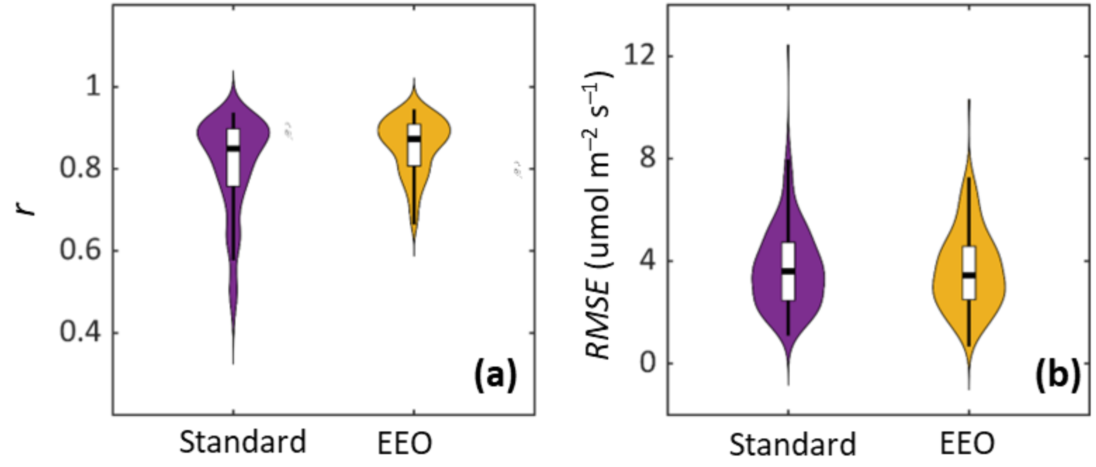
Across all the FLUXNET2015 sites, the EEO-based scheme performed better than the standard scheme in predicting GPP variations at the half-hourly, monthly, and annual scales.

- Improve the underestimation （10.1% → 2.4% ）
- Higher accuracy (R^2 : 0.57 → 0.66;
  RMSE: 33.6 to 19.6 μmol CO_2 m^{-2} $month^{-1}$)

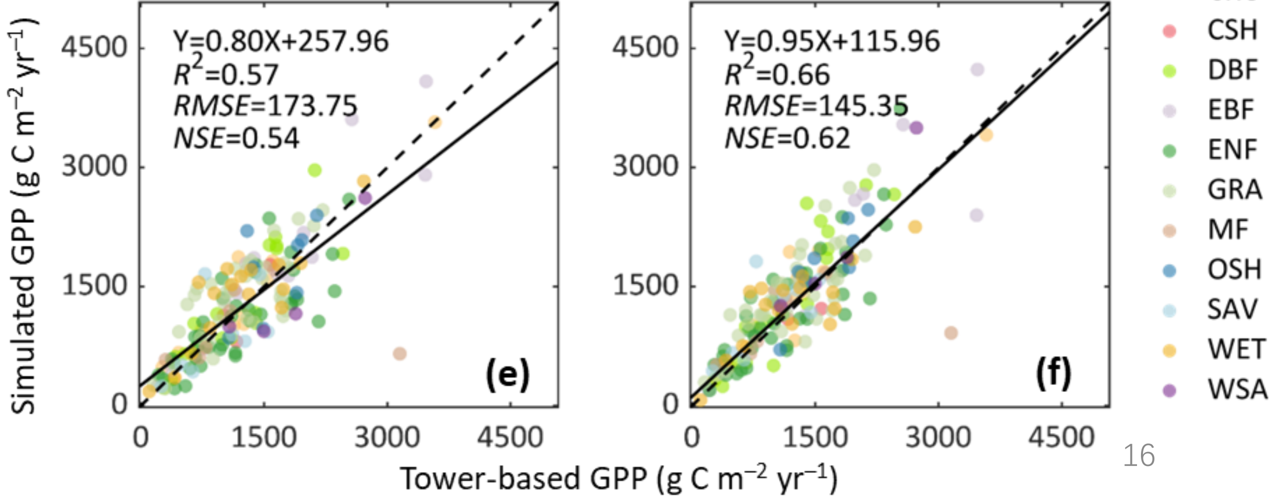
Monthly



Half hourly

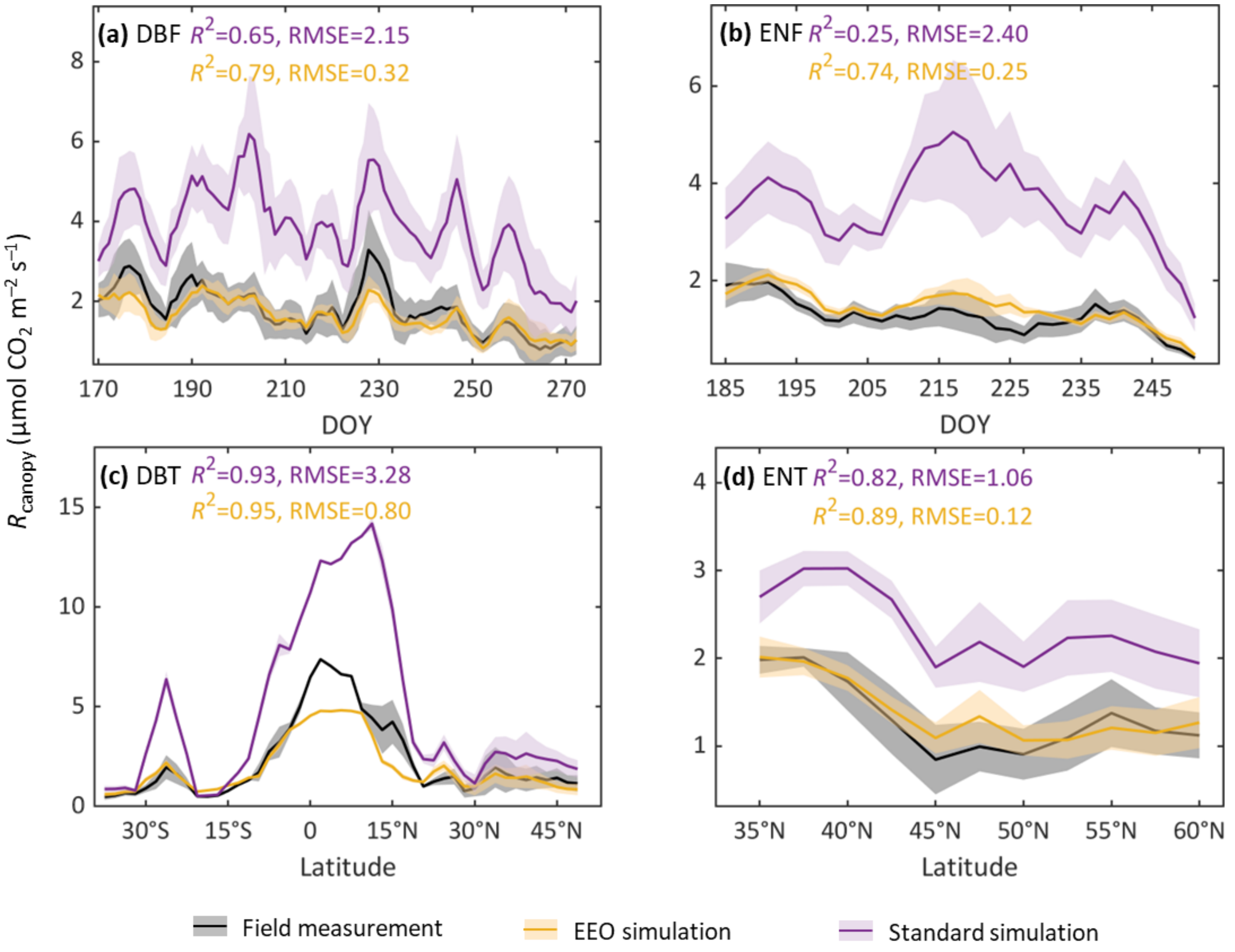


Site average



Result 2: Evaluation of Carbon Flux Variations-R_{canopy}

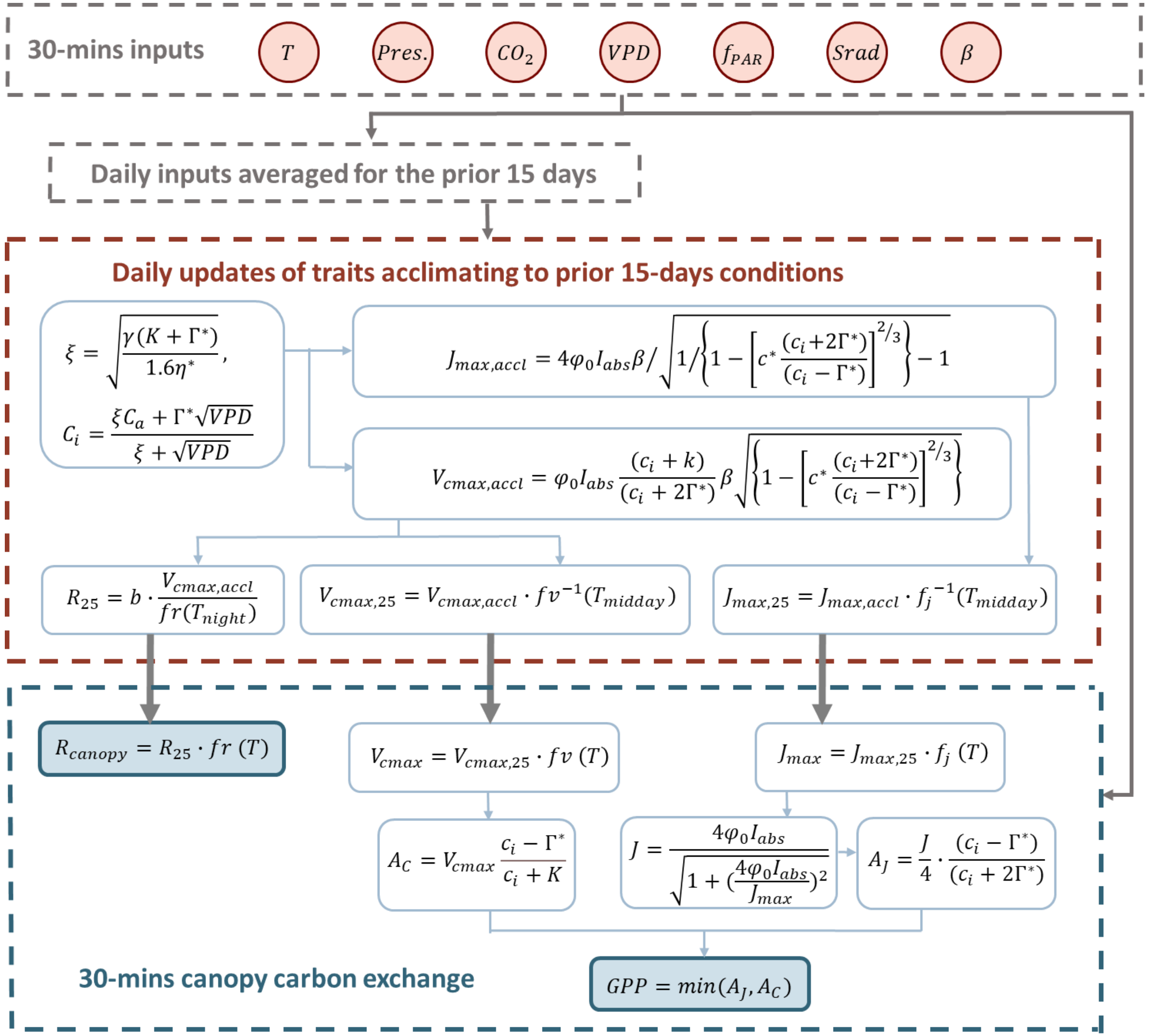
- Standard scheme produced an excessive CO_2 release from leaf respiration, and overestimated measured R_{canopy} by more than twice.
- EEO-based scheme produced a more accurate R_{canopy} with a maximum bias of 10%.



Take home messages

- The EEO-based scheme produces more realistic simulations of GPP and R_{canopy}, which are underestimated and overestimated respectively in the standard scheme. ➔ result in less net CO_2 uptake by land ecosystems using the standard scheme.
- The EEO-based scheme captures most of the variation of photosynthetic and respiratory traits across different locations and over time.
- The EEO-based scheme has fewer parameters than the standard one and is simple to implement. The new scheme is also less computationally demanding as it avoid the need for iterative solutions.

Flowchart of the trait-acclimation scheme incorporated in Noah MP



30-mins inputs

T

$Pres.$

CO_2

VPD

f_{PAR}

$Srad$

β

Daily inputs averaged for the prior 15 days

Daily updates of traits acclimating to prior 15-days conditions

$$\xi = \sqrt{\frac{\gamma(K+\Gamma^*)}{1.6\eta^*}},$$

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$$V_{cmax,accl} = \varphi_0 I_{abs}\frac{(c_i+k)}{(c_i+2\Gamma^*)}\beta\sqrt{\left\{1-\left[c^*\frac{(c_i+2\Gamma^*)}{(c_i-\Gamma^*)}\right]^{2/3}\right\}}$$

$$R_{25} = b\cdot\frac{V_{cmax,accl}}{fr(T_{night})}$$

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$$J = \frac{4\varphi_0 I_{abs}}{\sqrt{1+(\frac{4\varphi_0 I_{abs}}{J_{max}})^2}}$$

$$A_J = \frac{J}{4}\cdot\frac{(c_i-\Gamma^*)}{(c_i+2\Gamma^*)}$$

30-mins canopy carbon exchange

$$GPP = min(A_J, A_C)$$

Thanks for your attention!

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