Moving toward the next-generation land surface modeling

Yujie Wang

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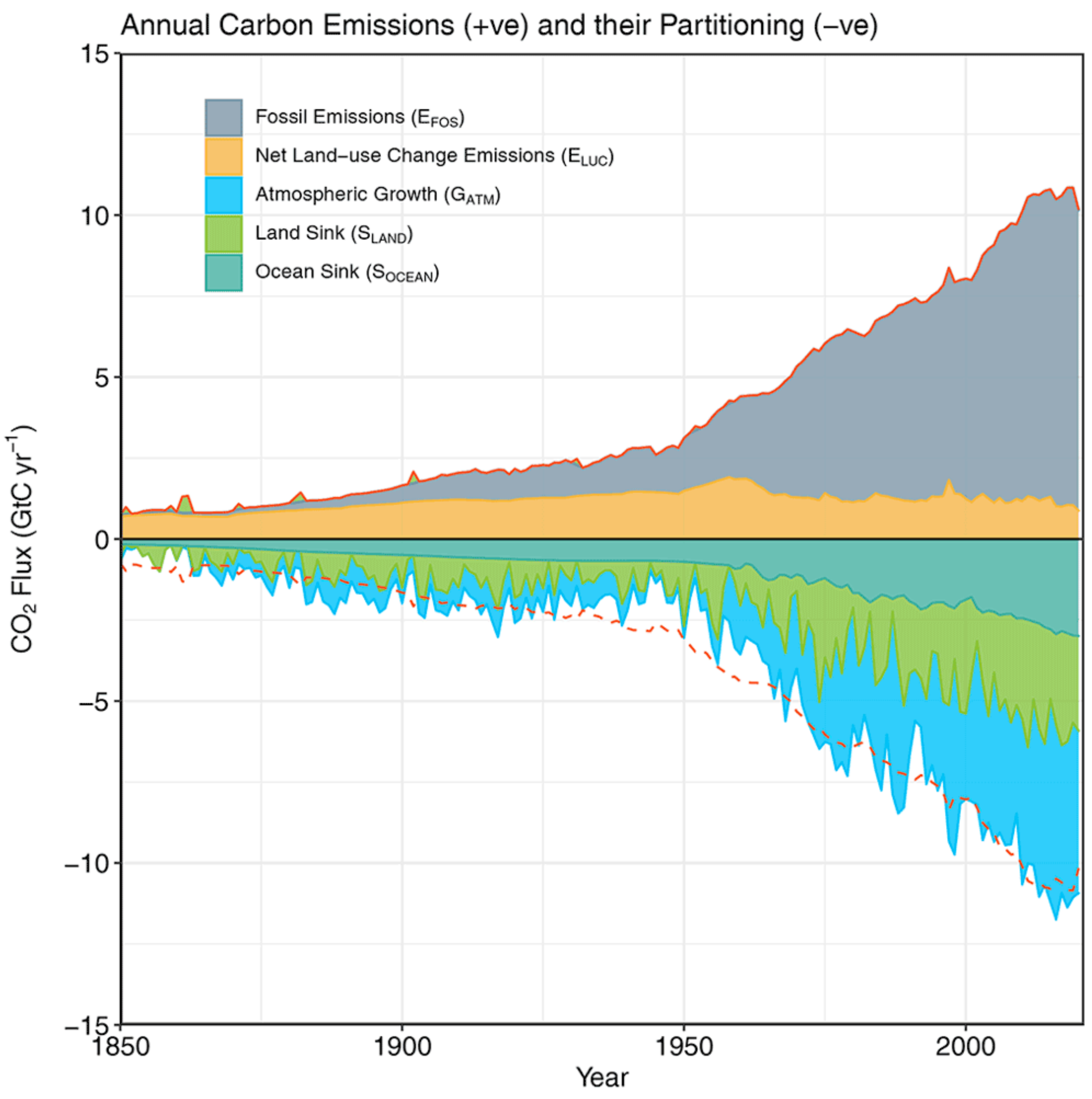
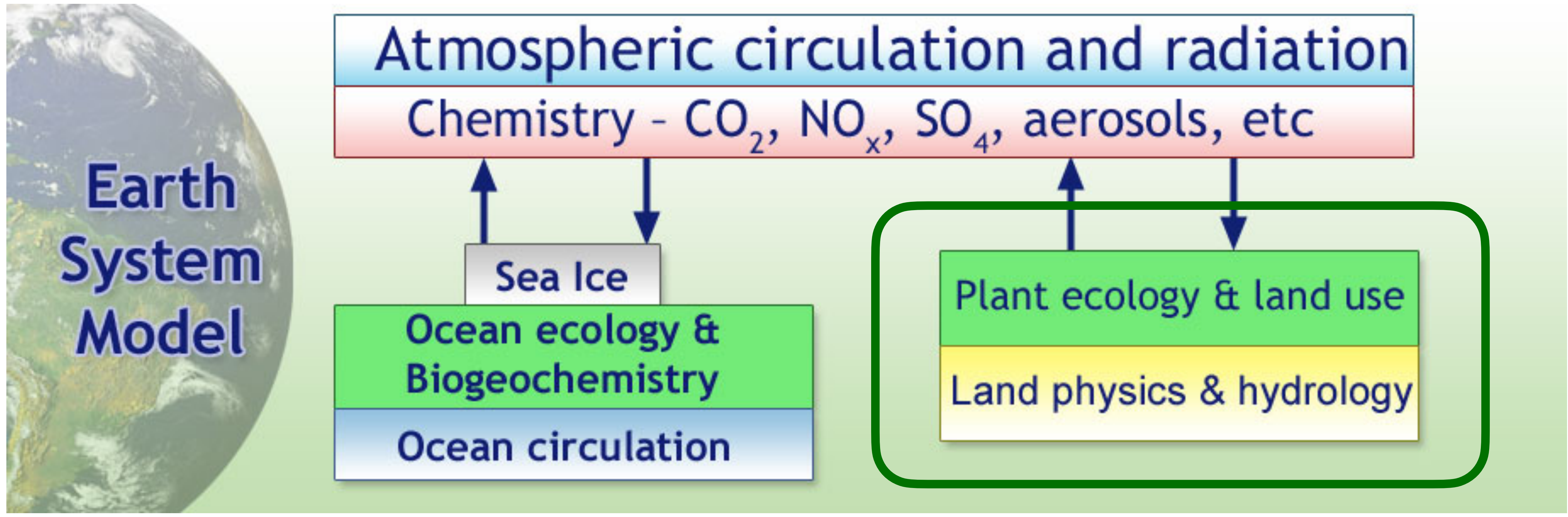
Land takes up **25%** of emitted CO_2, but we do not know how much nature can help in the future



Friedlingstein et al. (2022) Earth System Science Data

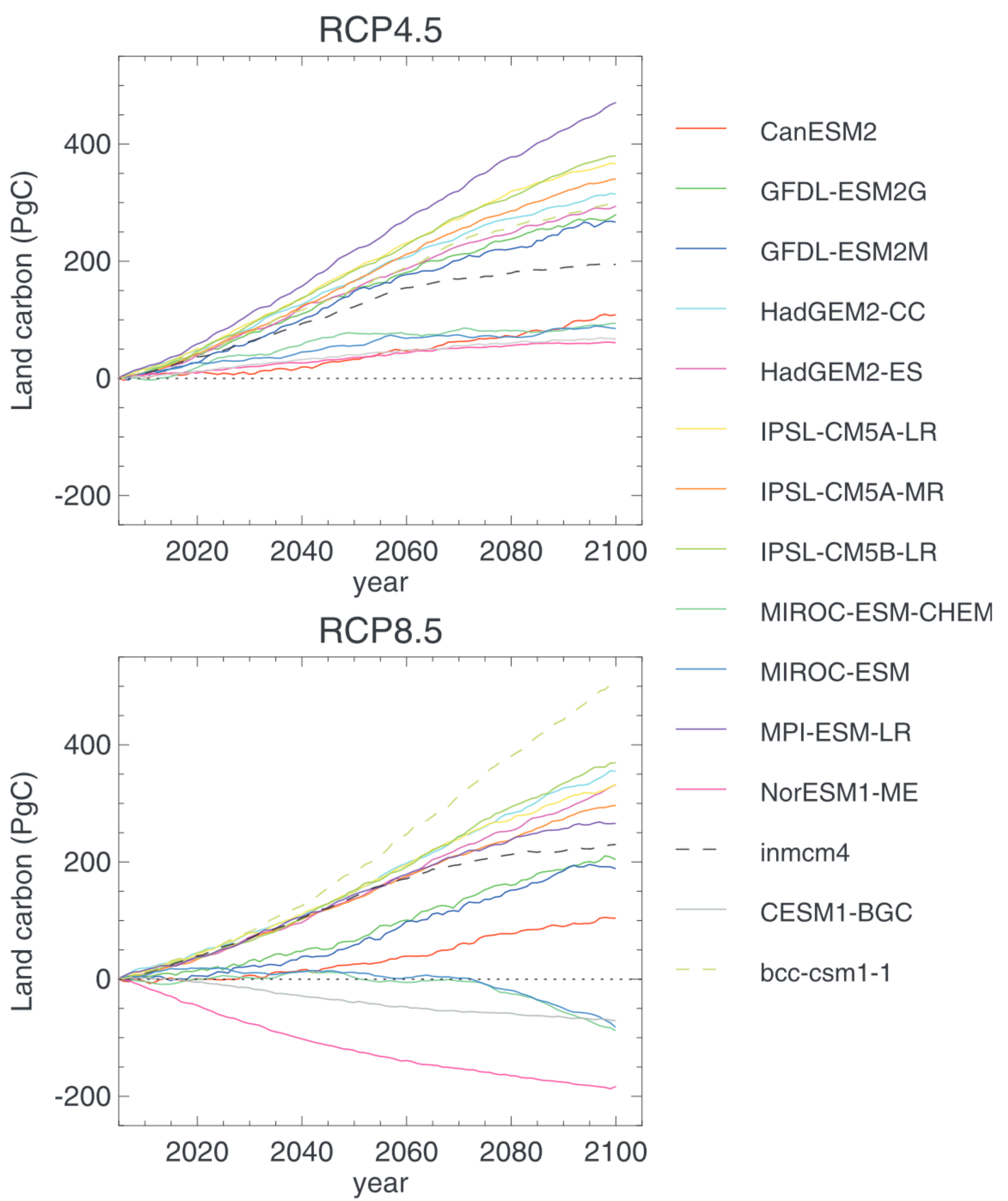
Climate Model

Earth System Model



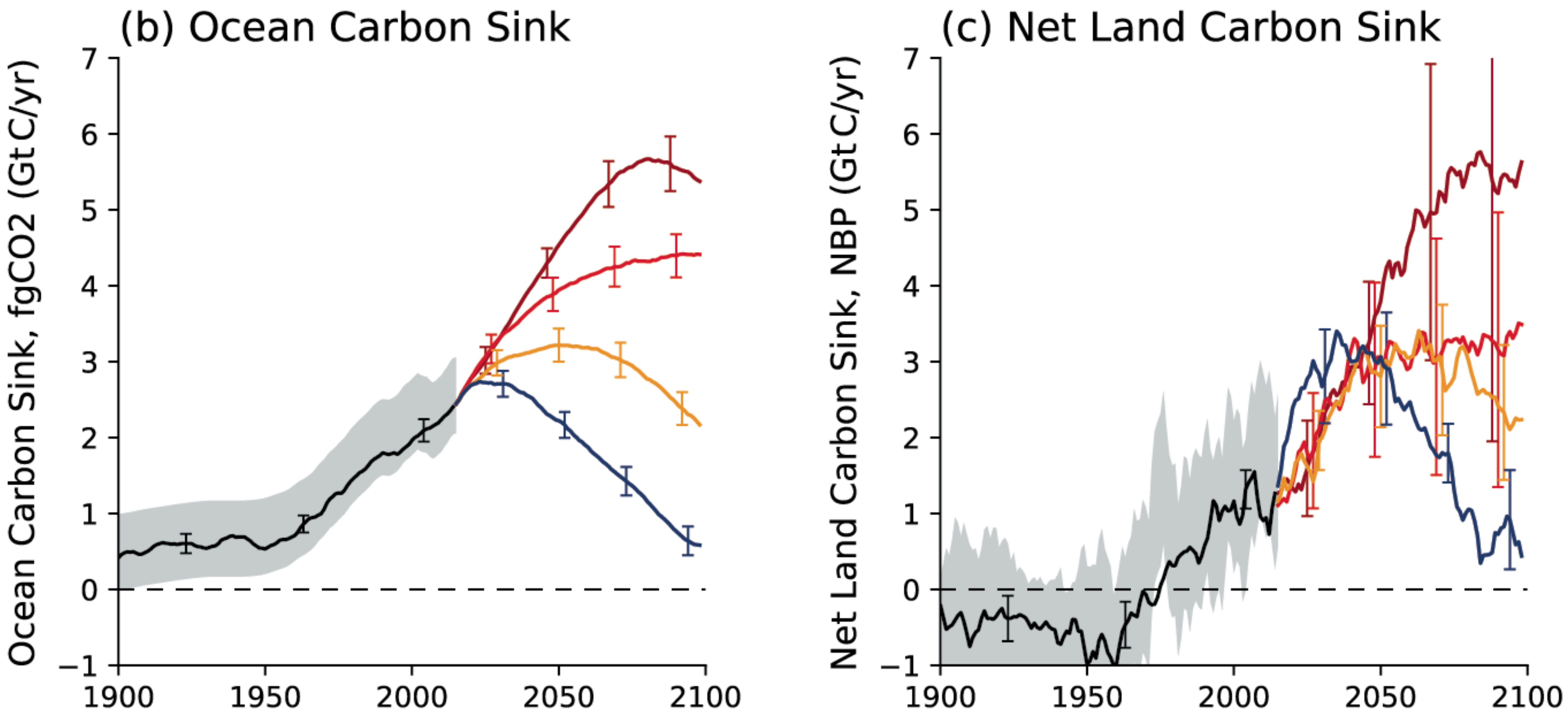
Land Surface Model

Climate models differ in their projections of land carbon sink strength, even in the directions



Jones et al. (2013) Journal of Climate

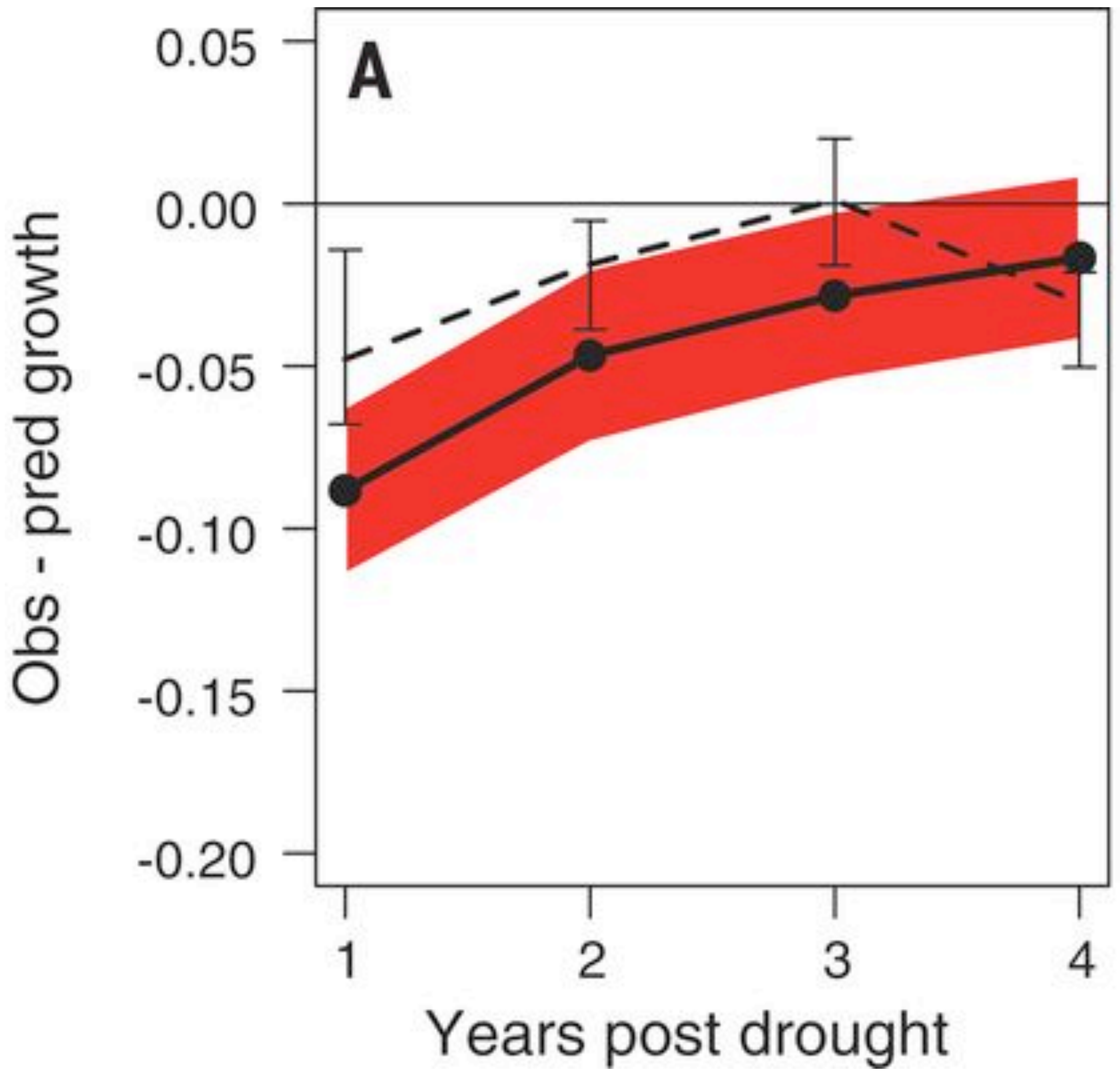
Climate models **differ** in their projections of land carbon sink strength, even in the **directions**



IPCC (2023)

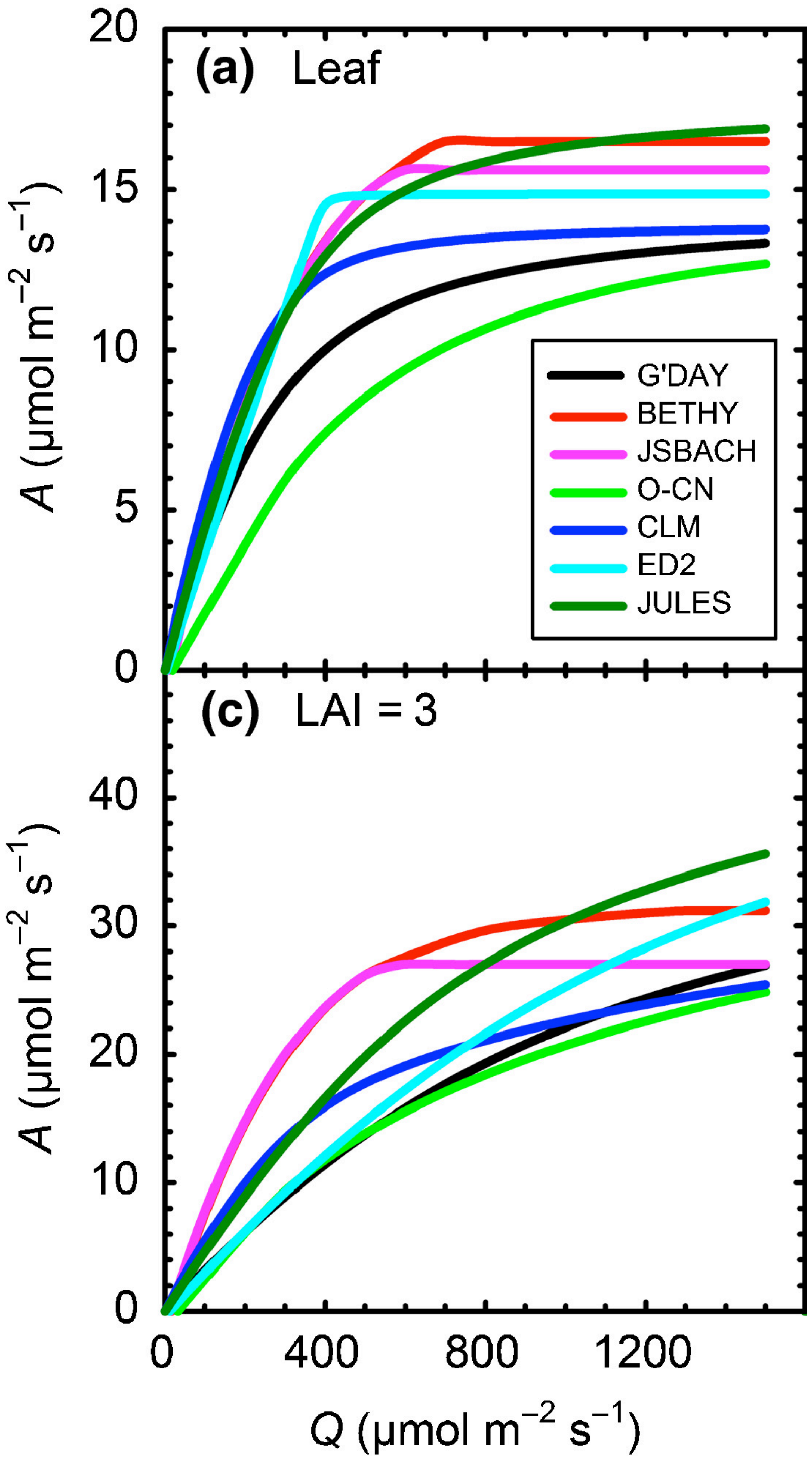
Potential Reasons

1. **Lack physiological representations**



Anderegg et al. (2015) Science

2. Contrasting model parameterization



Rogers et al. (2017) New Phytologist

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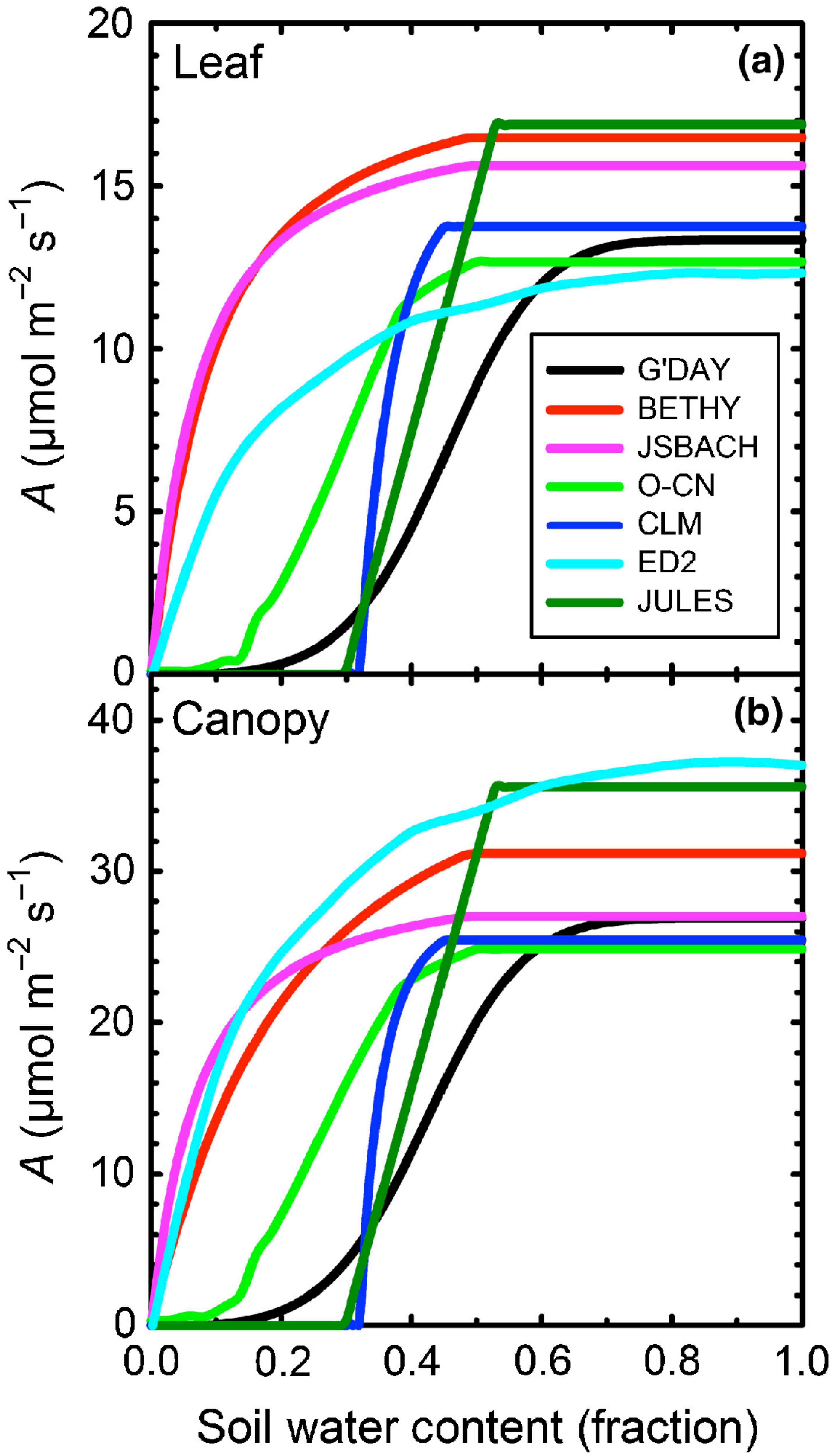
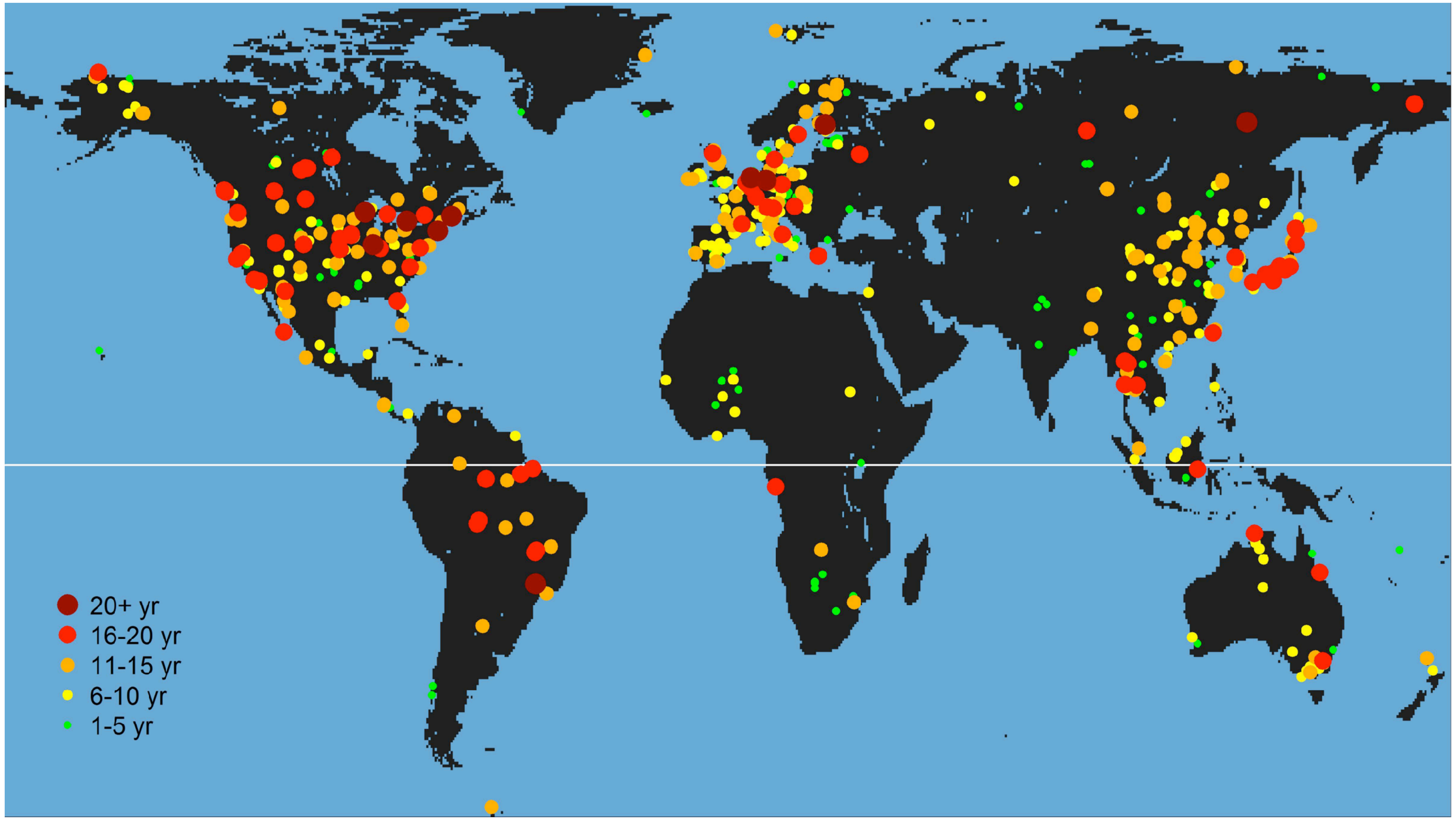


Rogers et al. (2017) New Phytologist

3. Limited data to calibrate the model

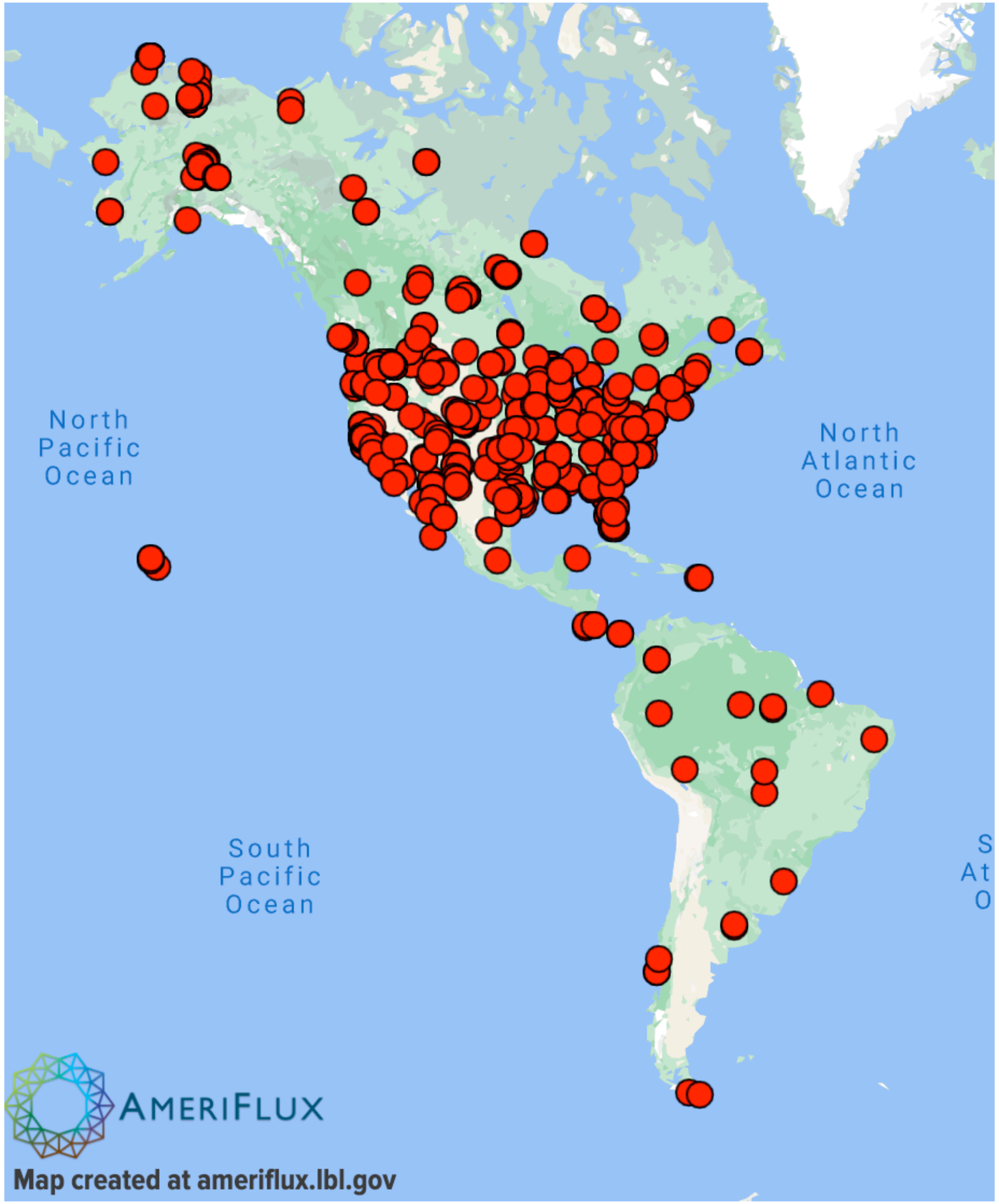


FluxNet 2015

3. Limited data to calibrate the model

ChinaFlux

3. Limited data to calibrate the model



AmeriFlux

Site ID	Policy	Data Product (Variables)	1990					1995					2000					2005					2010					2015					2020		
BR-CST	C	AmeriFlux BASE (32)																									✔	✔							
		AmeriFlux FLUXNET																									✔	✔							
BR-Sa1	C	AmeriFlux BASE (17)													✔	✔	✔	✔	✔	✔	✔	✔	✔	✔											
BR-Sa3	L	AmeriFlux BASE (26)											✔	✔	✔	✔	✔																		
CA-Ca1	C	AmeriFlux BASE (33)							✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔												
CA-Ca2	C	AmeriFlux BASE (28)										✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔												
CA-Ca3	C	AmeriFlux BASE (39)												✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	

Challenges

1. Schemes

Improve model representation of soil-plant-air continuum

2. Setups

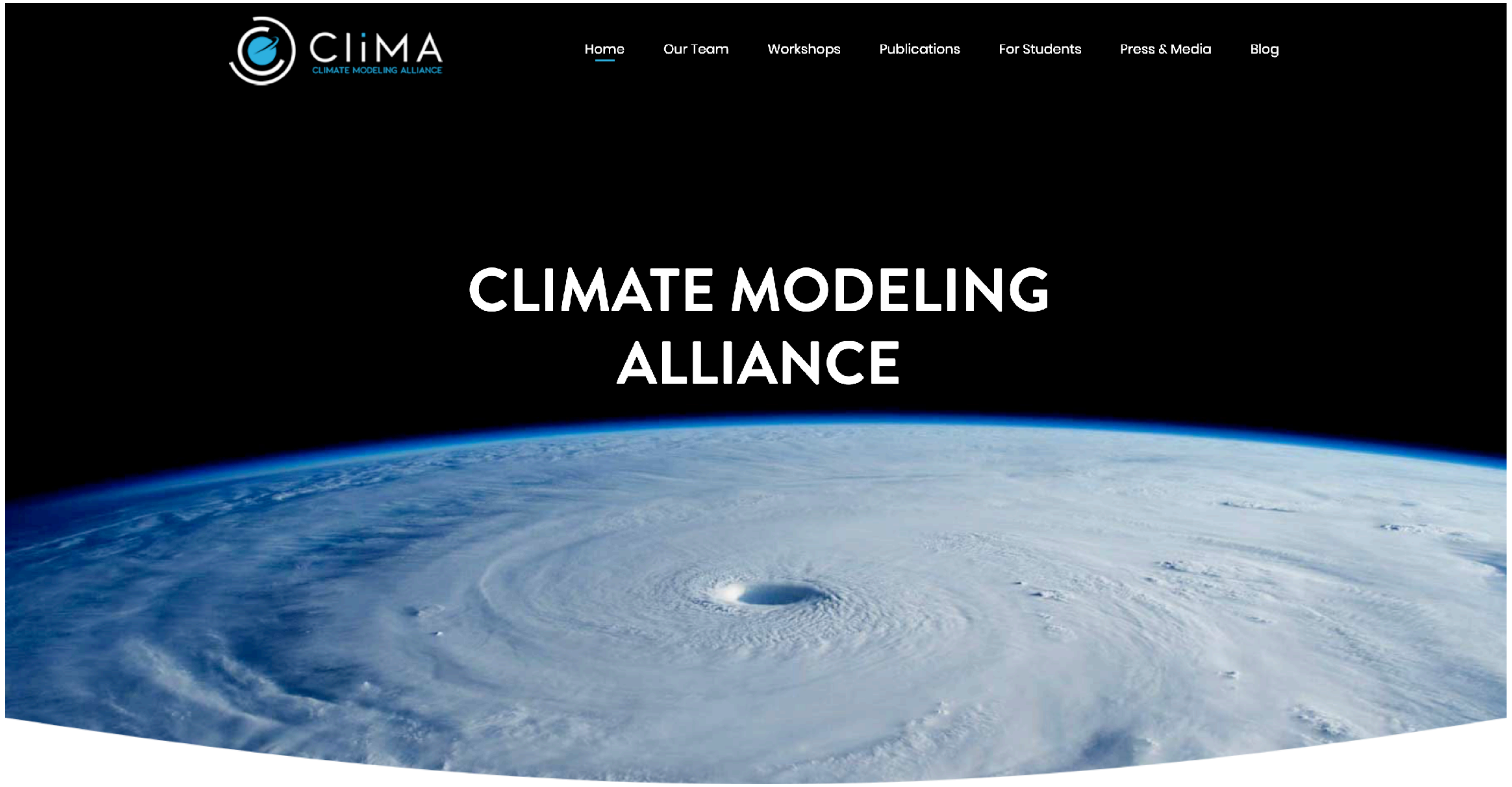
Advance model parameters configuration

3. Calibration

Use more data to calibrate the models

Next-Generation
Land Surface Model

CliMA Land



Next generation

What make a next generation model?

Learn from data

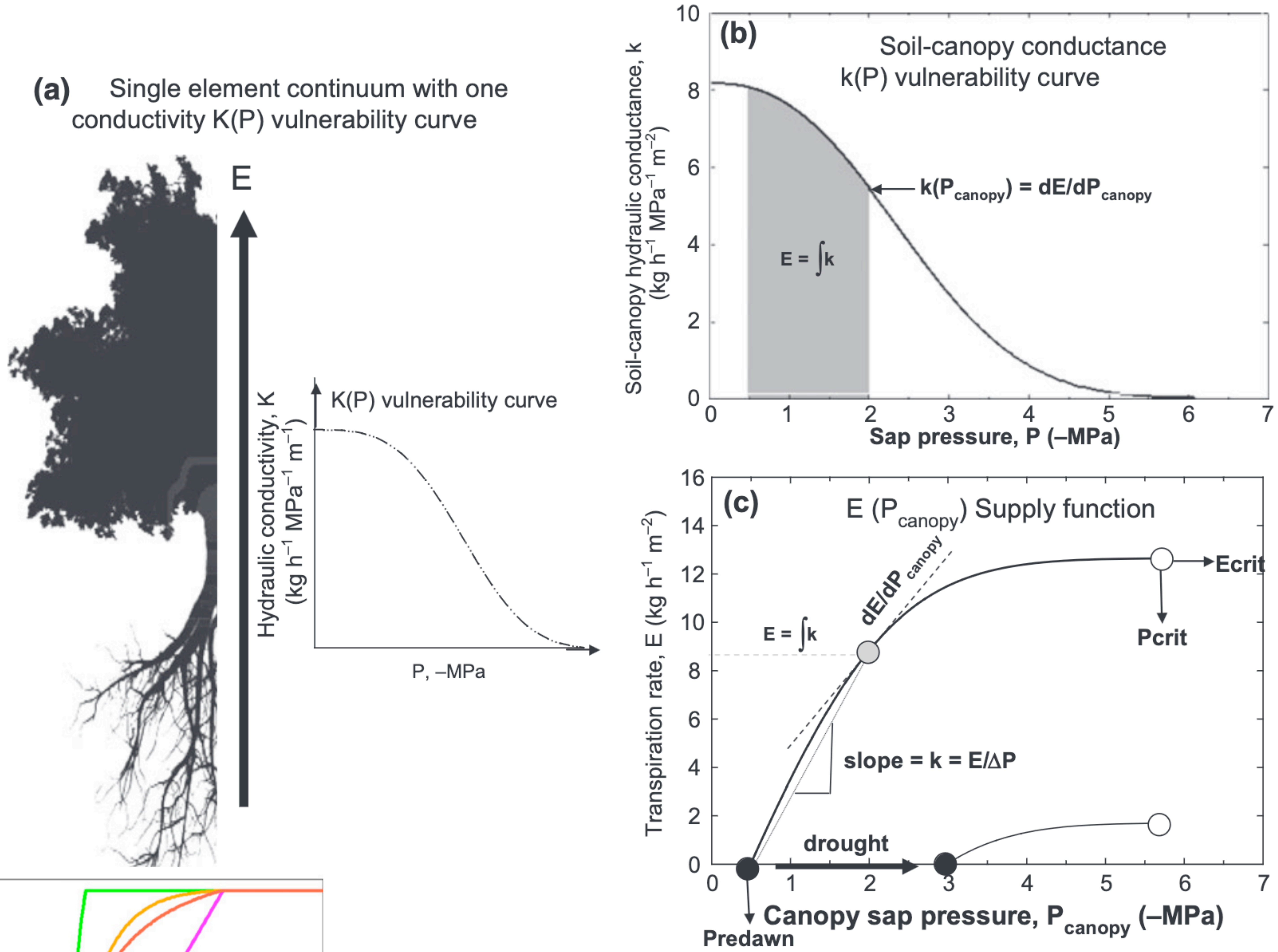
- What to learn?
- How to learn?
- Whom to learn?

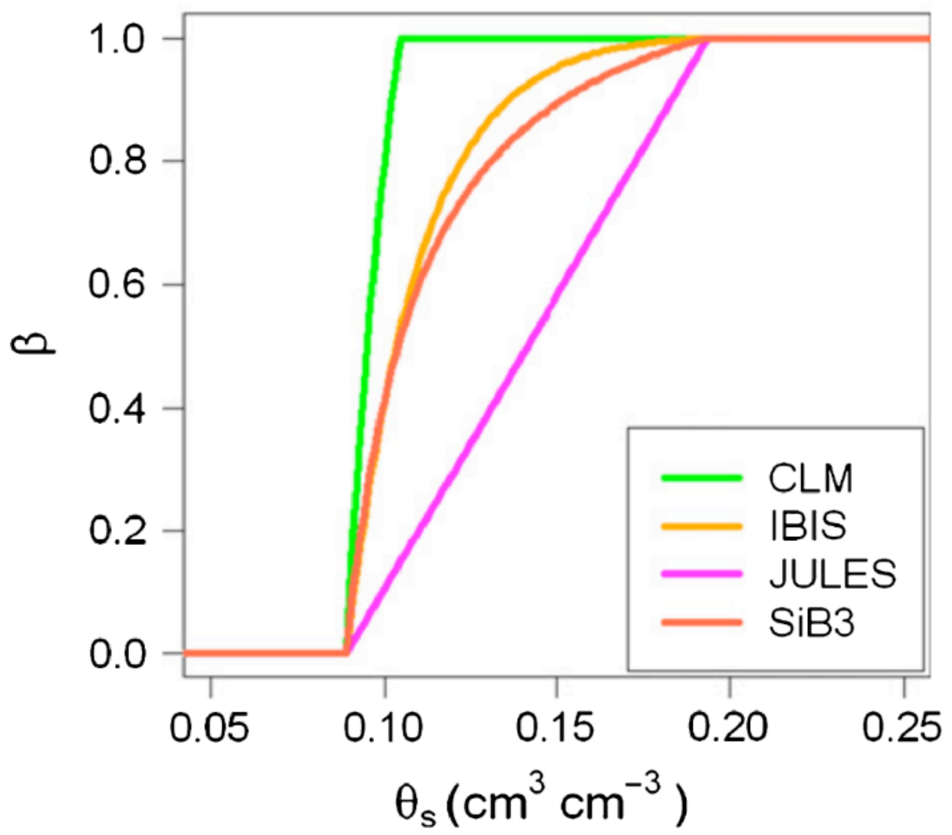
Model framework

- Modularity
- Scalability
- Architecture
- User friendly

1. Schemes

Improve model representation of plant water relations





Sperry and Love (2015) New Phytologist

2. Setups

Advance model parameter configuration for leaf traits

Plant Functional Type	χ_L	α^{leaf}_{vis}	α^{leaf}_{nir}	α^{stem}_{vis}	α^{stem}_{nir}	τ^{leaf}_{vis}	τ^{leaf}_{nir}
NET Temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10
NET Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10
NDT Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10
BET Tropical	0.10	0.10	0.45	0.16	0.39	0.05	0.25
BET temperate	0.10	0.10	0.45	0.16	0.39	0.05	0.25
BDT tropical	0.01	0.10	0.45	0.16	0.39	0.05	0.25
BDT temperate	0.25	0.10	0.45	0.16	0.39	0.05	0.25
BDT boreal	0.25	0.10	0.45	0.16	0.39	0.05	0.25

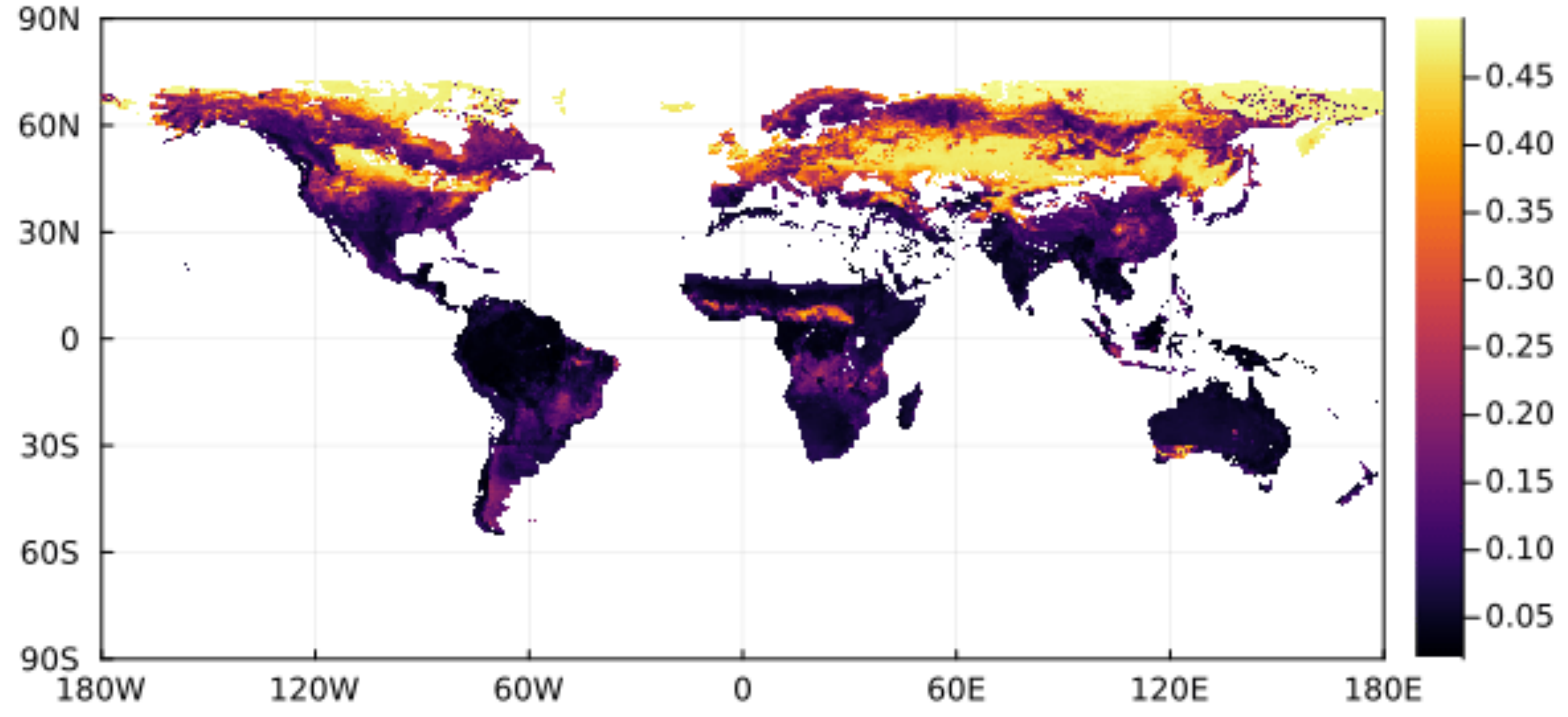


Table from CLM5 Tech Notes

2. Setups

Advance model parameter configuration for leaf traits

Plant Functional Type	χ_L	α_{vis}^{leaf}	α_{nir}^{leaf}	α_{vis}^{stem}	α_{nir}^{stem}	τ_{vis}^{leaf}	τ_{nir}^{leaf}
NET Temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10
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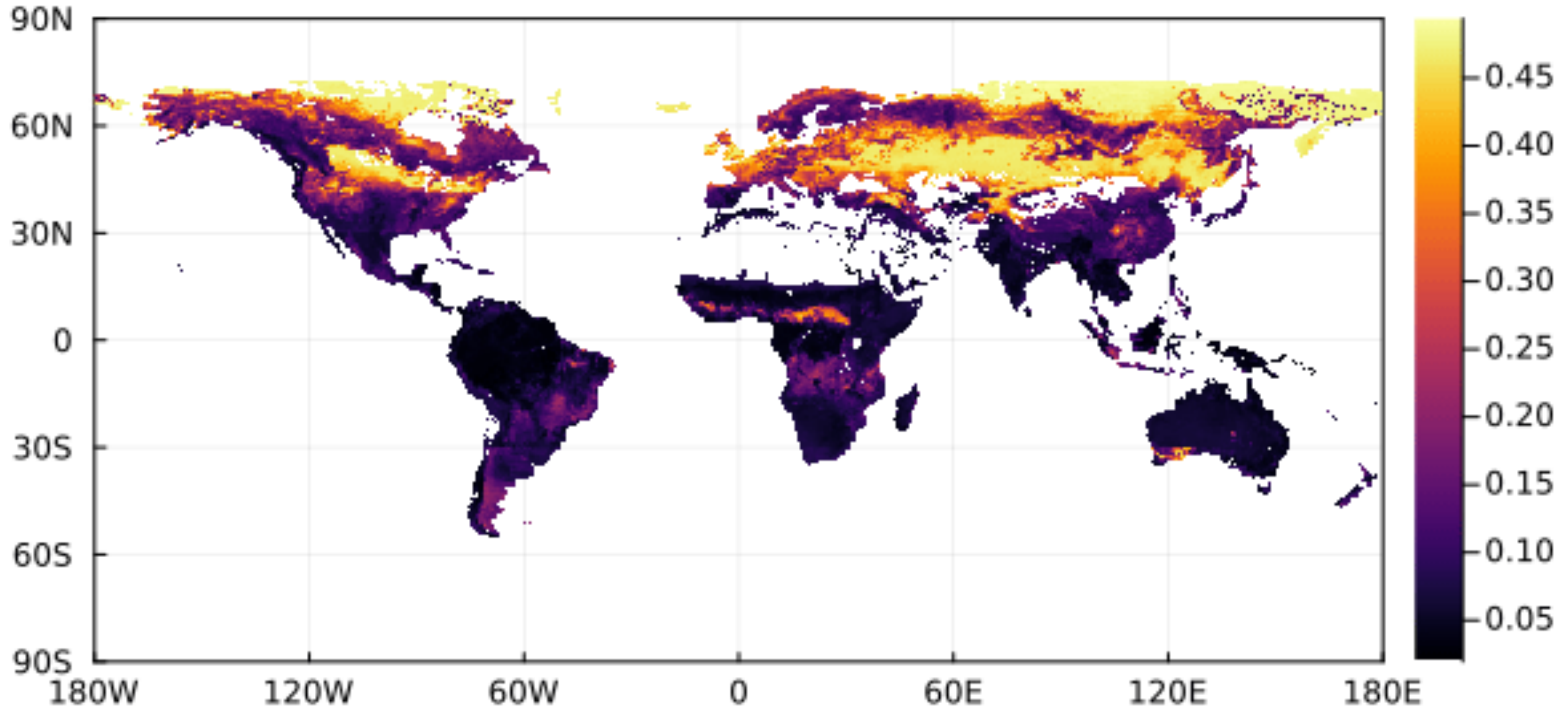
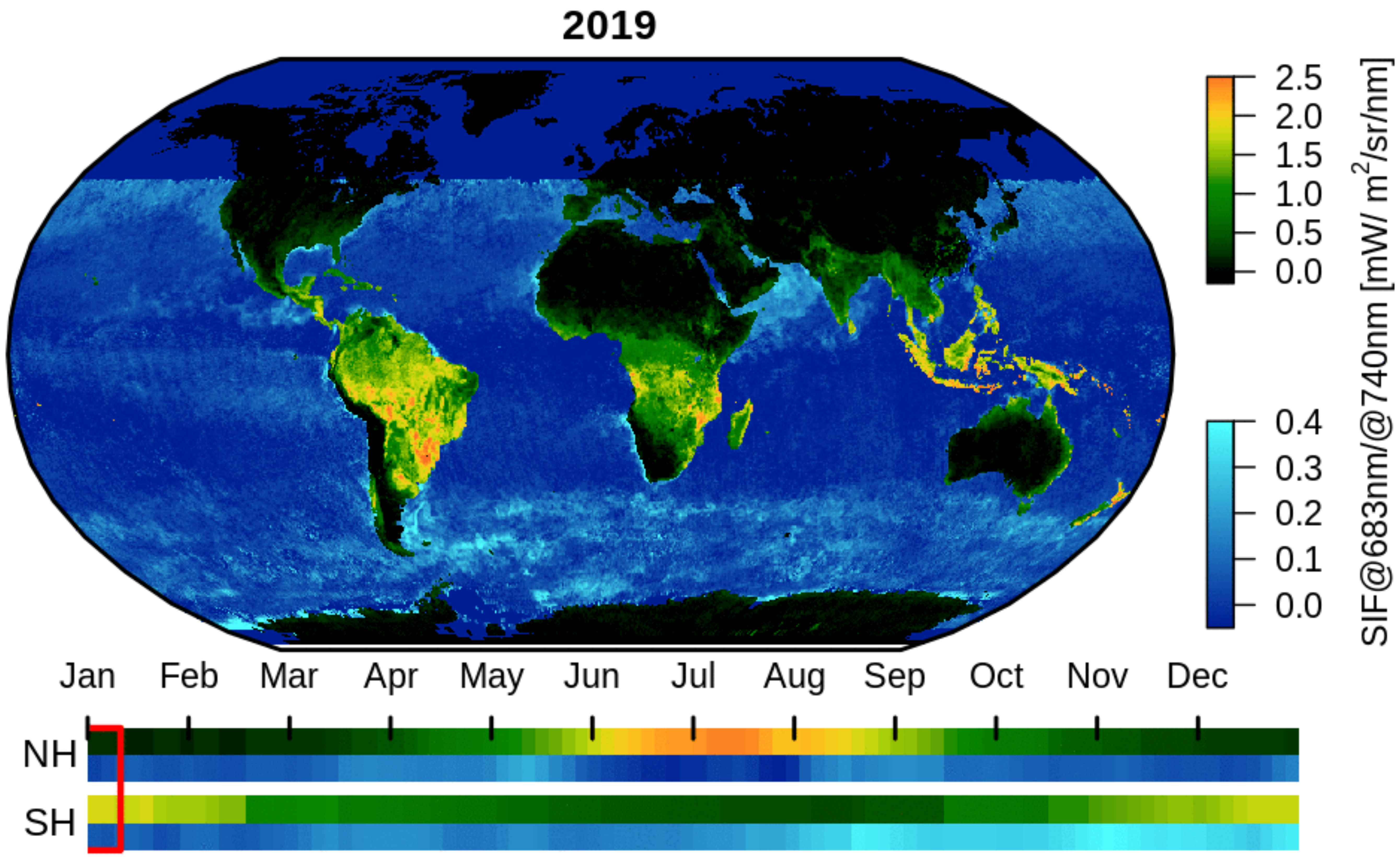


Table from CLM5 Tech Notes

3. Calibration

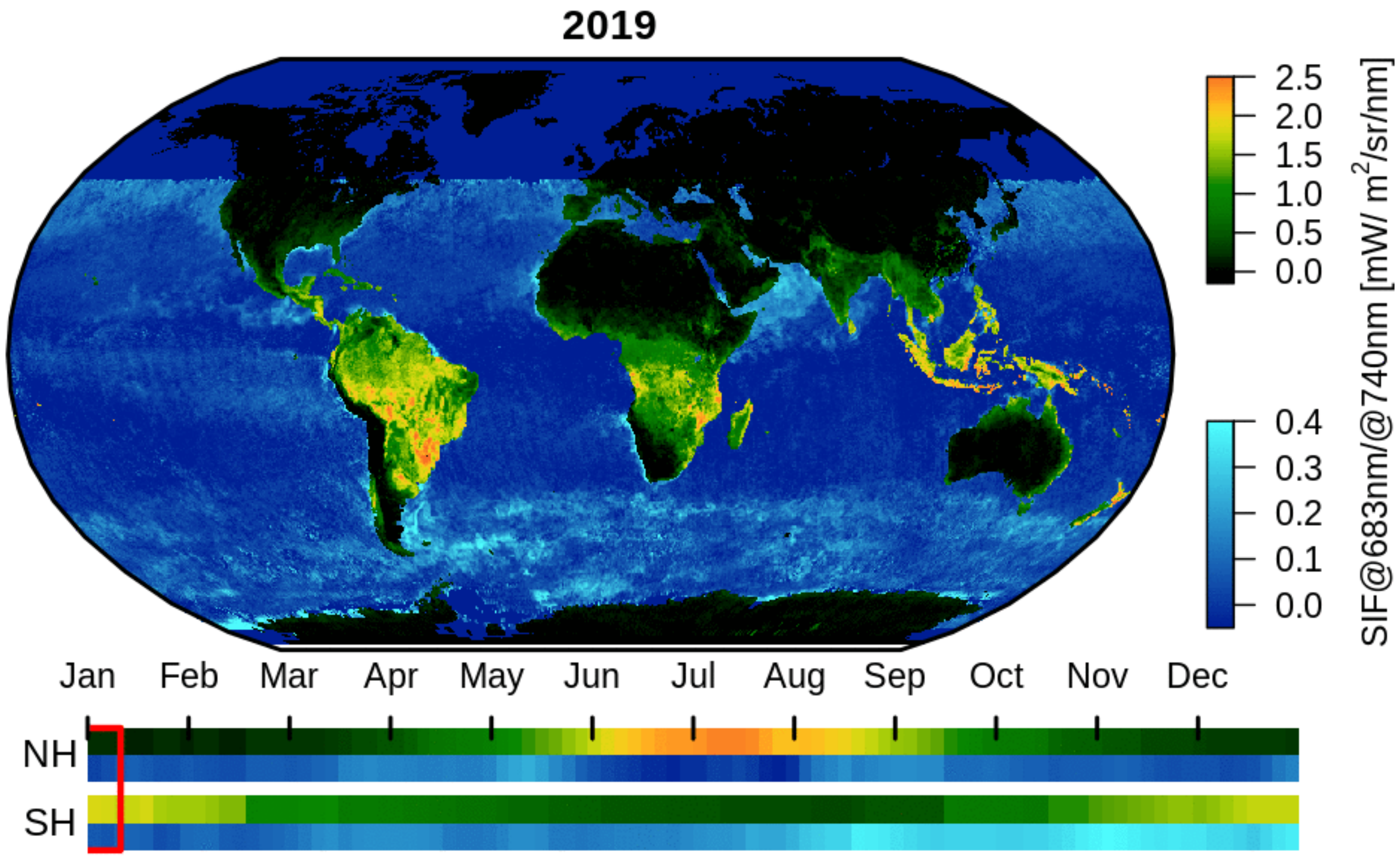
Use remote sensing data to calibrate the models



Köhler et al. (2018, 2020) Geophysical Research Letters

3. Calibration

Use remote sensing data to calibrate the models



Köhler et al. (2018, 2020) Geophysical Research Letters

Towards a more physiology-based representation of **daytime** stomatal conductance

1. Schemes

Improve model representation of soil-plant-air continuum

2. Setups

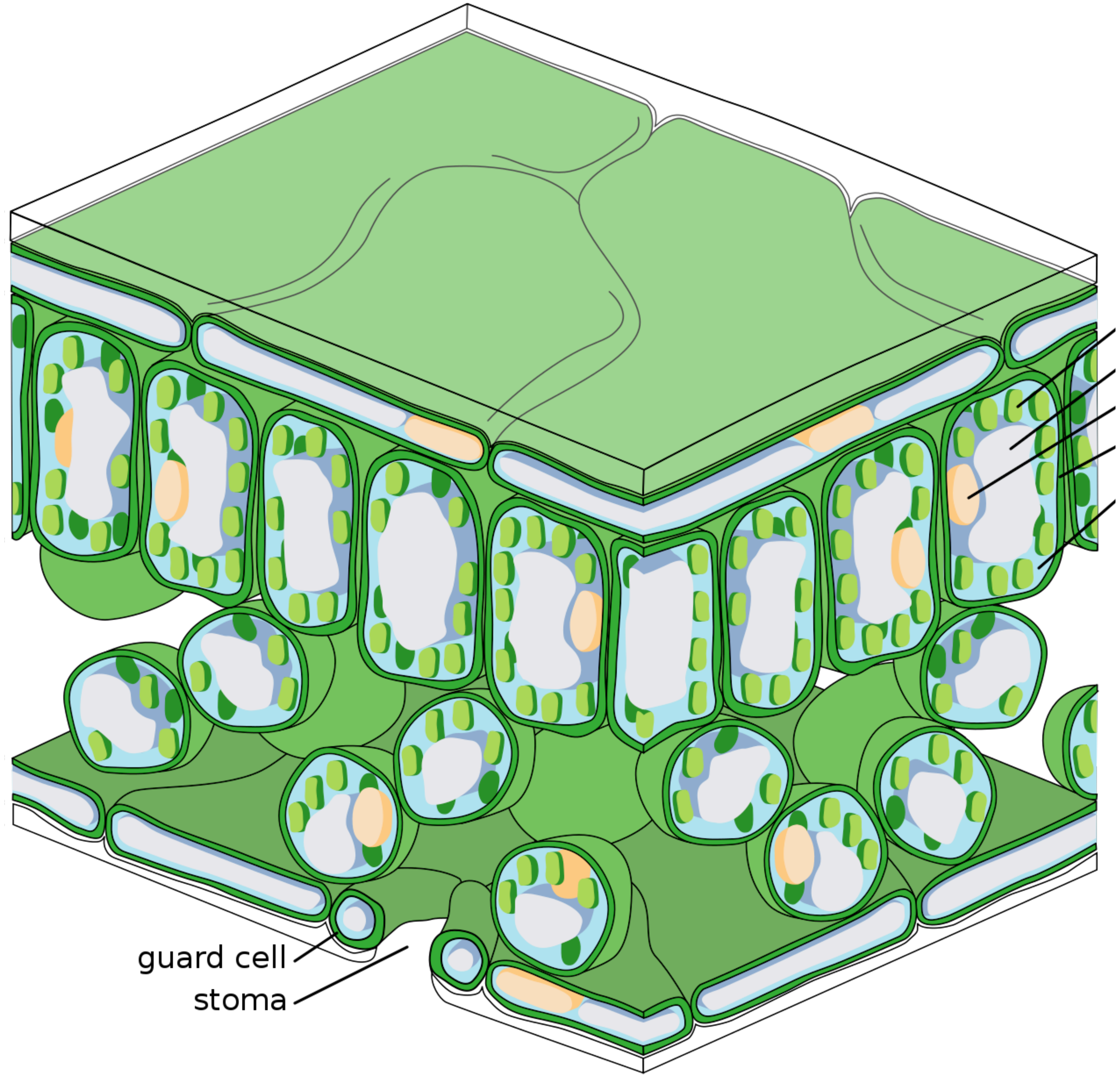
Advance model parameters configuration

3. Calibration

Use more data to calibrate the models

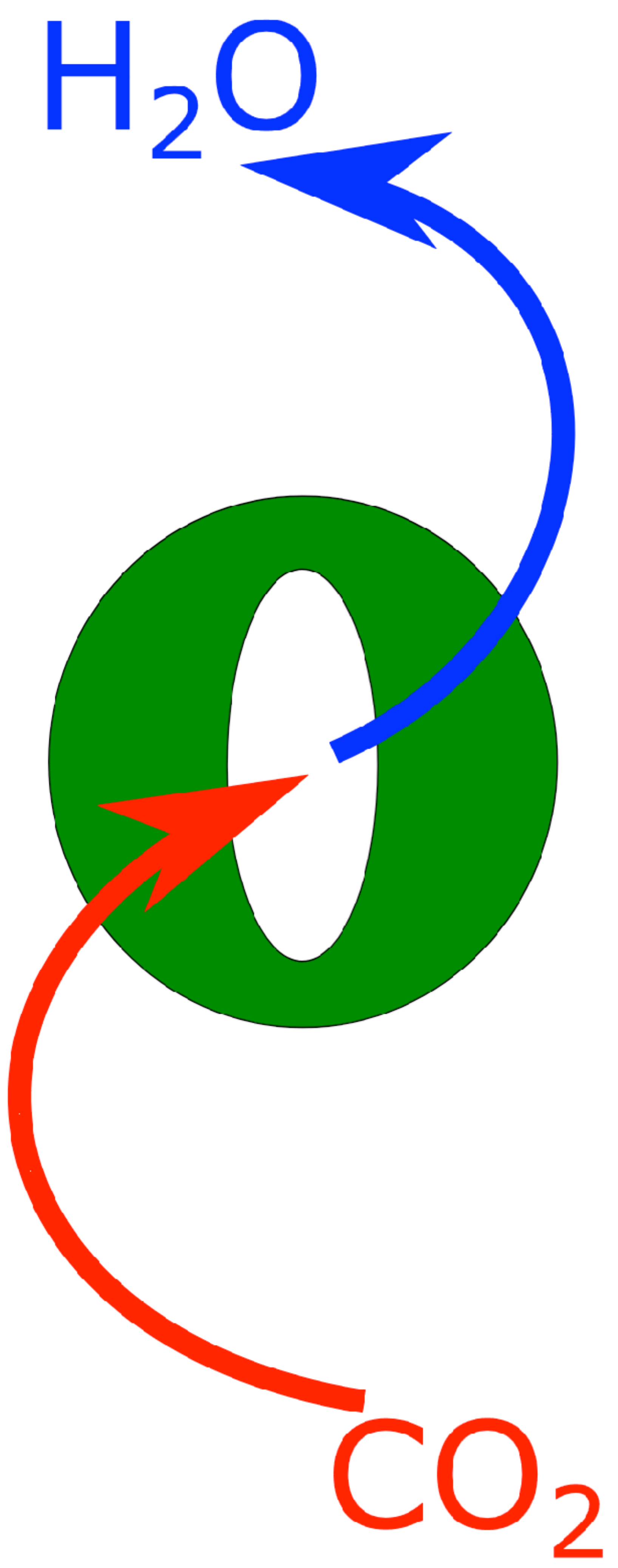
~30% of precipitation back to air

almost all of land CO_2 fixation



Physiology

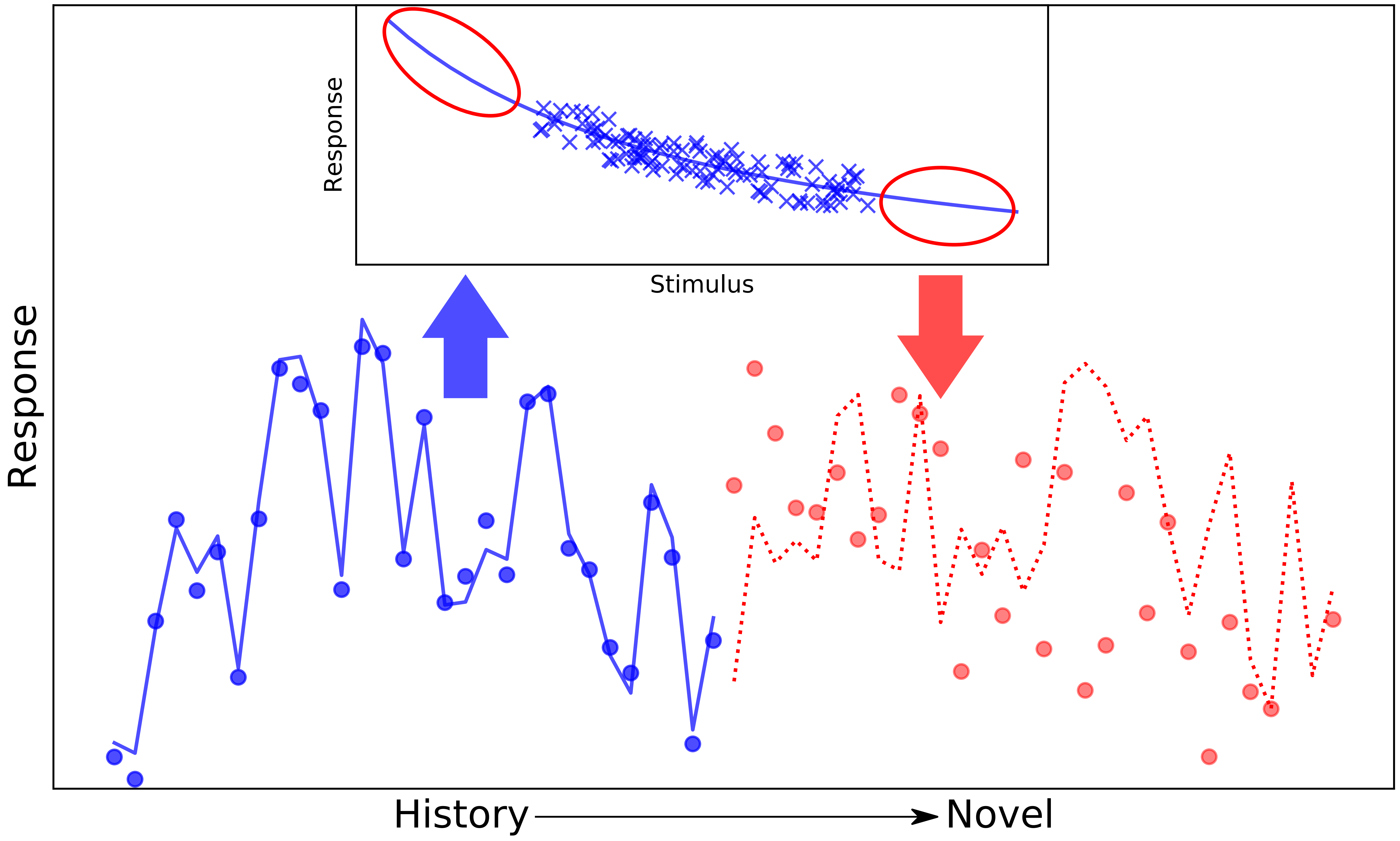
- ABA
- Leaf turgor
- Hydraulic conductance
- Photosynthetic capacity
- Mesophyll conductance



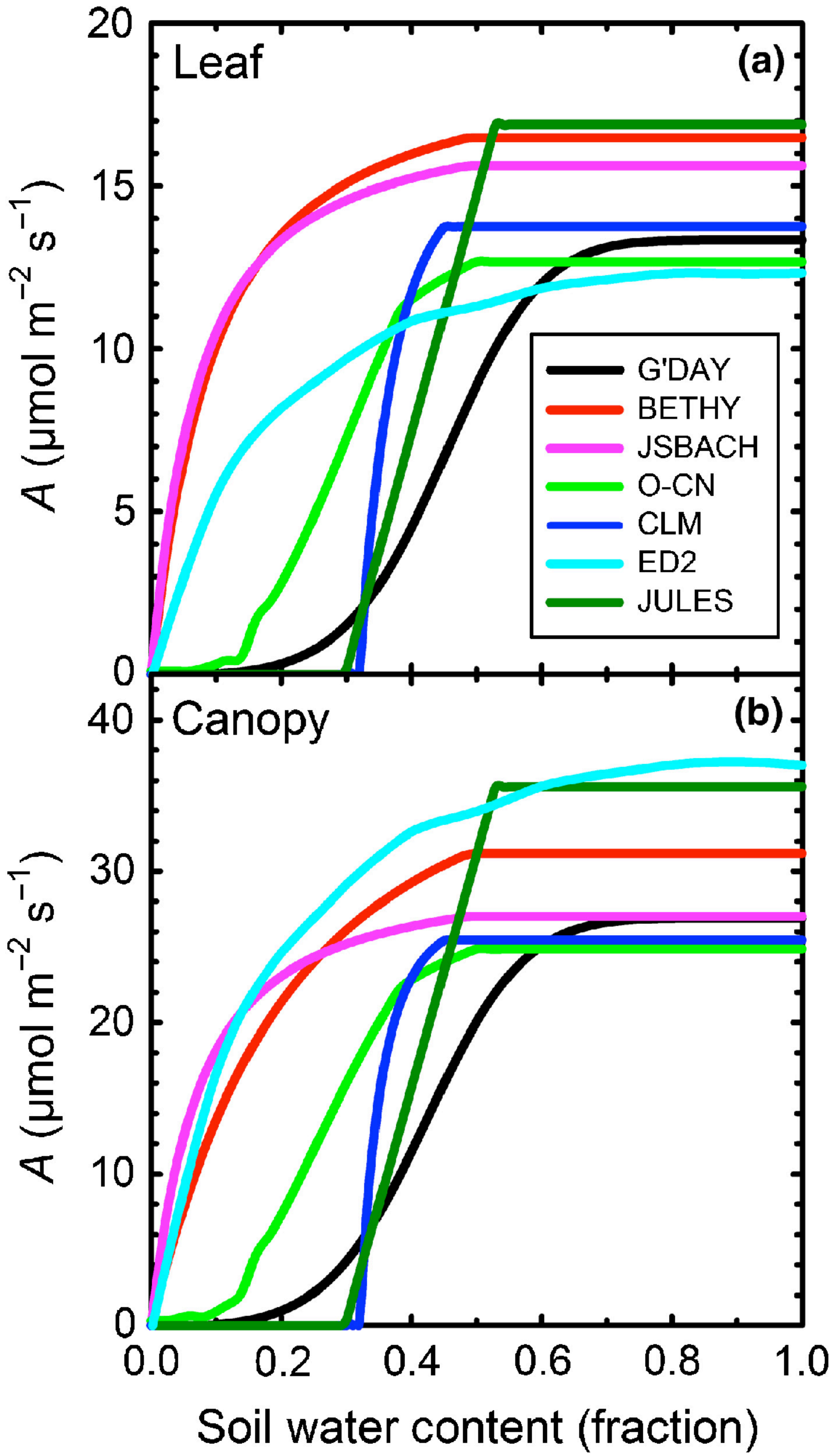
Environment

- Atmospheric CO_2
- Air humidity
- Air temperature
- Radiation
- Wind speed
- Soil moisture

Statistical models are efficient, but cannot well capture the responses to novel environment

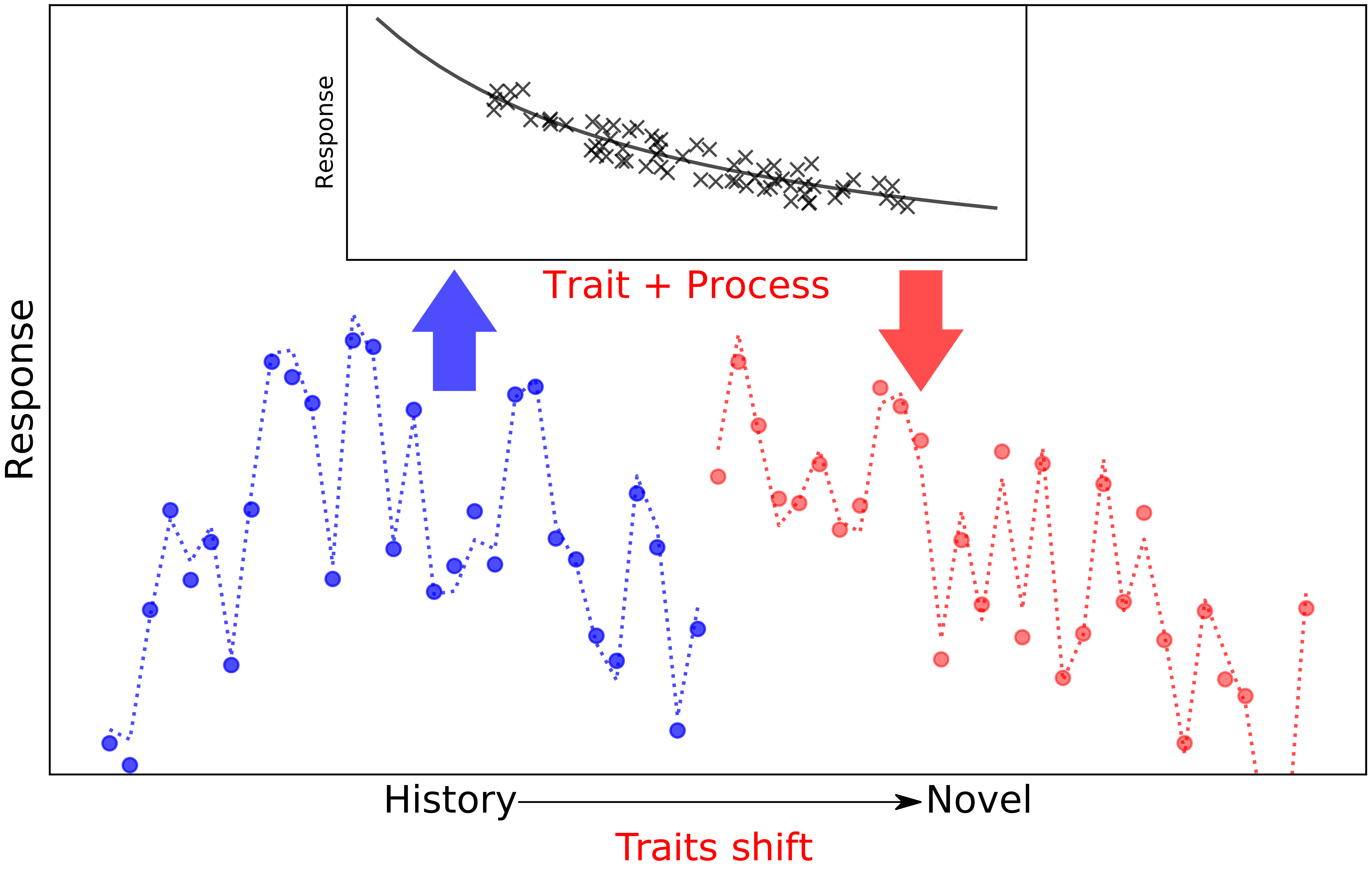


Statistical models are efficient, but cannot well capture the responses to novel environment



Rogers et al. (2017) New Phytologist

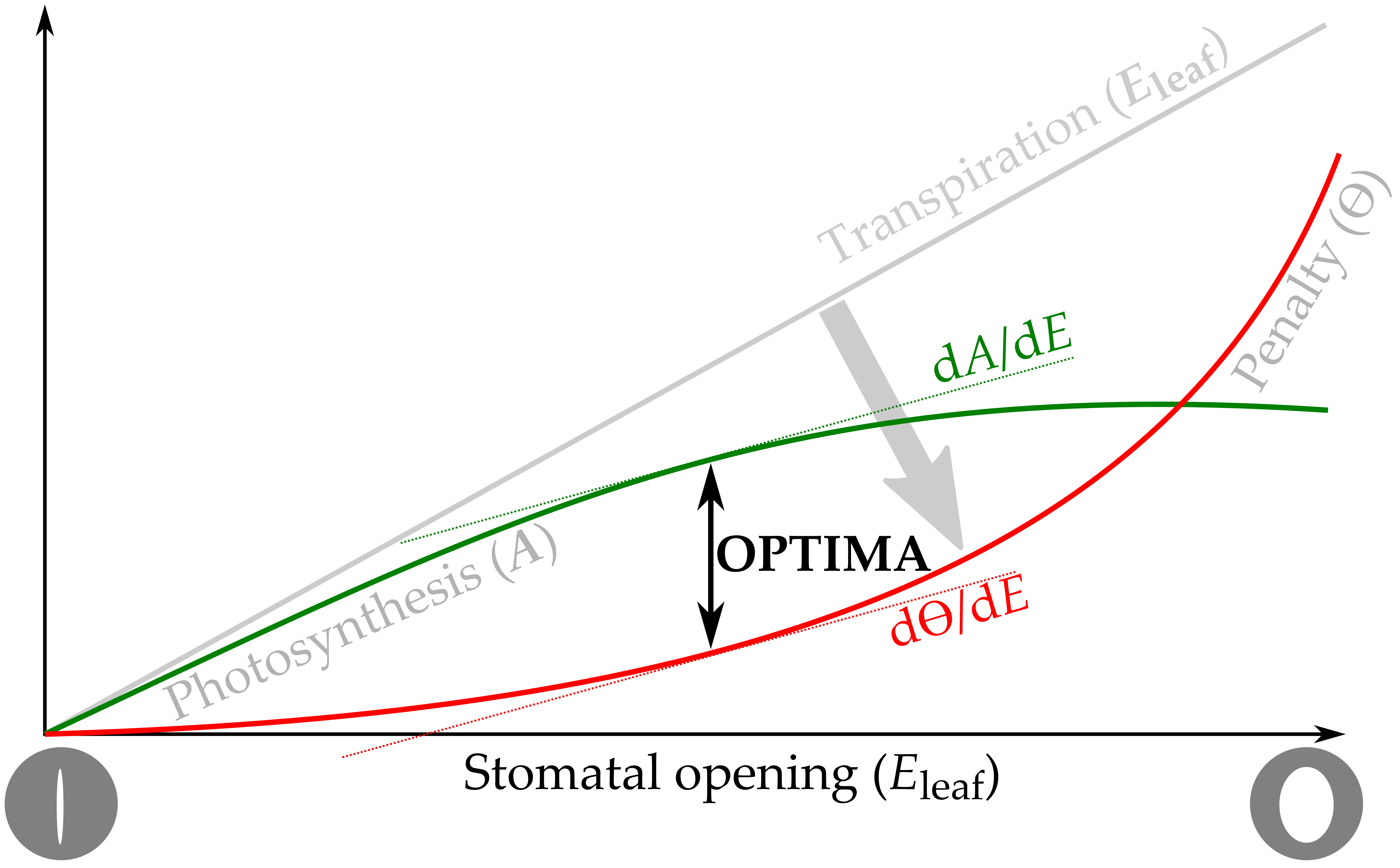
Mechanistic models are less efficient, but can capture the responses to novel environment due to the use of traits and processes

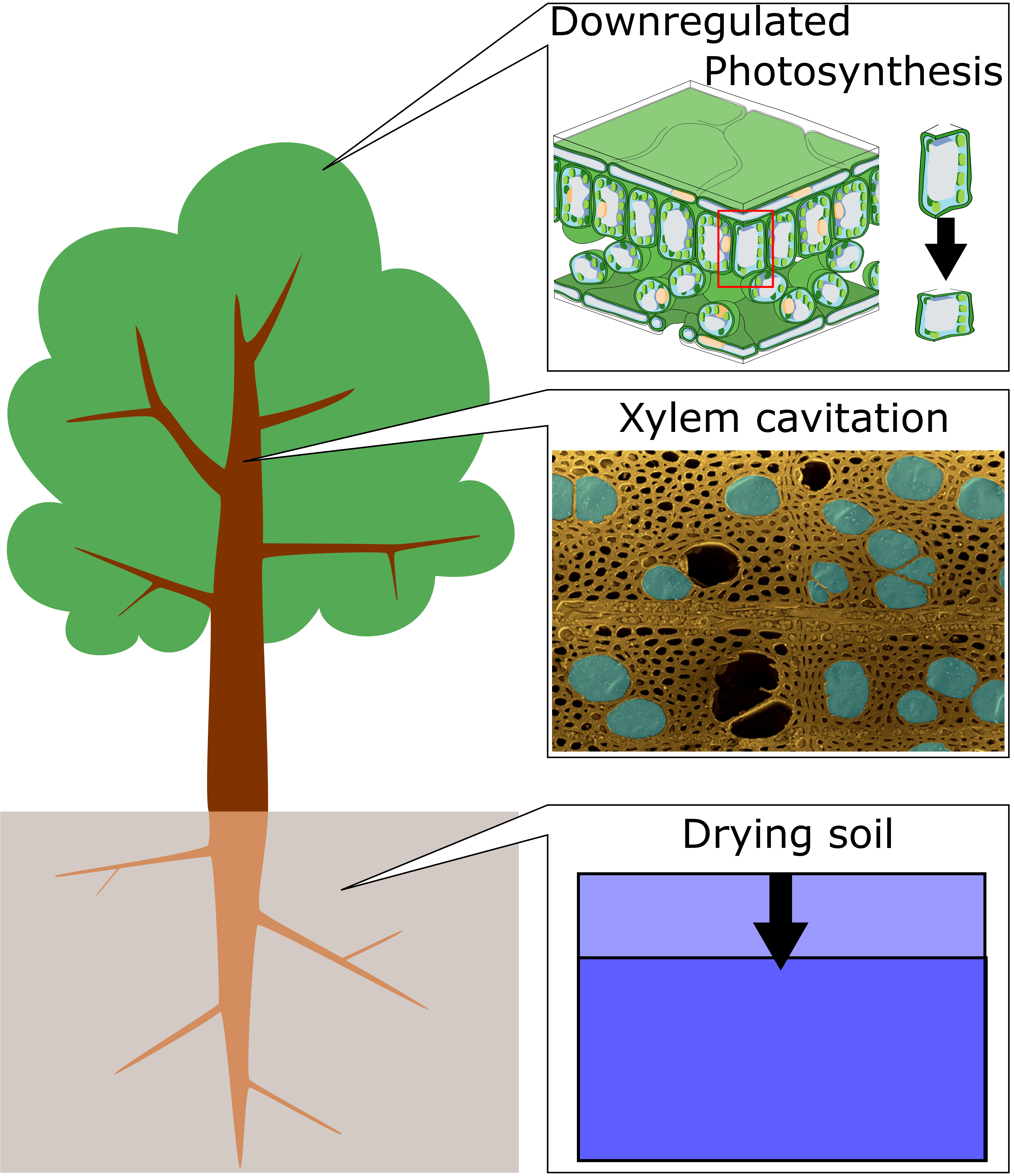


Optimality

Maximize the difference between gain and cost when

$$\frac{dA}{dE_{leaf}} = \frac{d\Theta}{dE_{leaf}}$$





Holtta *et al.* (2017)
Dewar *et al.* (2018)
Huang *et al.* (2018)
… …

Wolf *et al.* (2016)
Sperry *et al.* (2017)
Anderegg *et al.* (2018)
Eller *et al.* (2019)
… …

Cowan & Farquhar (1977)
… …
Manzoni *et al.* (2013)
Prentice *et al.* (2014)
Lu *et al.* (2016)
… …

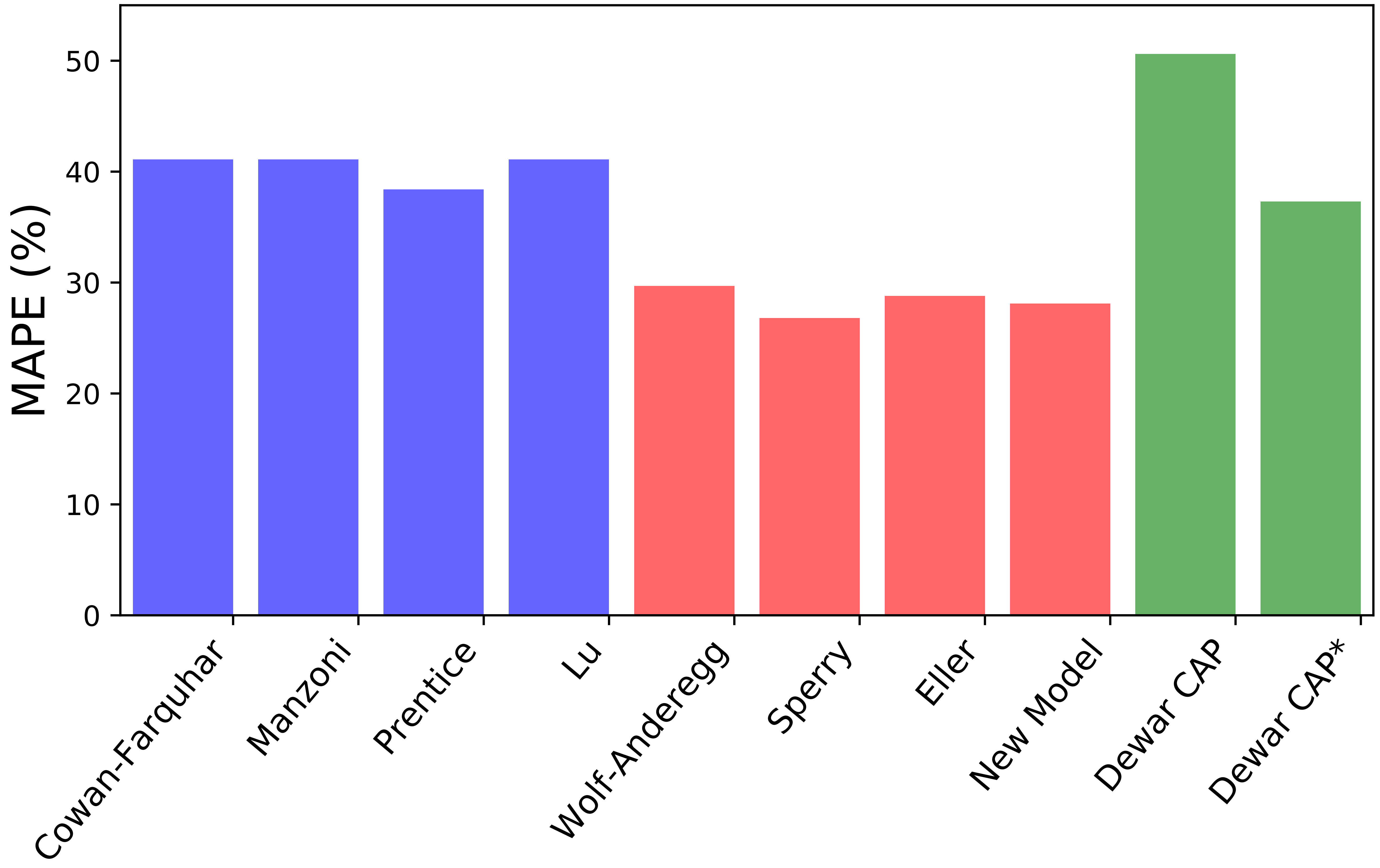
Model	Reference	Water Penalty (Θ or Θ')	Marginal Penalty ($\mathrm{d}\Theta/\mathrm{d}E$ or $\mathrm{d}\Theta'/\mathrm{d}E$)	Criteria I–III	Response Criteria IV–VII DCPK
Cowan-Farquhar	(Cowan and Farquhar, 1977)	$\Theta = \frac{E_{\text{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN
Manzoni	(Manzoni et al., 2013)	$\Theta = \frac{E_{\text{leaf}}}{\Lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\Lambda}$	YNN	NNNN
Prentice	(Prentice et al., 2014)	$\Theta = A \cdot \left(1 - \frac{1}{c_{\mathrm{E}}E_{\text{leaf}} + c_{\mathrm{V}}V_{\text{cmax}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\text{leaf}} + \frac{c_{\mathrm{V}}}{c_{\mathrm{E}}}V_{\text{cmax}}}$	YNY	YYNN
Lu	(Lu et al., 2016)	$\Theta = \frac{E_{\text{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN
Wolf-Anderegg	(Wolf et al., 2016) (Anderegg et al., 2018)	$\Theta = aP^2 + bP + c$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{2aP + b}{K}$	YYN	NNYY
Sperry	(Sperry et al., 2017)	$\Theta = A_{\text{max}} \cdot \left(1 - \frac{K}{K_{\text{max}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A_{\text{max}}}{K_{\text{max}}}$	YYY	YYYY
Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\text{max},0}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A}{K}$	YYY	YYYN
New Model		$\Theta = A \cdot \frac{E_{\text{leaf}}}{E_{\text{crit}}}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\text{crit}} - E_{\text{leaf}}}$	YYY	YYYY
Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{\text{ww}} \cdot \frac{\mathrm{SC}}{\mathrm{SC}_{\text{max}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{\mathrm{SC}_{\text{max}} - \mathrm{SC}} \cdot \frac{\mathrm{dSC}}{\mathrm{d}E}$	YYY	YYYY
Dewar CAP	(Dewar et al., 2018)	$\Theta' = A_{\text{ww}} \cdot \frac{P}{P_{\text{crit}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{K \cdot (P_{\text{crit}} - P)}$	YYY	YYYY

Wang et al. (2020) New Phytologist

Birch dataset

Growth chamber

- CO_2
- Air humidity
- Soil moisture

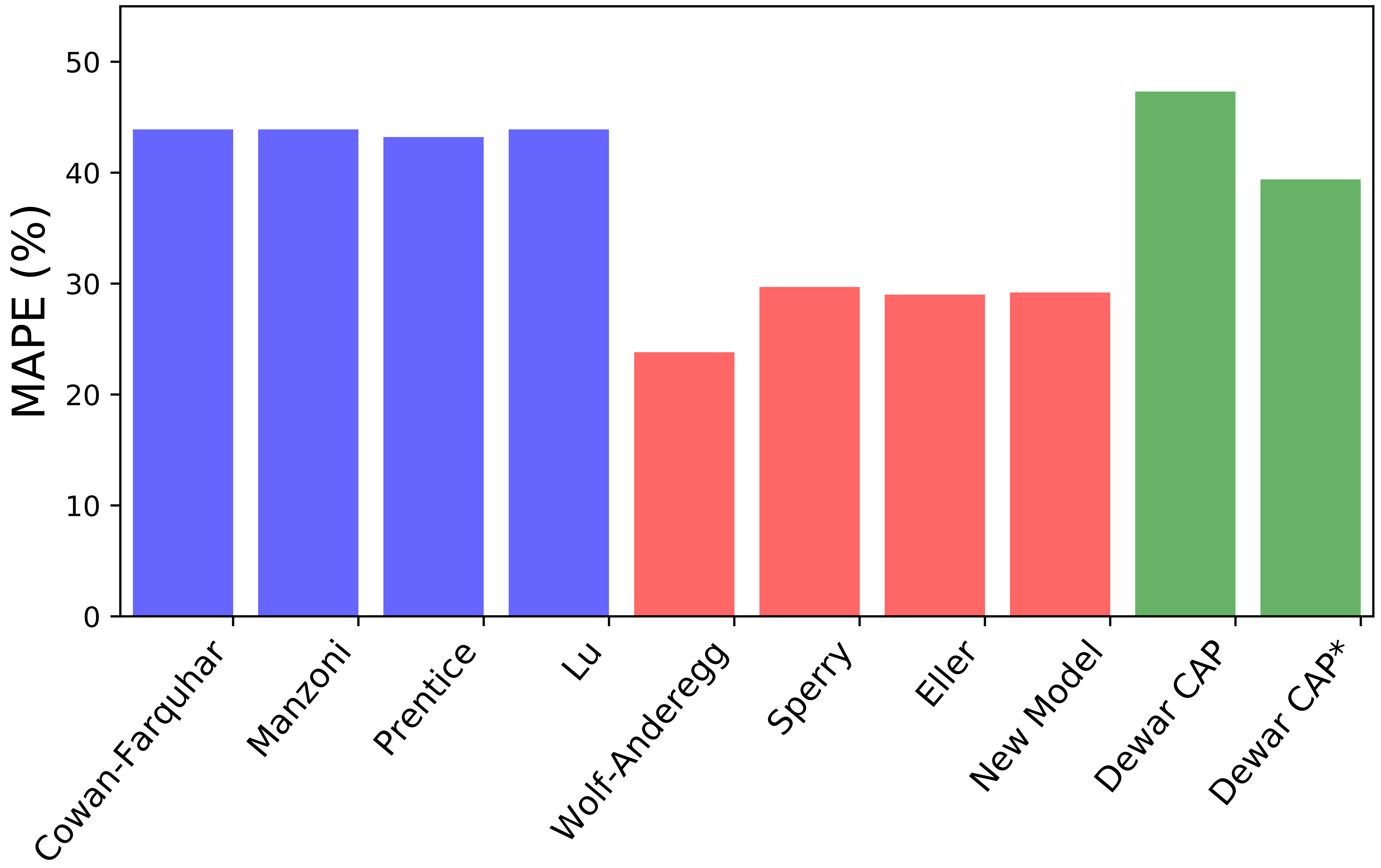


Data from Wang et al. (2019) Tree Physiology

Aspen dataset

Research garden

- **Soil moisture**
- **Air humidity***

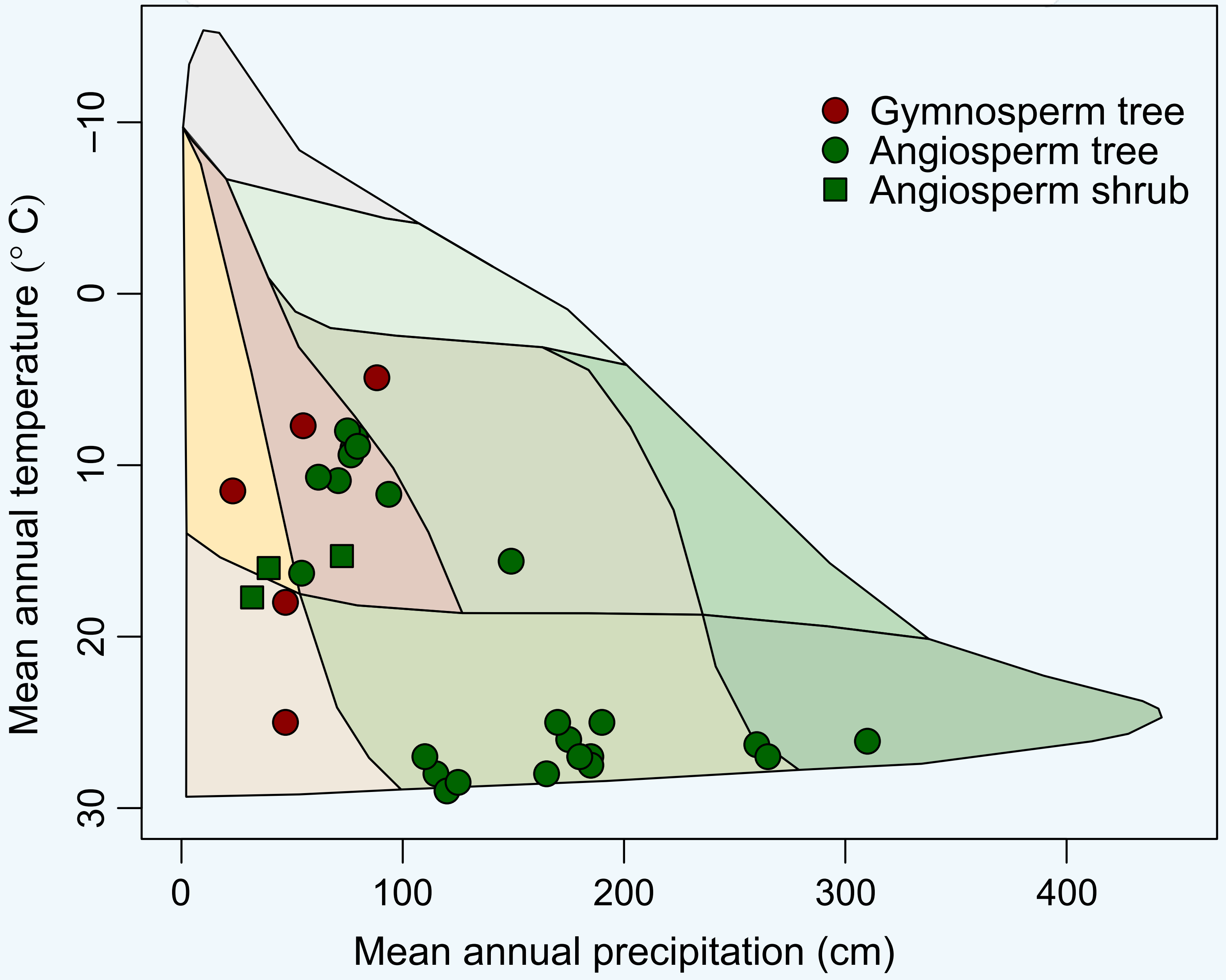


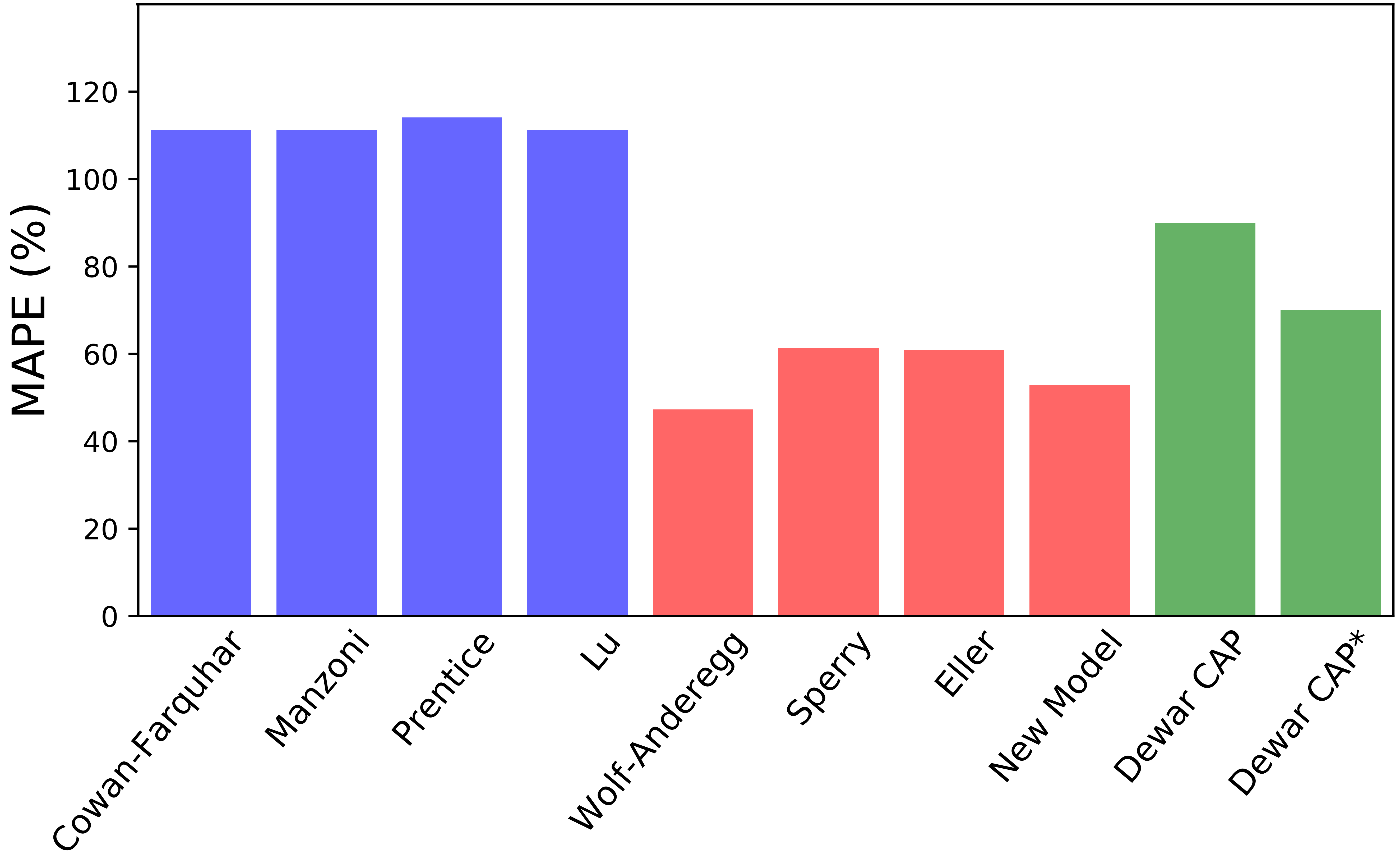
Data from Venturas et al. (2018) New Phytologist

Compiled dataset

Natural forests

- Soil moisture*
- Air humidity*





Data from Anderegg et al. (2018) Ecology Letters

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Lu	(Lu et al., 2016)	$\Theta = \frac{E_{\mathrm{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN
Wolf-Anderegg	(Wolf et al., 2016) (Anderegg et al., 2018)	$\Theta = aP^2 + bP + c$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{2aP + b}{K}$	YYN	NNYY
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Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\mathrm{max},0}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A}{K}$	YYY	YYYN
New Model		$\Theta = A \cdot \frac{E_{\mathrm{leaf}}}{E_{\mathrm{crit}}}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\mathrm{crit}} - E_{\mathrm{leaf}}}$	YYY	YYYY
Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{\mathrm{ww}} \cdot \frac{\mathrm{SC}}{\mathrm{SC}_{\mathrm{max}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{\mathrm{SC}_{\mathrm{max}} - \mathrm{SC}} \cdot \frac{\mathrm{dSC}}{\mathrm{d}E}$	YYY	YYYY
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Wang et al. (2020) New Phytologist

Towards a more physiology-based representation of **nighttime** stomatal conductance

1. Schemes

Improve model representation of soil-plant-air continuum

2. Setups

Advance model parameters configuration

3. Calibration

Use more data to calibrate the models

CLIMATE MODELING ALLIANCE

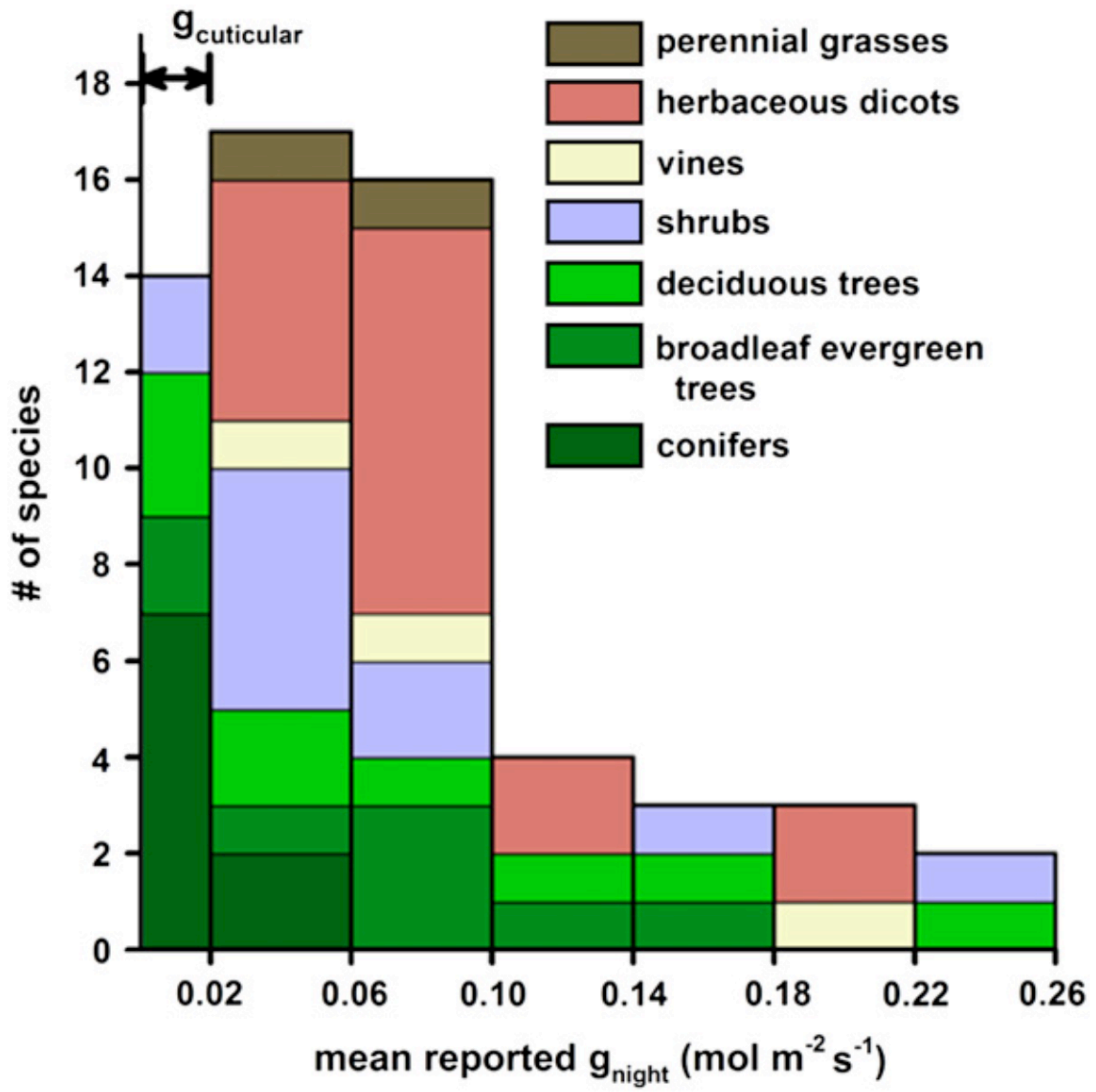
THE UNIVERSITY OF UTAH 1850

Caltech

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Nighttime E

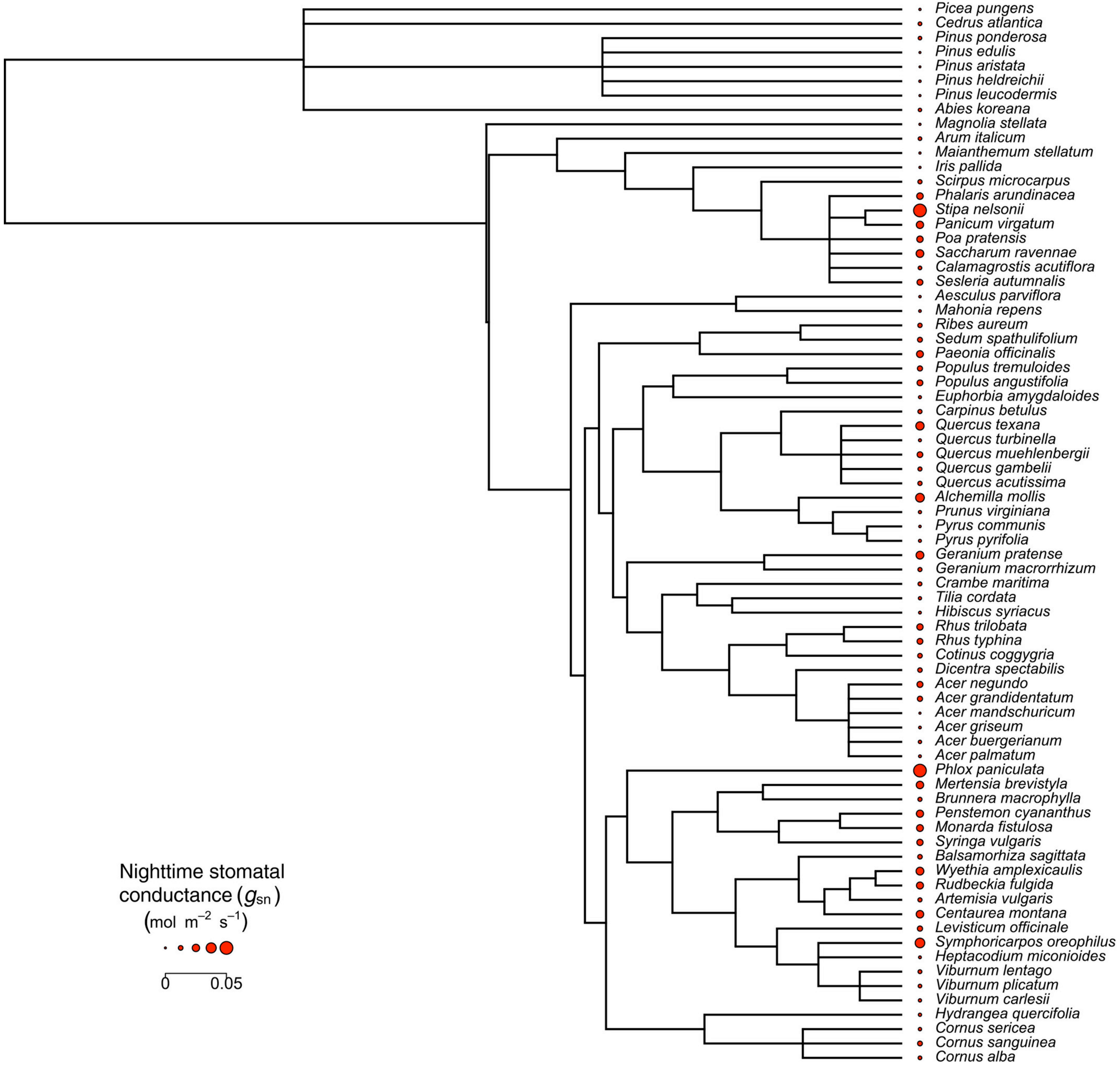
About 10% to 15% of the daytime E



Caird et al. (2007) Plant Physiology

Nighttime E

Found in various species



Yu et al. (2019) New Phytologist

Major drivers?

- Leaky stomata
- Nutrient uptake
- Oxygen uptake
- Competition
- Evaporative cooling
- Circadian rhythm

Responses to

- Air humidity
- CO_2
- Soil moisture
- Leaf temperature
- Leaf respiration

Optimality

Maximize the difference between gain and cost

Gain

- All benefits

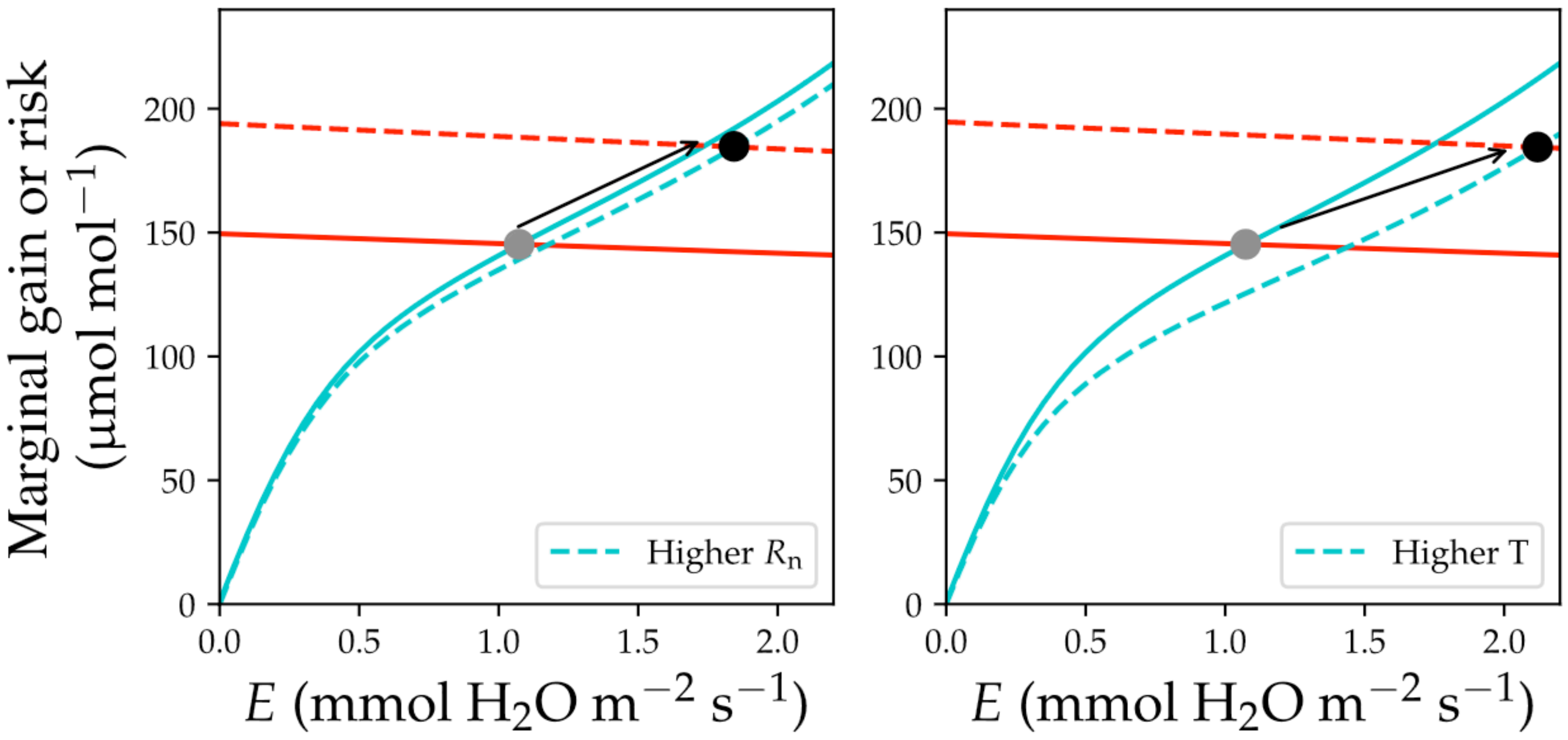
Risk

- Daytime photosynthesis

$$-\frac{\partial R_{\mathrm{leaf}}}{\partial E_{\mathrm{n}}} - f_{\mathrm{f}} \cdot \frac{A_{\mathrm{d}}(E_{\mathrm{n}})}{E_{\mathrm{crit}} - E_{\mathrm{n}}} = 0$$

Optimality

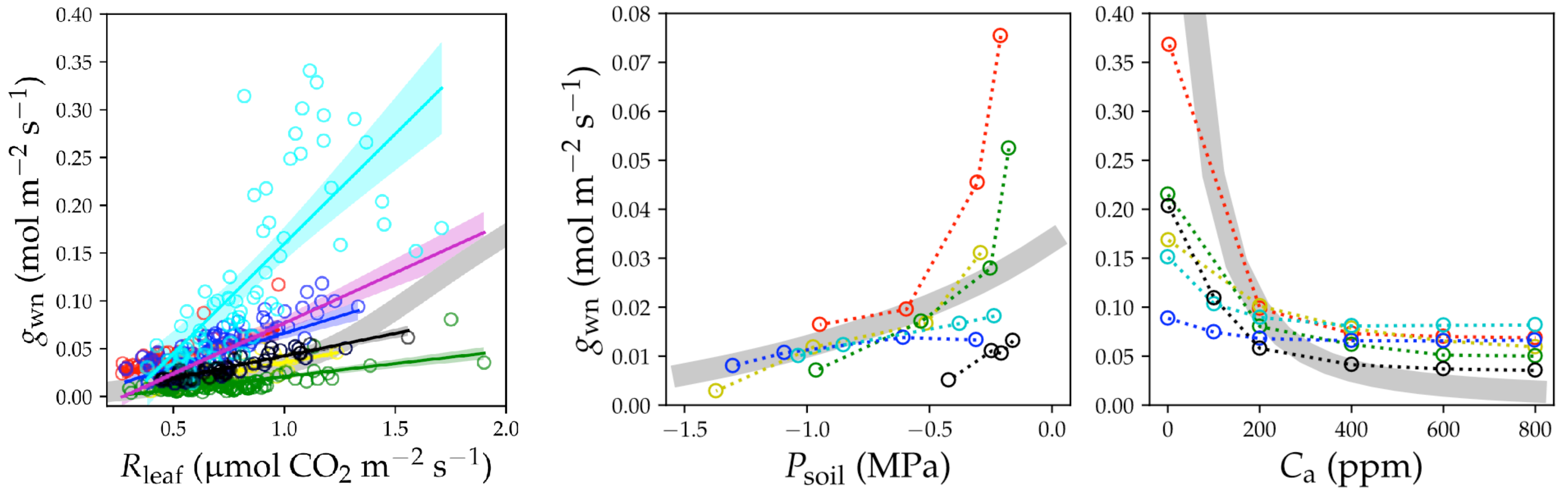
Maximize the difference between gain and cost



Wang et al. (2021) New Phytologist

Optimality

Maximize the difference between gain and cost



Wang et al. (2021) New Phytologist

A highly modularized next generation land surface model—CliMA Land

1. Schemes
Improve model representation of soil-plant-air continuum

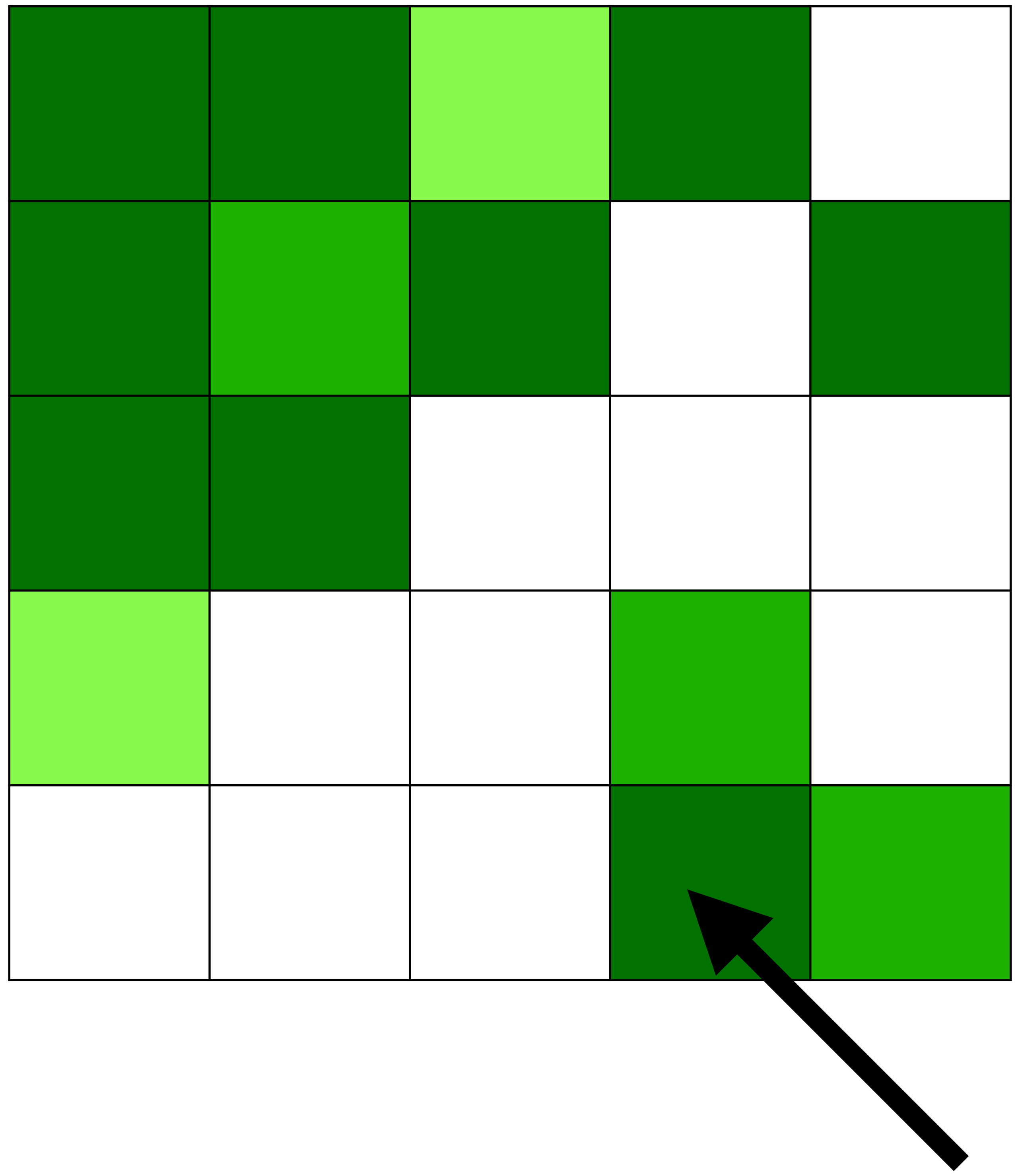
2. Setups
Advance model parameters configuration

3. Calibration
Use more data to calibrate the models

Tradeoffs

- Complexity
- Accuracy
- Delivery
- Efficiency

Traits are what we need to learn



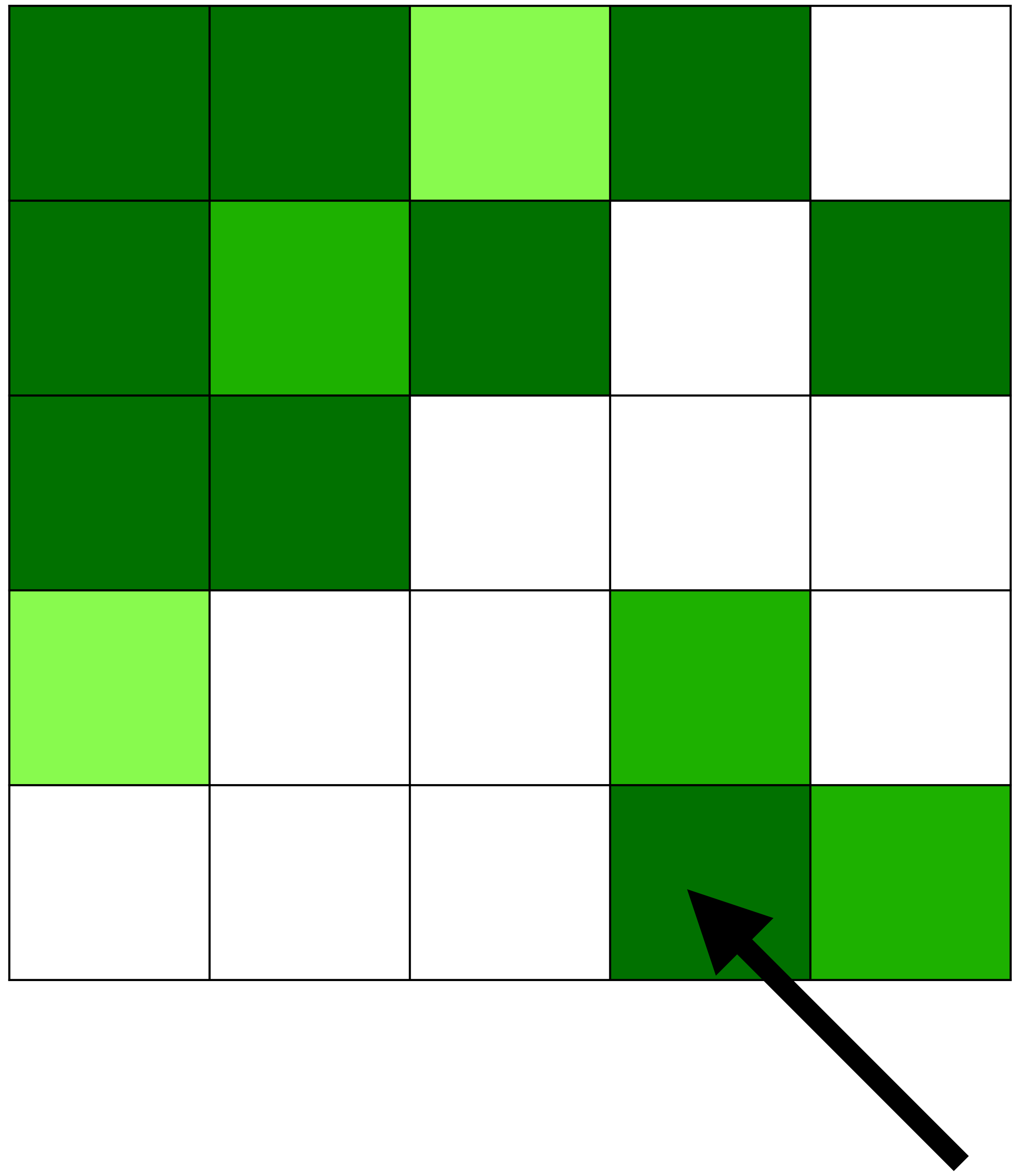
Minimum Element

Soil-plant-air continuum

Tradeoffs

- Complexity
- Accuracy
- Delivery
- Efficiency

Traits are what we need to learn

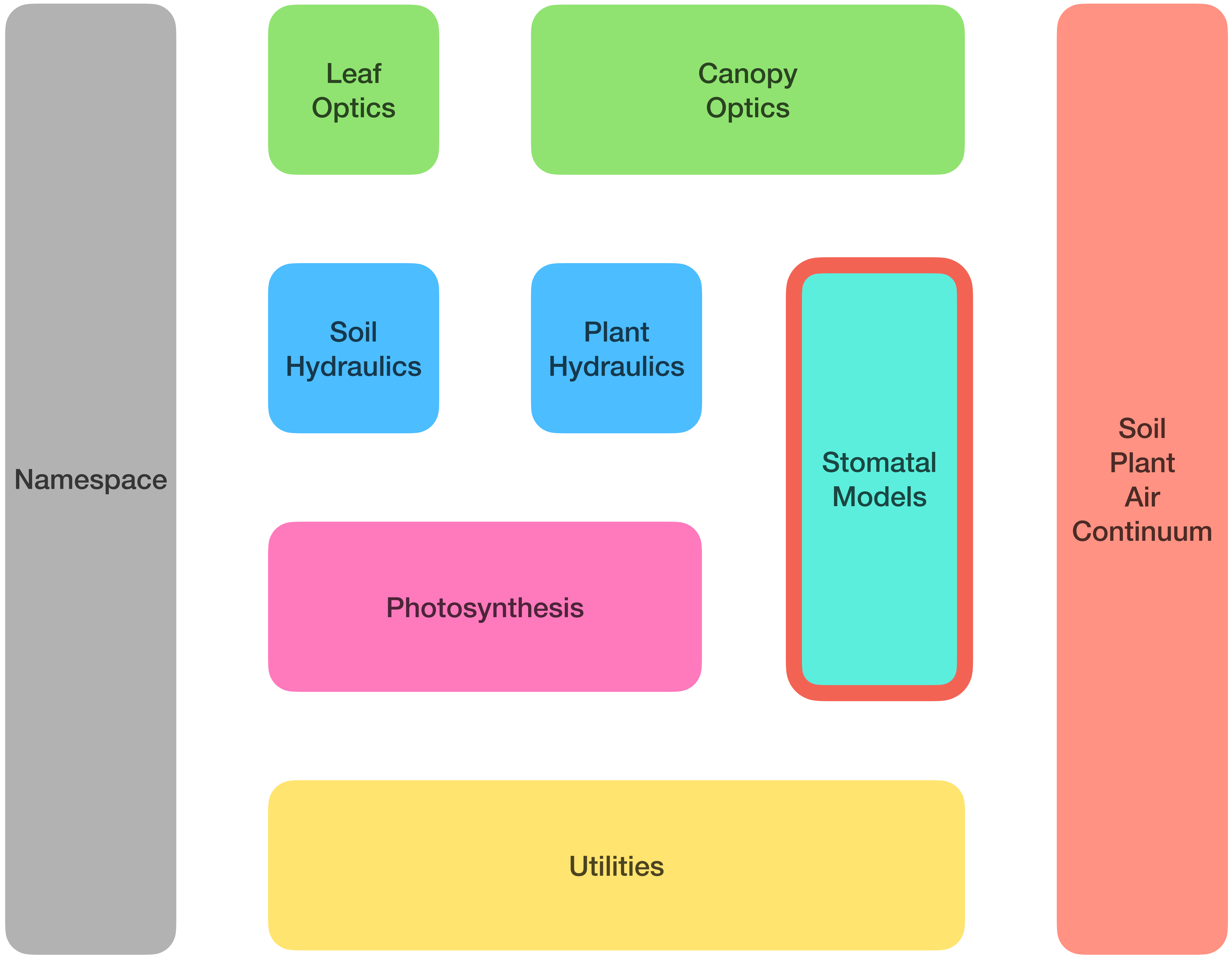


Minimum Element

Soil-plant-air continuum

1. Modularity

Each module can be used as a standalone package



https://github.com/CliMA/Land

1. Modularity

Each module can be used as a standalone package

```
config = EmeraldLand.Namespace.SPACConfiguration{FT}();
bio = EmeraldLand.Namespace.LeafBio(config);
EmeraldLand.LeafOptics.leaf_spectra!(config, bio, FT(5));
```

2. User friendly

Convenient functions to begin with

GUI on the way for teaching purpose

```
config = EmeraldLand.Namespace.SPACConfiguration{FT}();
spac = EmeraldLand.Namespace.BulkSPAC(config);
EmeraldLand.SPAC.initialize!(config, spac);
EmeraldLand.SPAC.spac!(config, spac, FT(1));
```

3. Freedom

Various model schemes to choose from

Namespace
Free combinations

Leaf Optics
Broadband
Hyper-spectral

Canopy Optics
Broadband / hyper-spectral
Single to multiple layers

Soil Hydraulics
Van Genuchten
Brooks Corey

Plant Hydraulics
Multiple VC forms
Custom structure
SS or NSS

Stomatal Models
(Empirical)
Ball Berry
Leuning
Medyln
Gentine

(Optimality)
Wolf-Anderegg-Pacala
Sperry
Eller
Wang

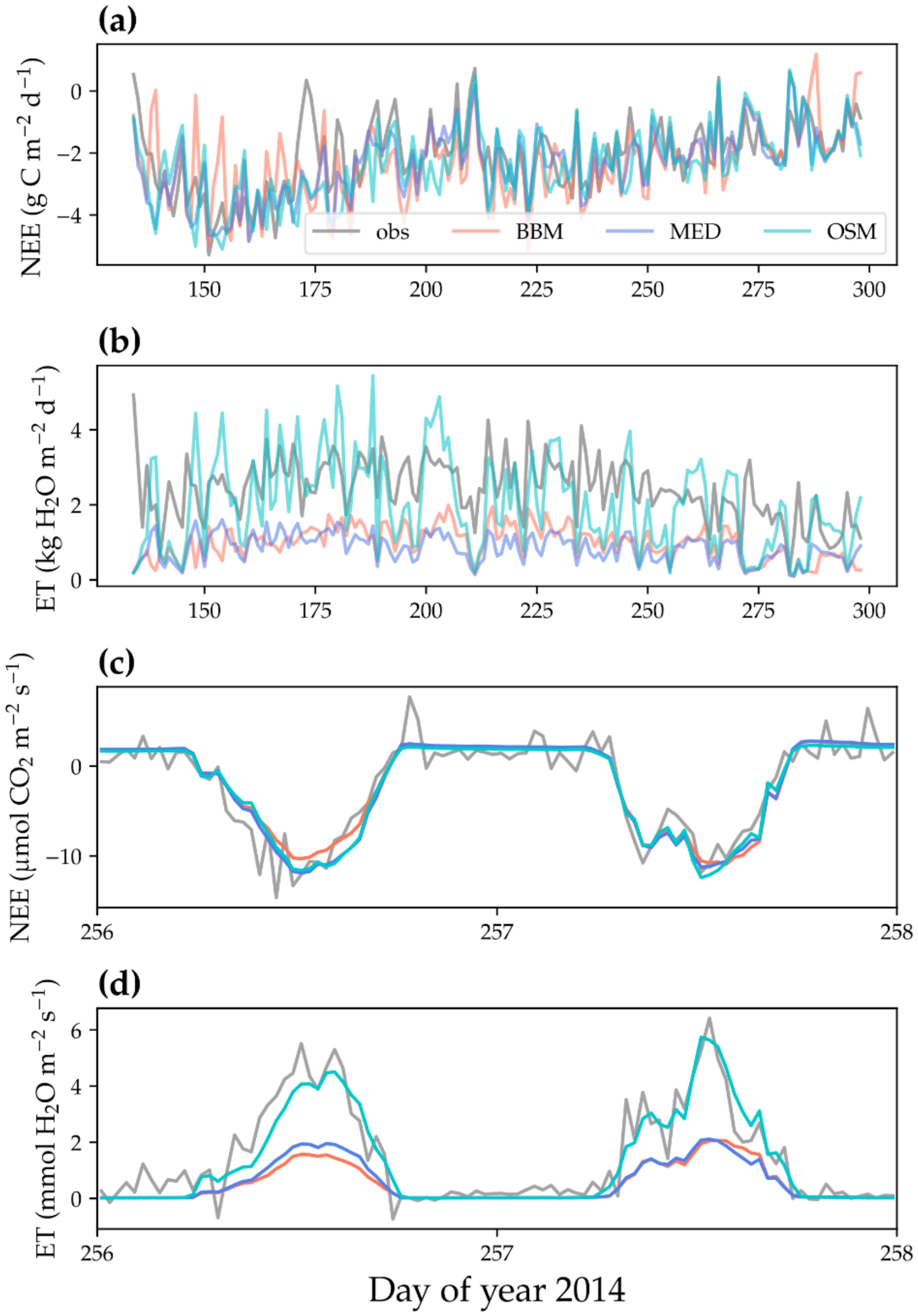
Photosynthesis
Classic C3 model
Classic C4 model
New Cytochrome C3 model

Utilities
Shared constants
Solvers
IO Tools

Soil Plant Air Continuum
Single elements
Complex SPAC

3. Freedom

Example 1: Comparison of three stomatal models

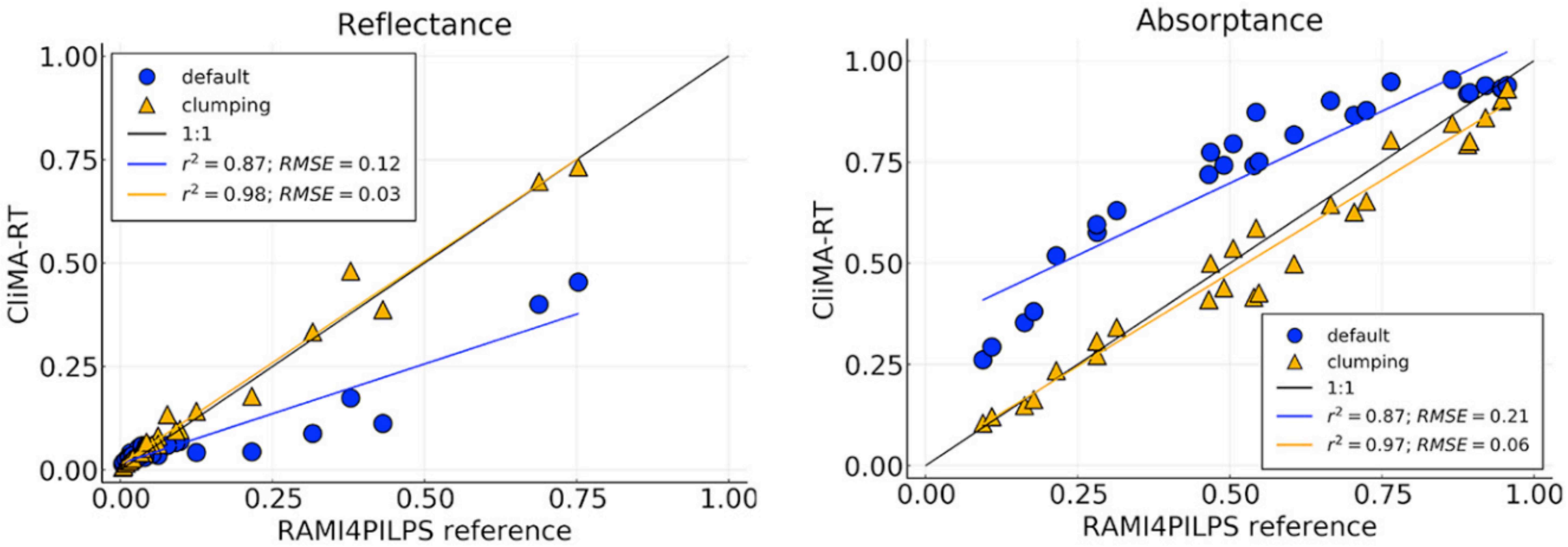


Wang et al. (2021) Geoscientific Model Development

3. Freedom

Example 2: Turn on/off clumping index

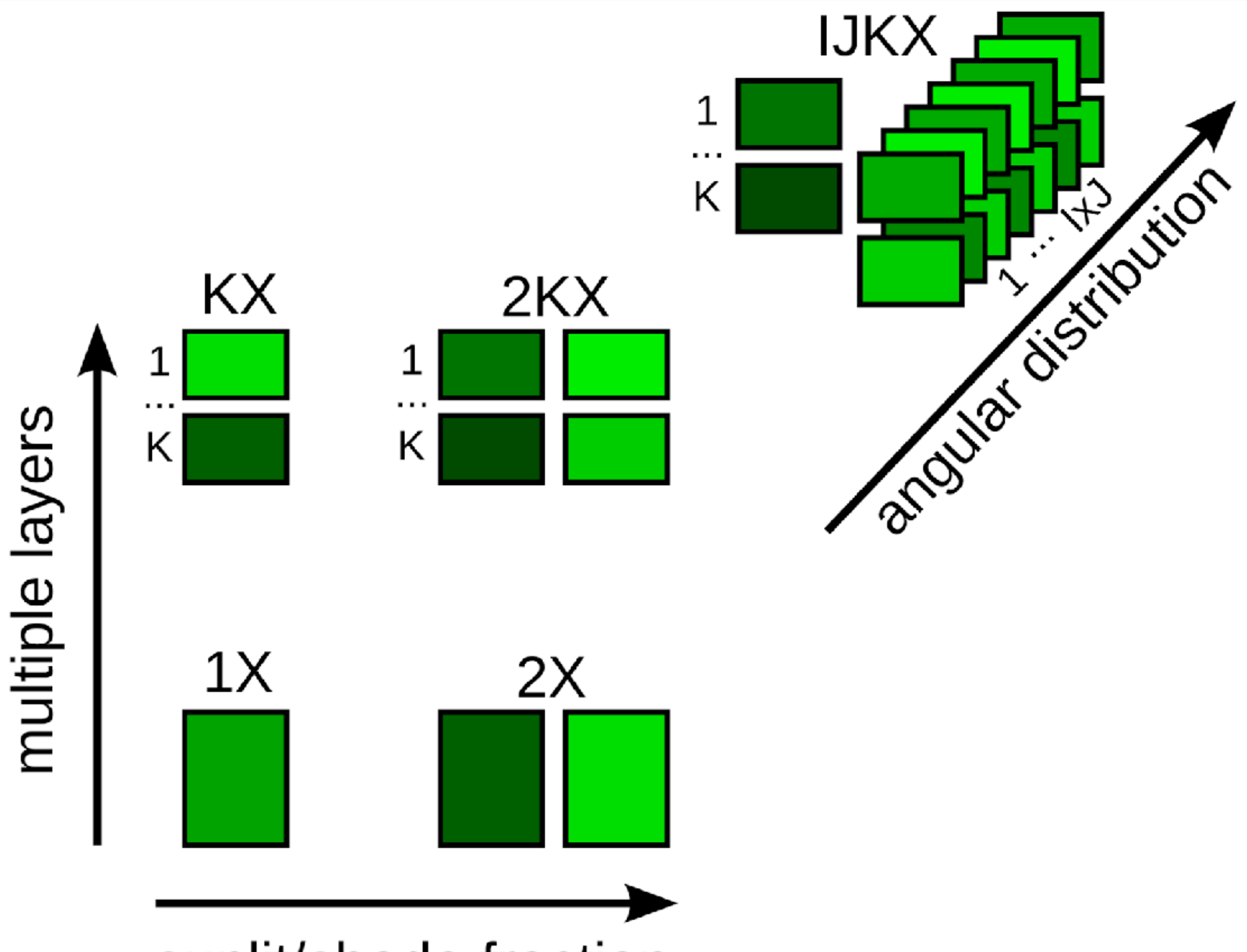
PAR (400 – 700 nm)

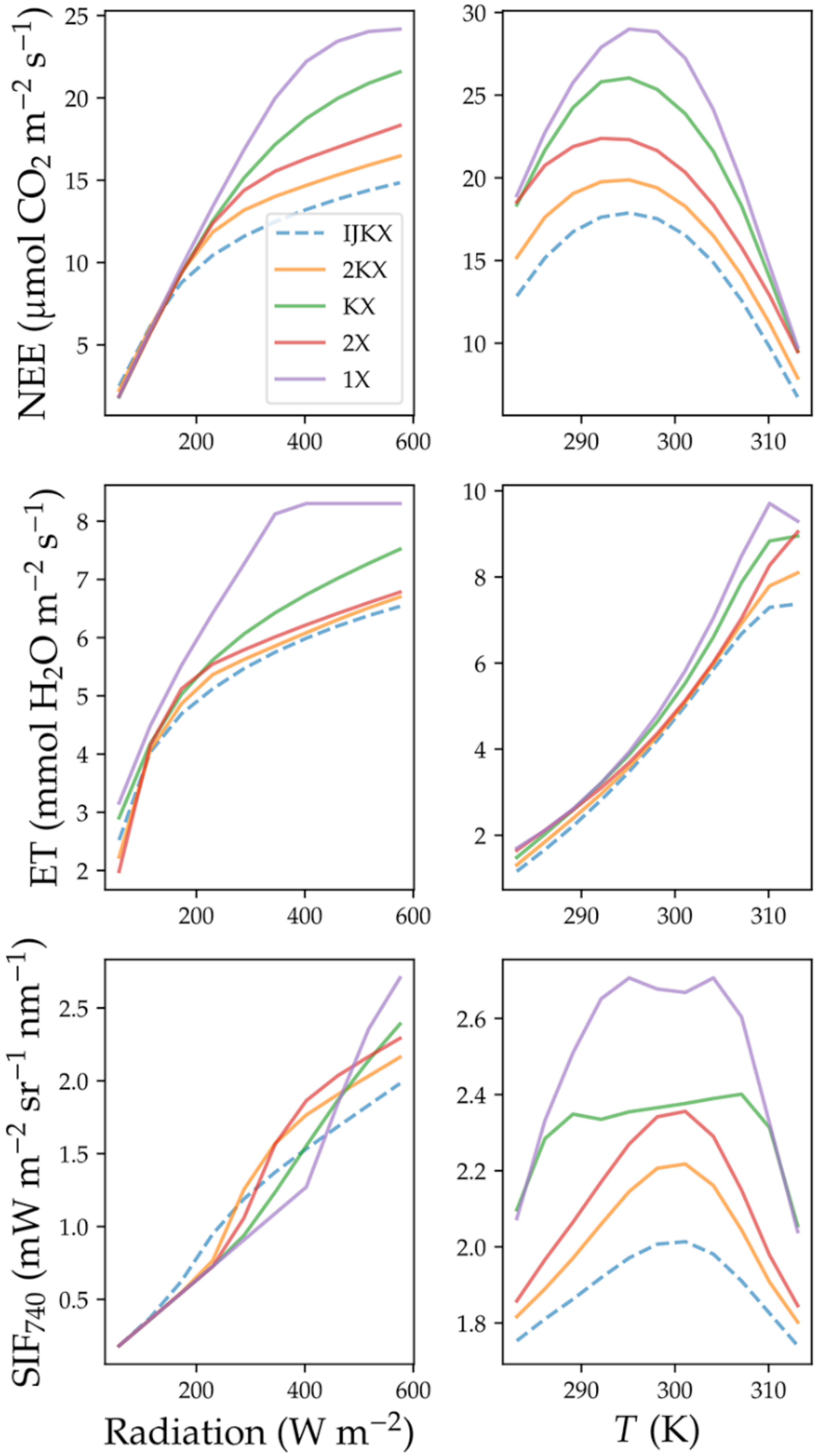


Braghiere et al. (2021) Remote Sensing of Environment

3. Freedom

Example 3: Comparison of canopy complexity





Wang et al. (2022) Biogeosciences

Database and software for sharing global scale datasets—GriddingMachine

1. Schemes

Improve model representation of soil-plant-air continuum

2. Setups

Advance model parameters configuration

3. Calibration

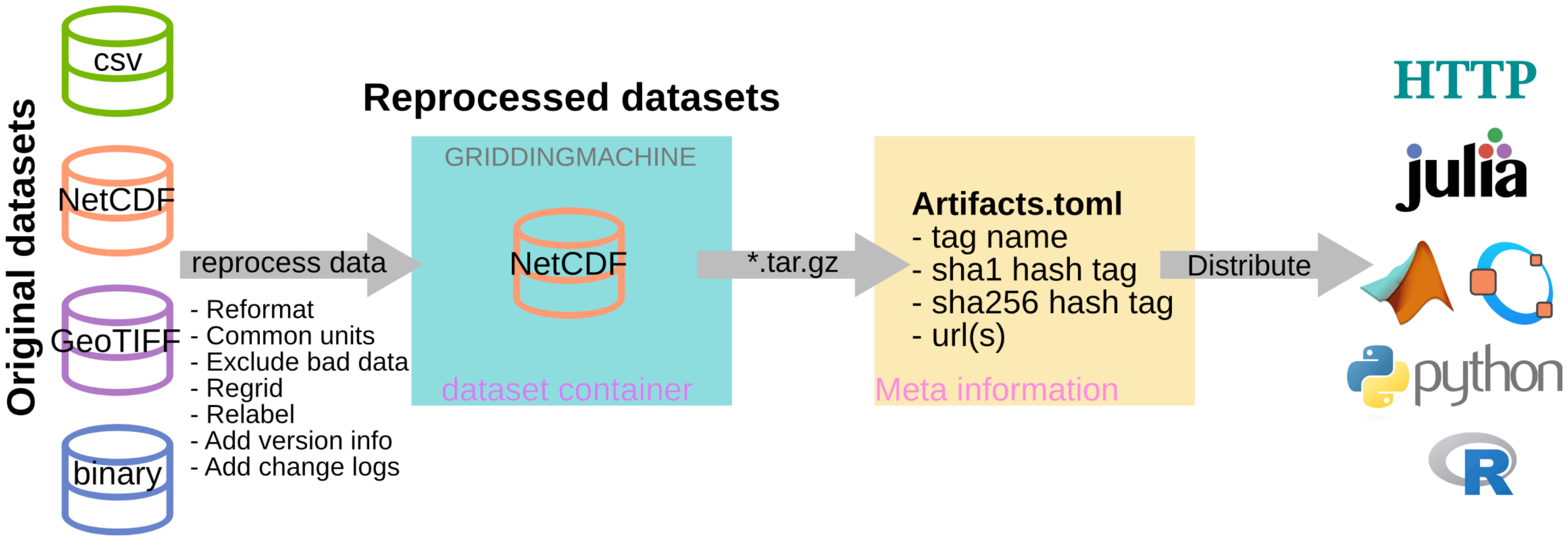
Use more data to calibrate the models

A byproduct

Need of traits at global scale to initialize CliMA Land

Challenges

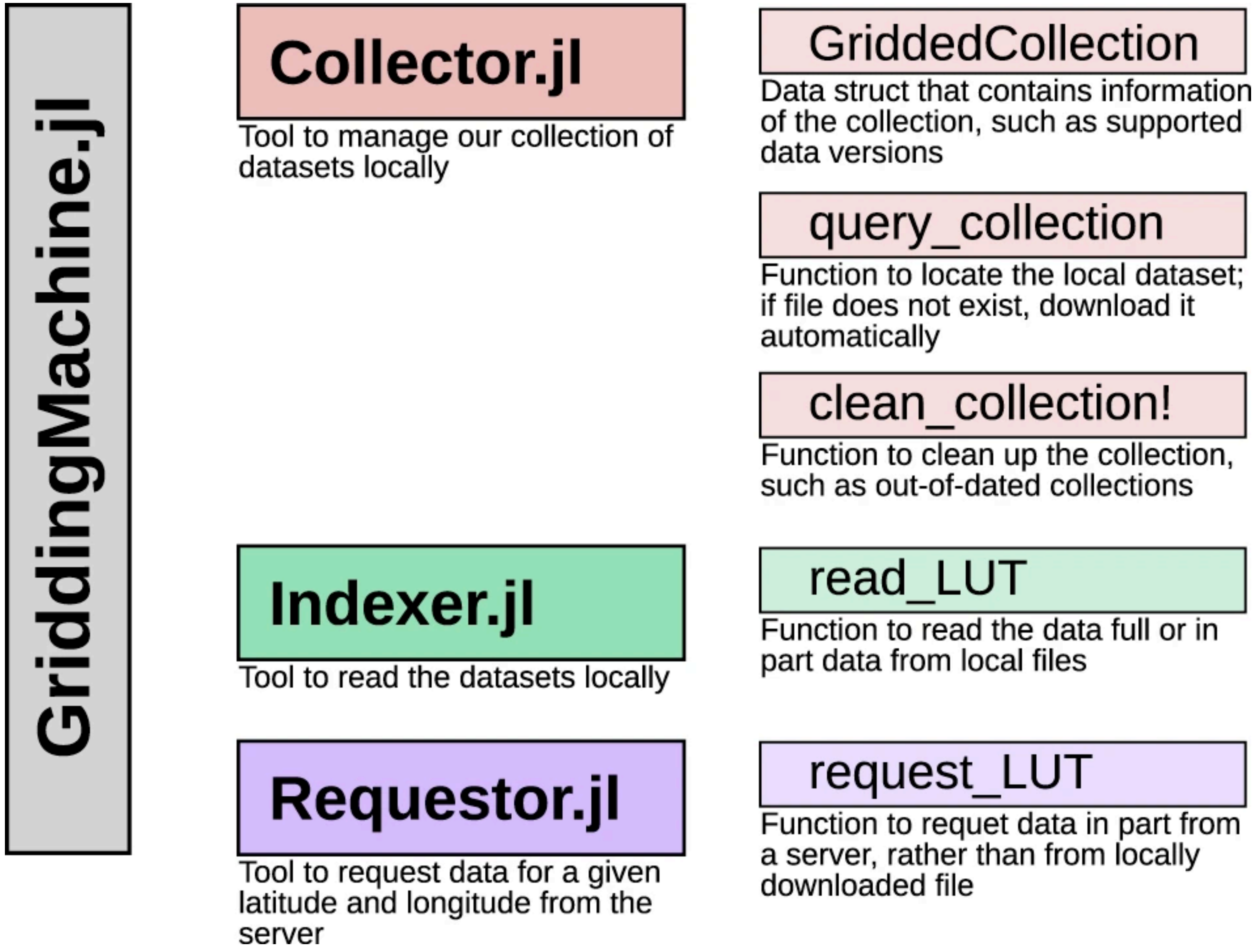
- Hosted on different websites
- Different formats
- Not directly usable (scaling)
- Different orientations
- Different coverages
- Different projections
- Non-standard units
- … …
- One forget where the files are



Wang et al. (2022) Scientific Data

GriddingMachine

Testing modules
- **Blender**
- **Fetcher**
- **Partitioner**



Wang et al. (2022) Scientific Data

Convenient API

TAG is the only thing you need to know

```
using GriddingMachine.Collector: query_collection;
file_path = query_collection("VCMAX_2X_1Y_V1");

using GriddingMachine.Requestor: request_LUT;
dat,std = request_LUT("LAI_MODIS_20X_1M_2020_V1", 31.82, 117.23);
```

Dataset type	LABEL	EXTRALABEL	IX	JT	YEAR	VK	Reference	Change logs
Gross primary productivity	GPP	MPI_RS	2X	1M, 8D	2001-2019	V1	Tramontana et al. (2016)	4,9
	GPP	VPM	5X, 12X	8D	2000-2019	V2	Zhang et al. (2017)	1,4
Leaf area index	LAI	MODIS	2X, 10X, 20X	1M, 8D	2000-2020	V1	Yuan et al. (2011)	1,4,9
Latent heat flux	LE	MPI_RS	2X	1M, 8D	2001-2015	V1	Jung et al. (2019)	4,9
Solar induced chlorophyll	SIF	TROPOMI_683, TROPOMI_683DC	1X, 2X, 4X,	1M, 8D	2018-2020	V2	Köhler et al. (2020)	1,8

https://github.com/CliMA/GriddingMachine.jl

API

Query data within area of interest

- **Partitioner**

```
# new feature under testing
using GriddingMachine.Partitioner: query_data;
data = query_data("TROPOMI.json", polygon, 2020; months=[1,2]);
```

First global simulation of CliMA Land: Bridging vegetation processes with remote sensing

1. Schemes

Improve model representation of soil-plant-air continuum

2. Setups

Advance model parameters configuration

3. Calibration

Use more data to calibrate the models

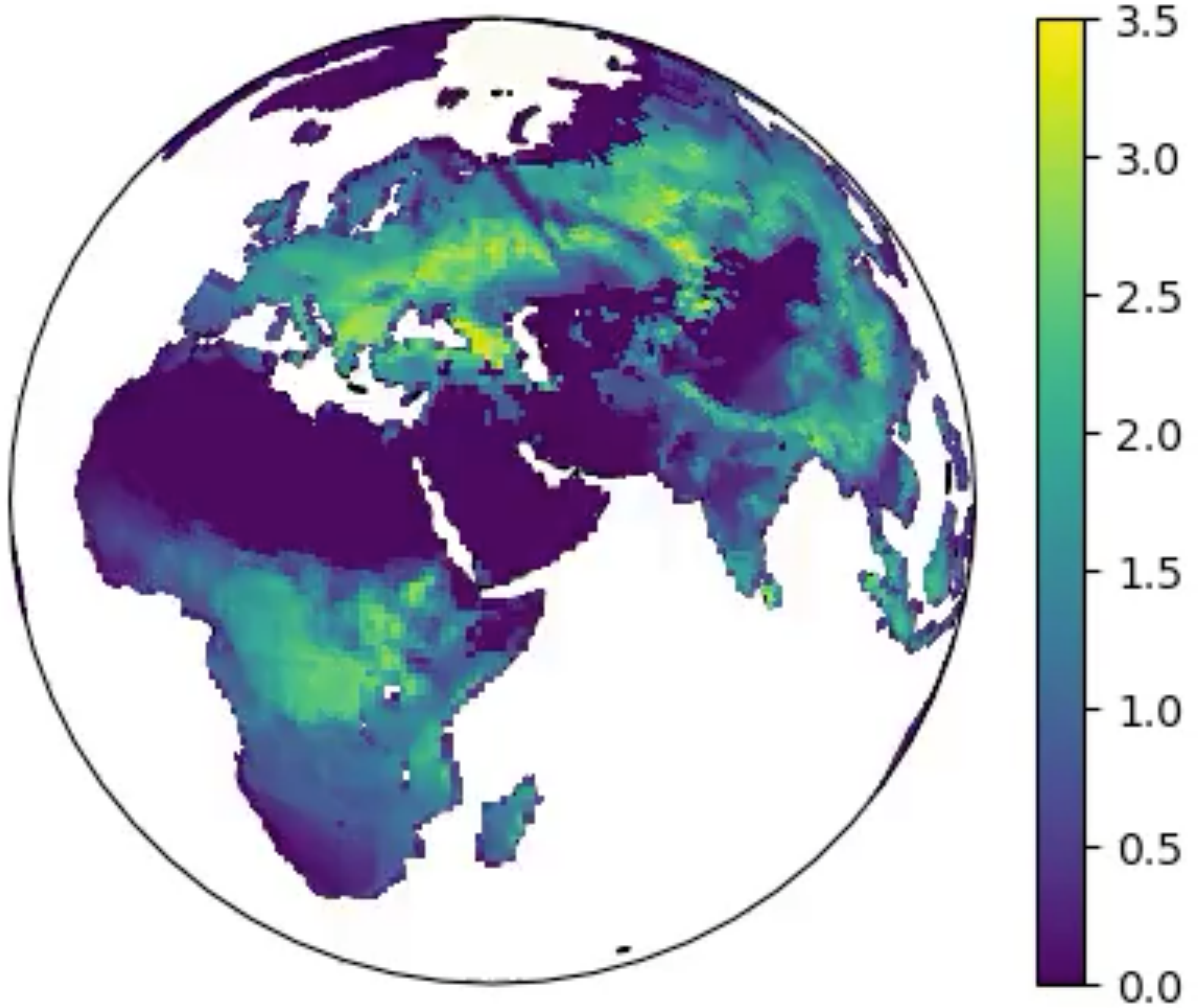
First global scale simulation of CliMA Land

Configurations

- Hyperspectral RT
- Empirical stomatal model
- Hourly ERA5 weather driver
- GriddingMachine inputs
- … …

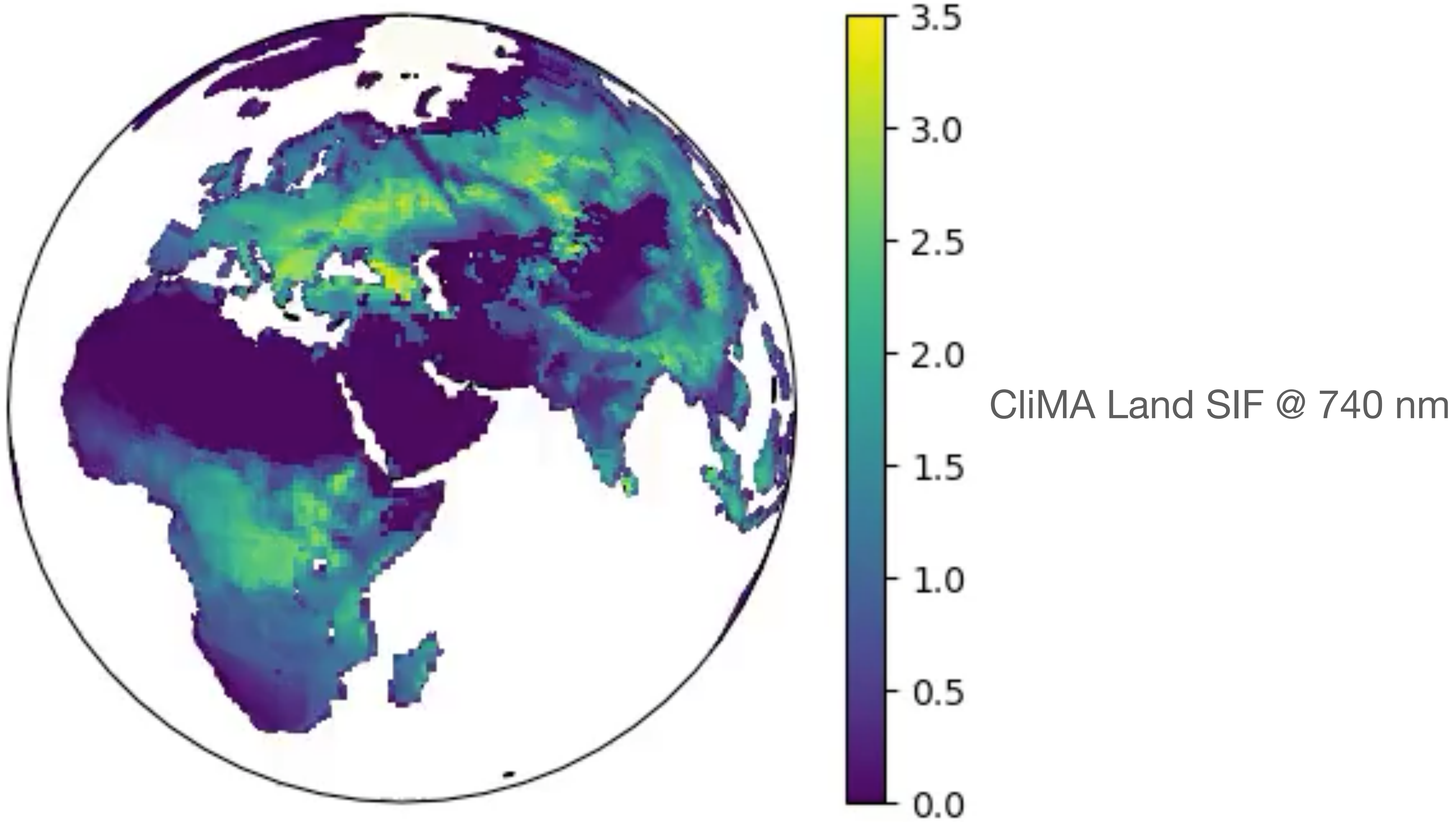
~2 h for annual simulation on hourly time step on 160 cores!

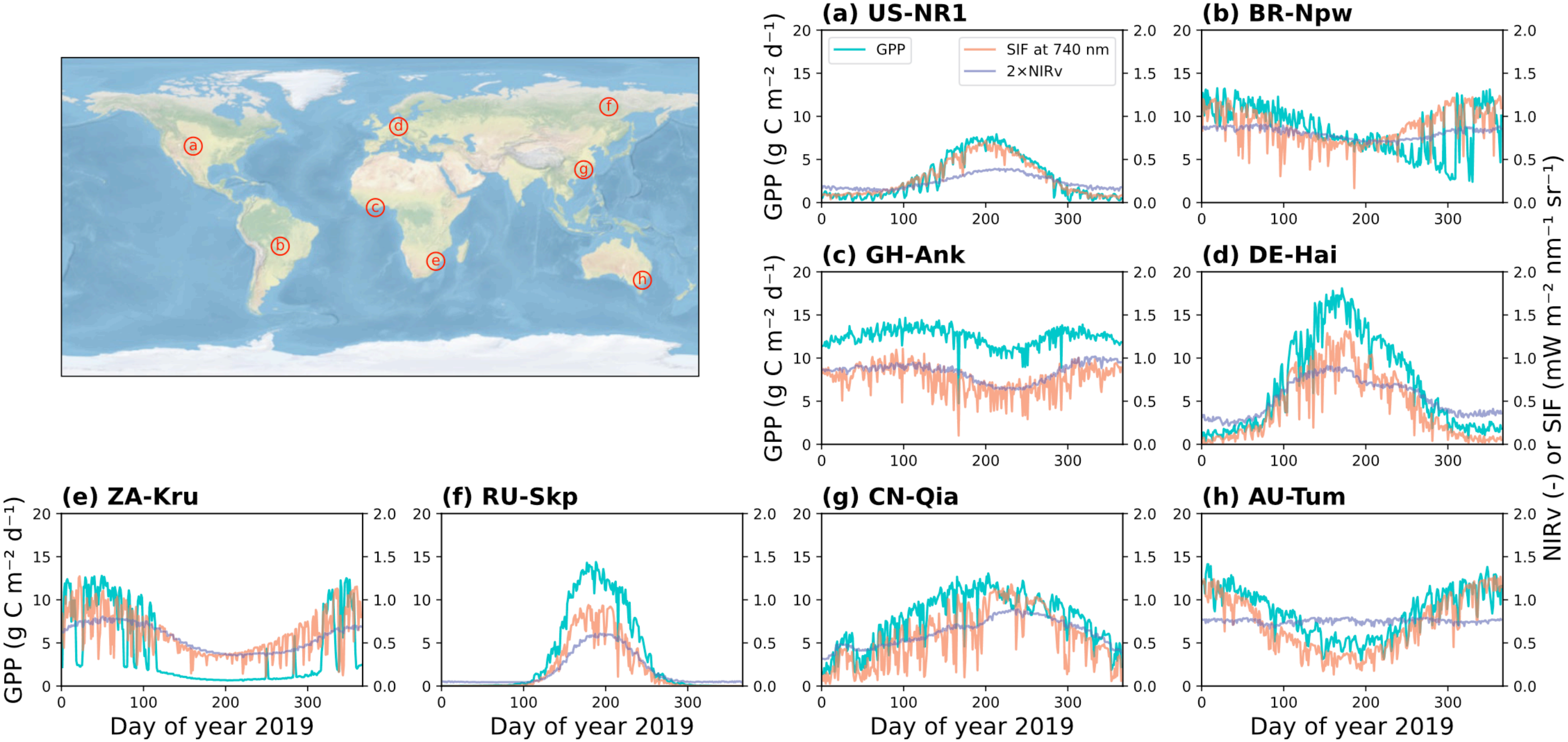
Global simulations of canopy optical properties that can be seen from space



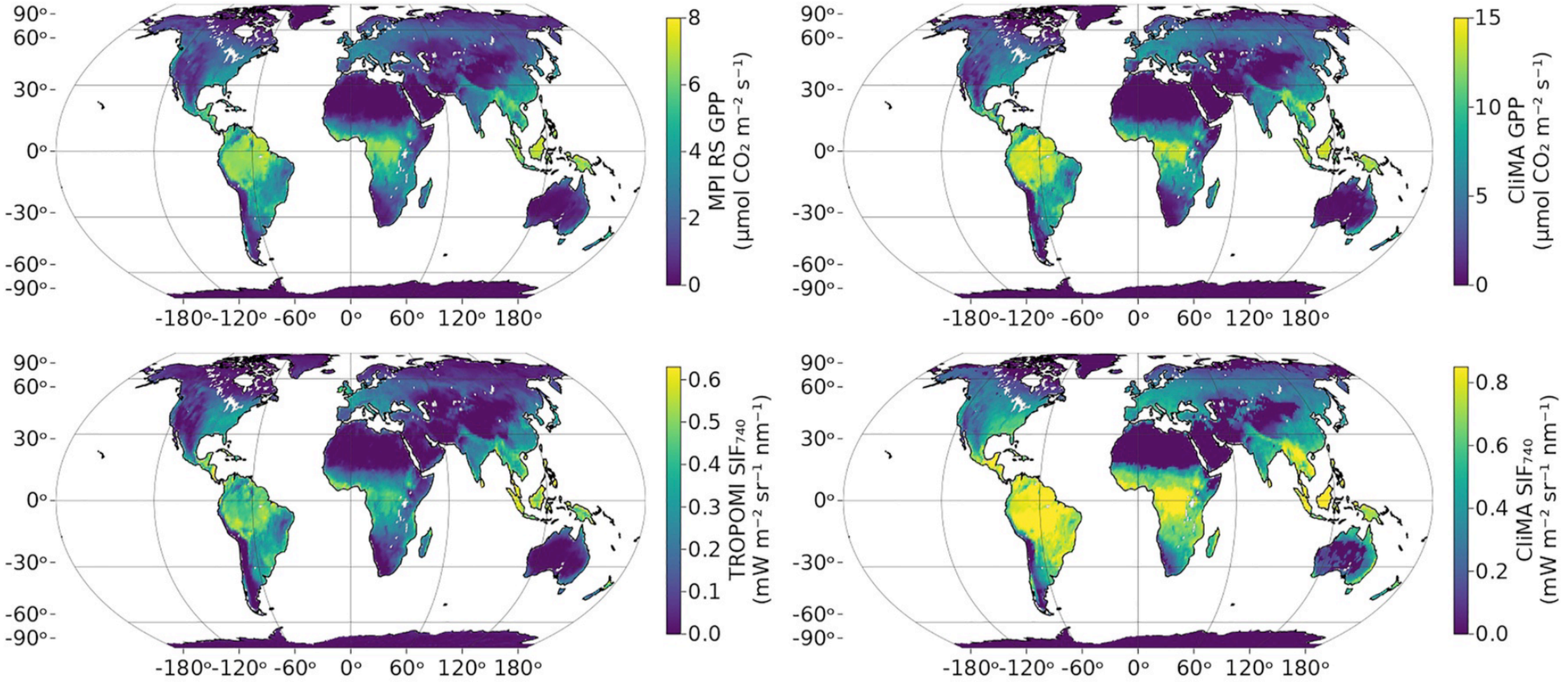
CliMA Land SIF @ 740 nm

Global simulations of canopy optical properties that can be seen from space



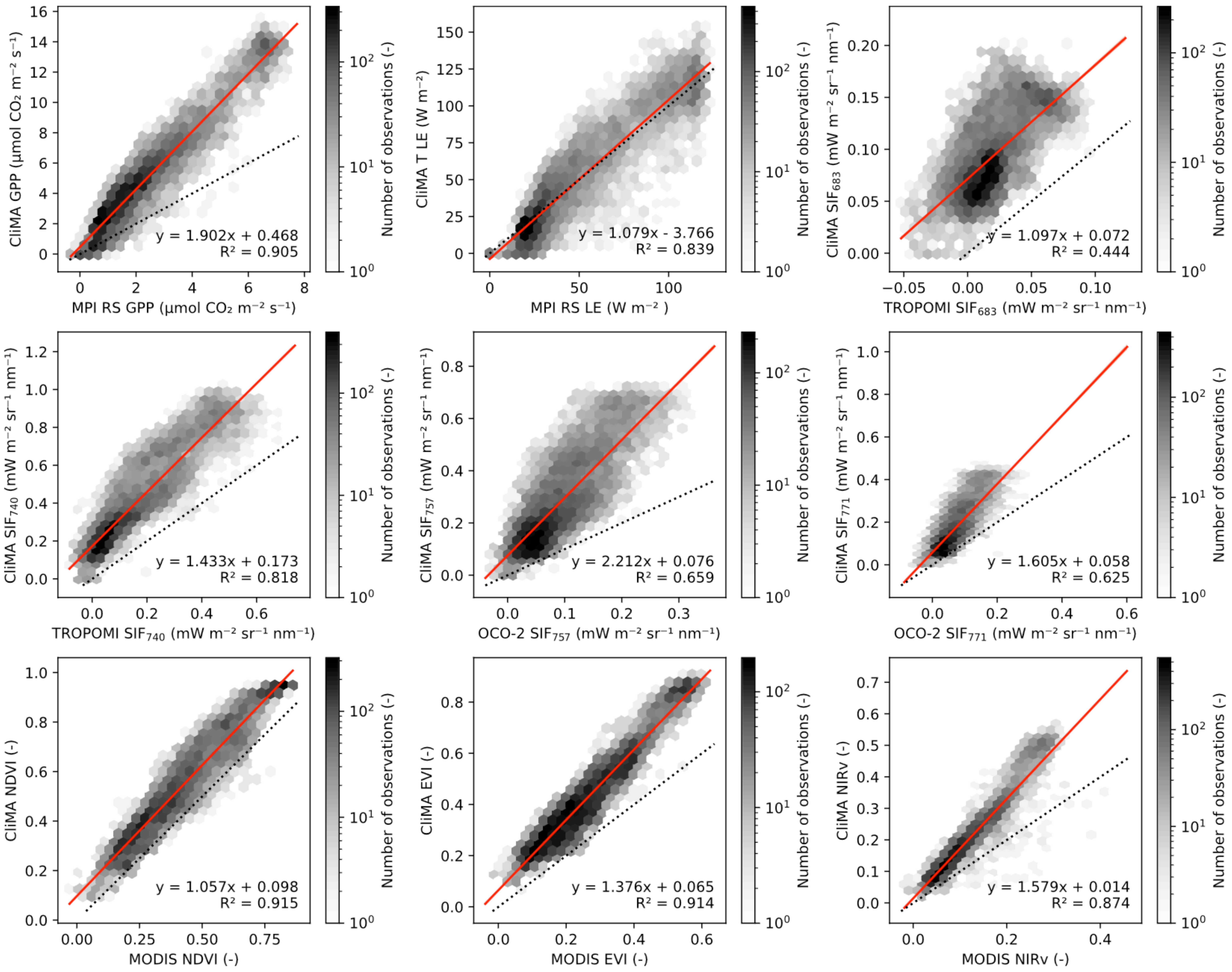


Wang et al. (2023) Journal of Advances in Modeling Earth Systems



Wang et al. (2023) Journal of Advances in Modeling Earth Systems

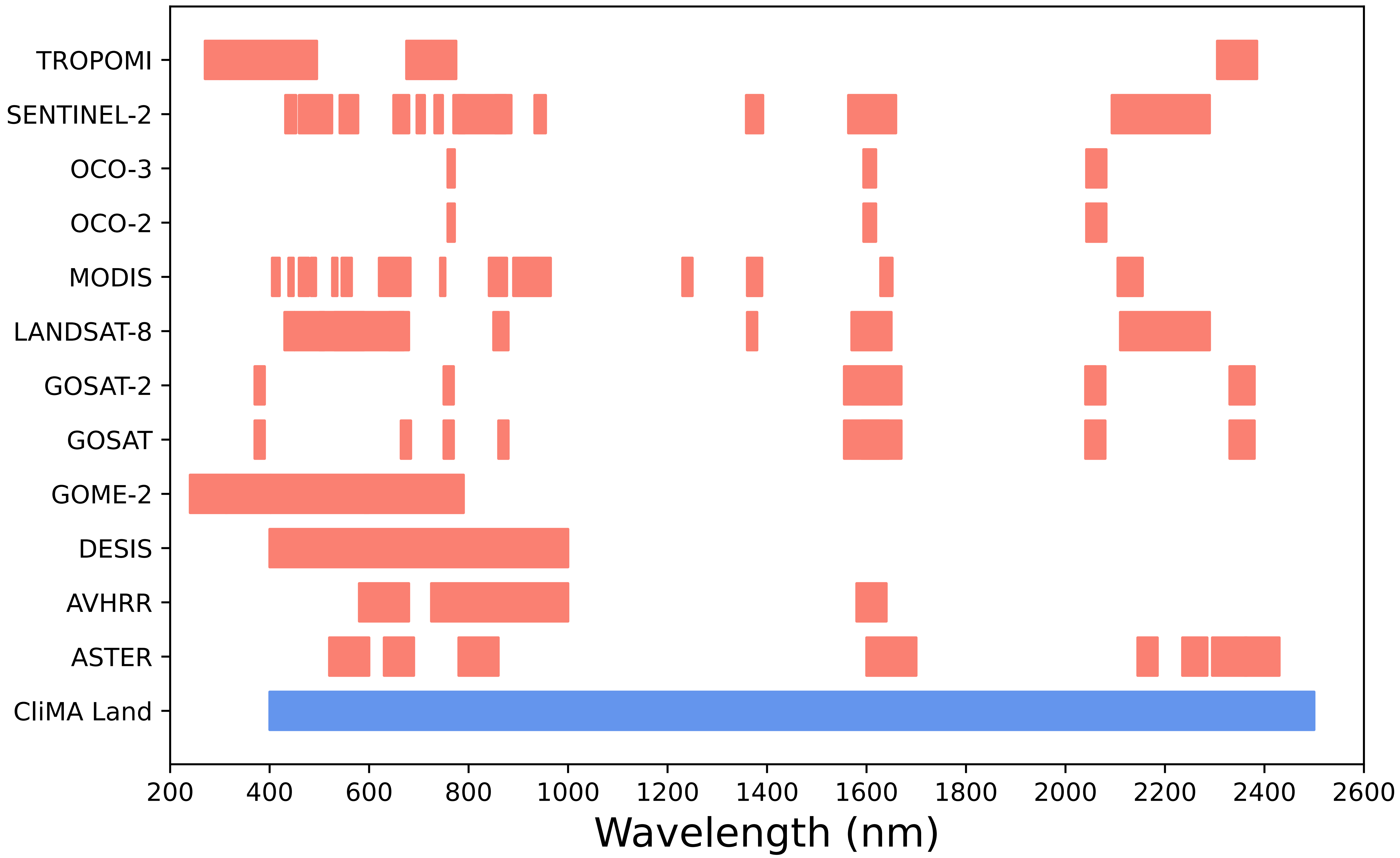
CliMA Land performs well for simulated quantities without any calibrations



Wang et al. (2023) Journal of Advances in Modeling Earth Systems

Remote Sensing

CliMA Land is capable of running hyper-spectral radiative transfer, allowing for using remote sensing data directly



Future research plans

1. Schemes

Improve model representation of soil-plant-air continuum

- **Develop more physiology-based model schemes**
- **Dynamic growth based on optimality theory**
- **Close the energy balance for UV, IR**
- **Add more complex ecosystem**
- **… …**

Future research plans

2. Setups

Advance model parameters configuration

- Coupling to CliMA Atmosphere and Ocean models
- Test more existing model configurations
- Add more application scenarios, such as agriculture
- Better documentation and demos
- … …

Future plans

3. Calibration

Use more data to calibrate the models

- Add more features to GriddingMachine
- Run data assimilation to calibrate the traits
  - Leaf area index
  - Chlorophyll content
  - Canopy structure
  - Optimization framework
- Explore nature based solutions against climate change

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