



Caltech



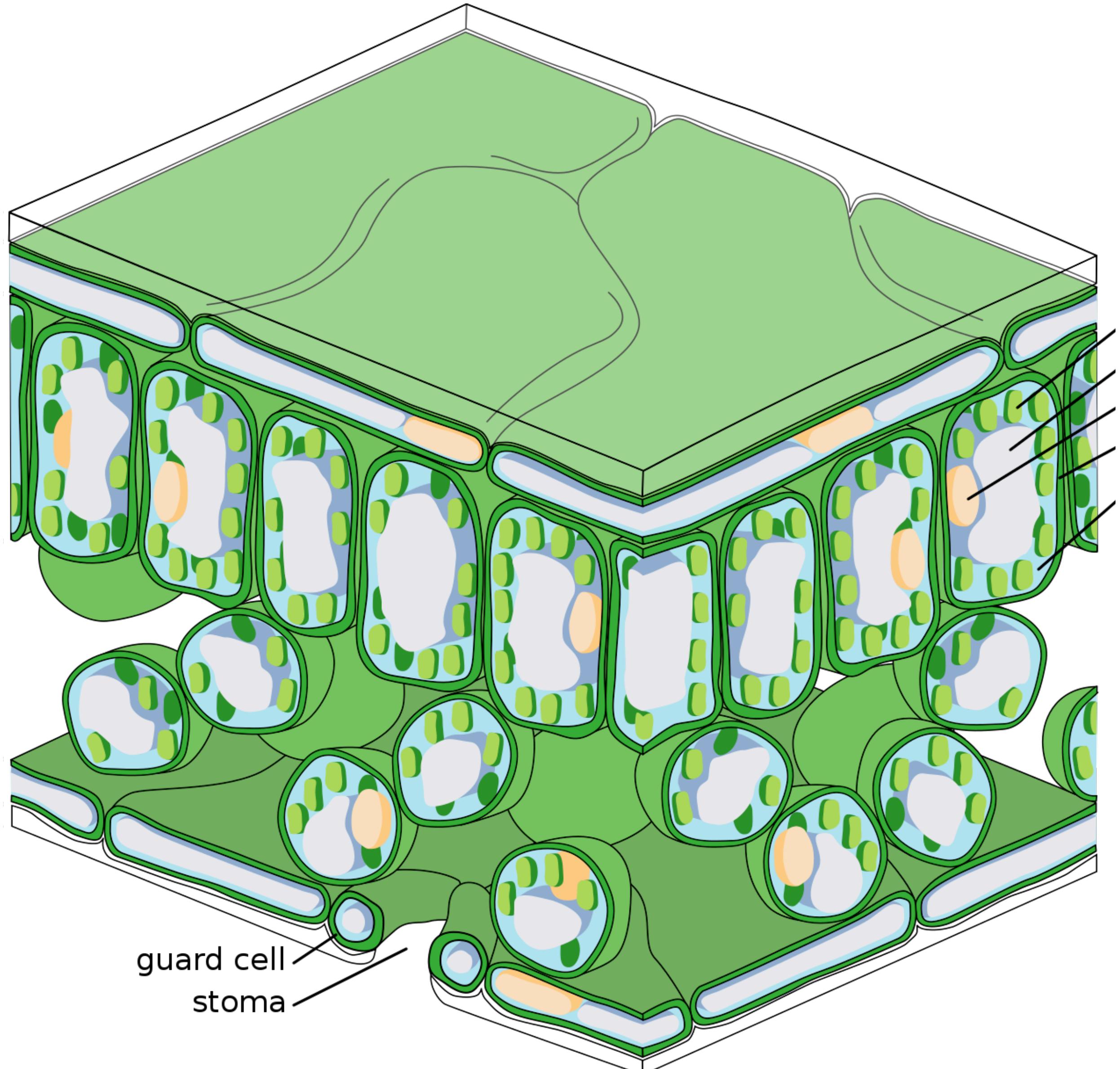
# Modeling vegetation processes from organ to global scale

**Yujie Wang**  
Research Scientist, Caltech



**~30% of  
precipitation  
back to air**

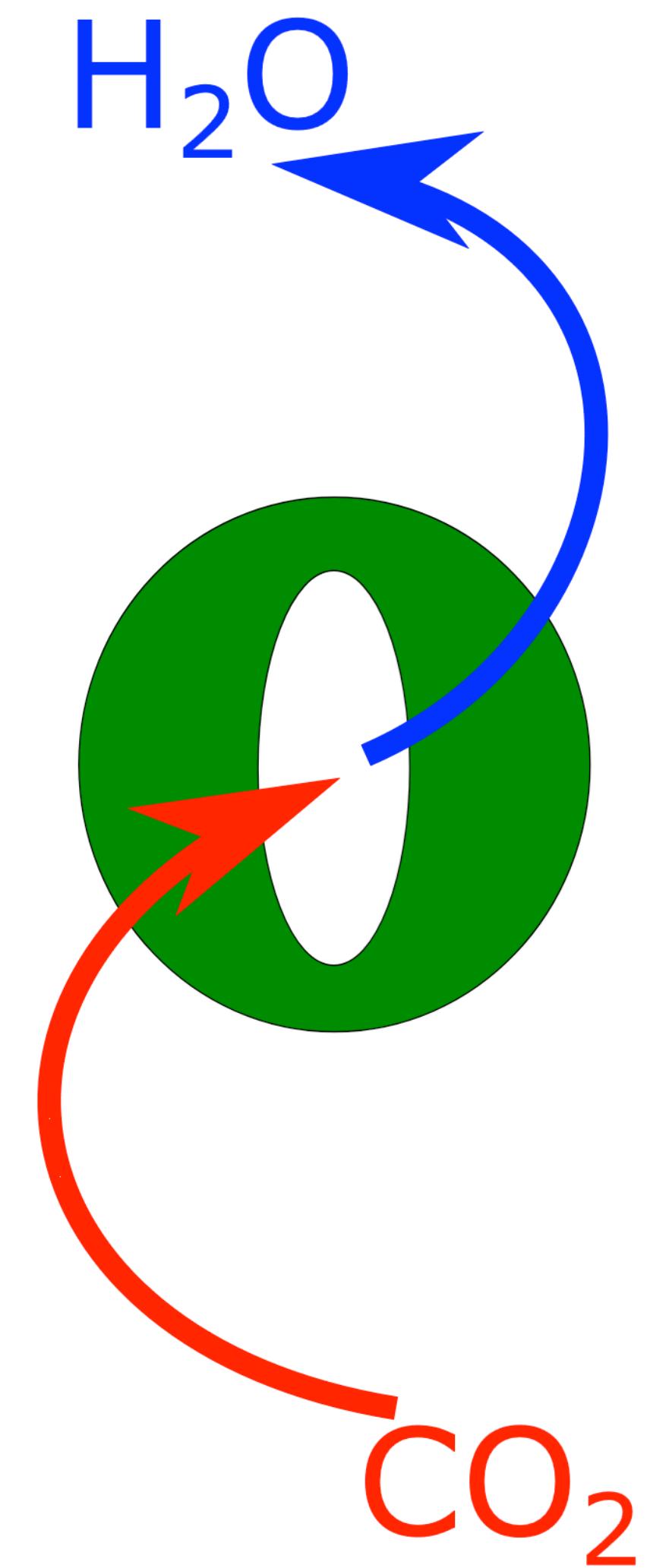
**almost all of  
land CO<sub>2</sub>  
fixation**





## Physiology

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

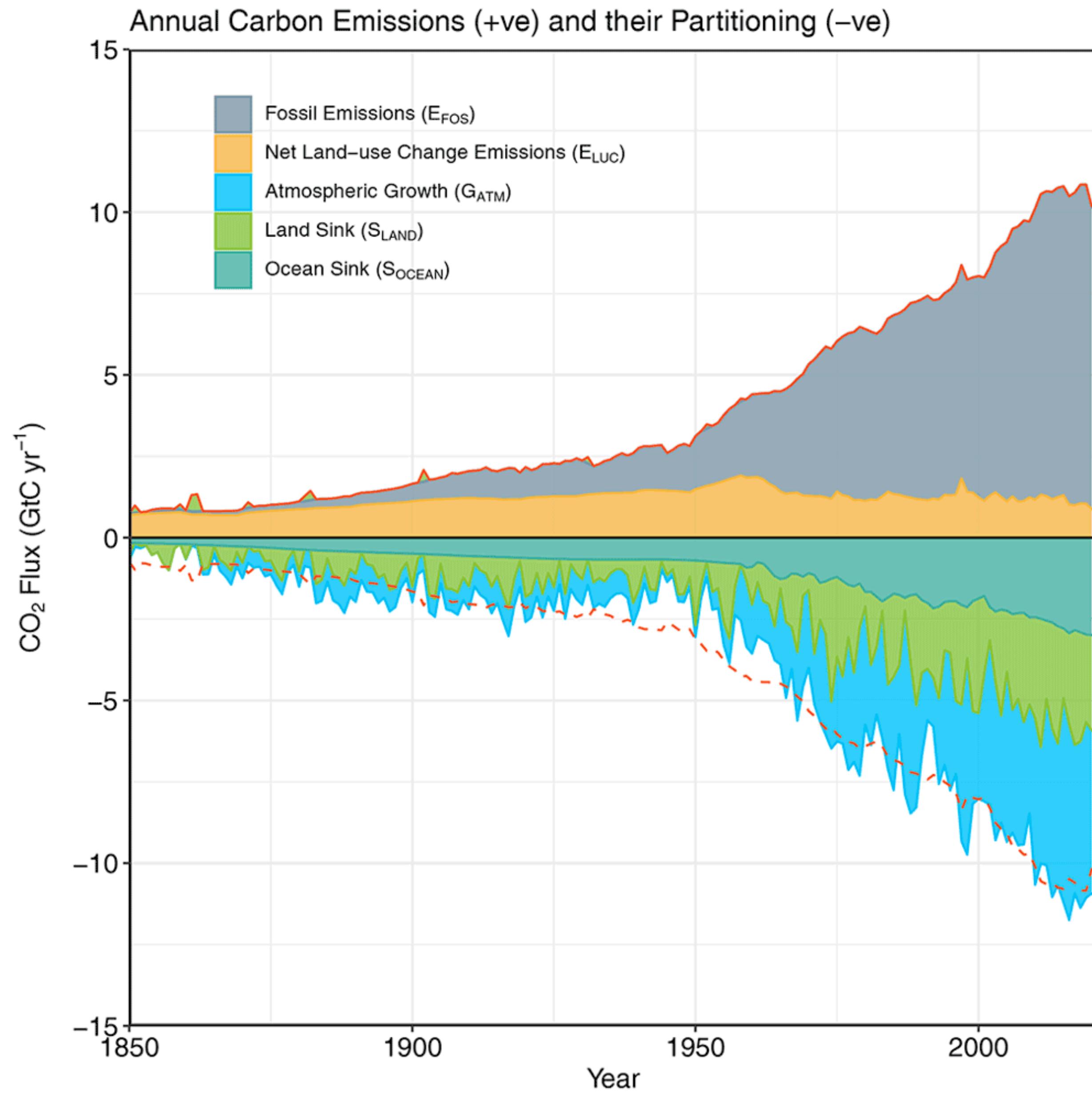


## Environment

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

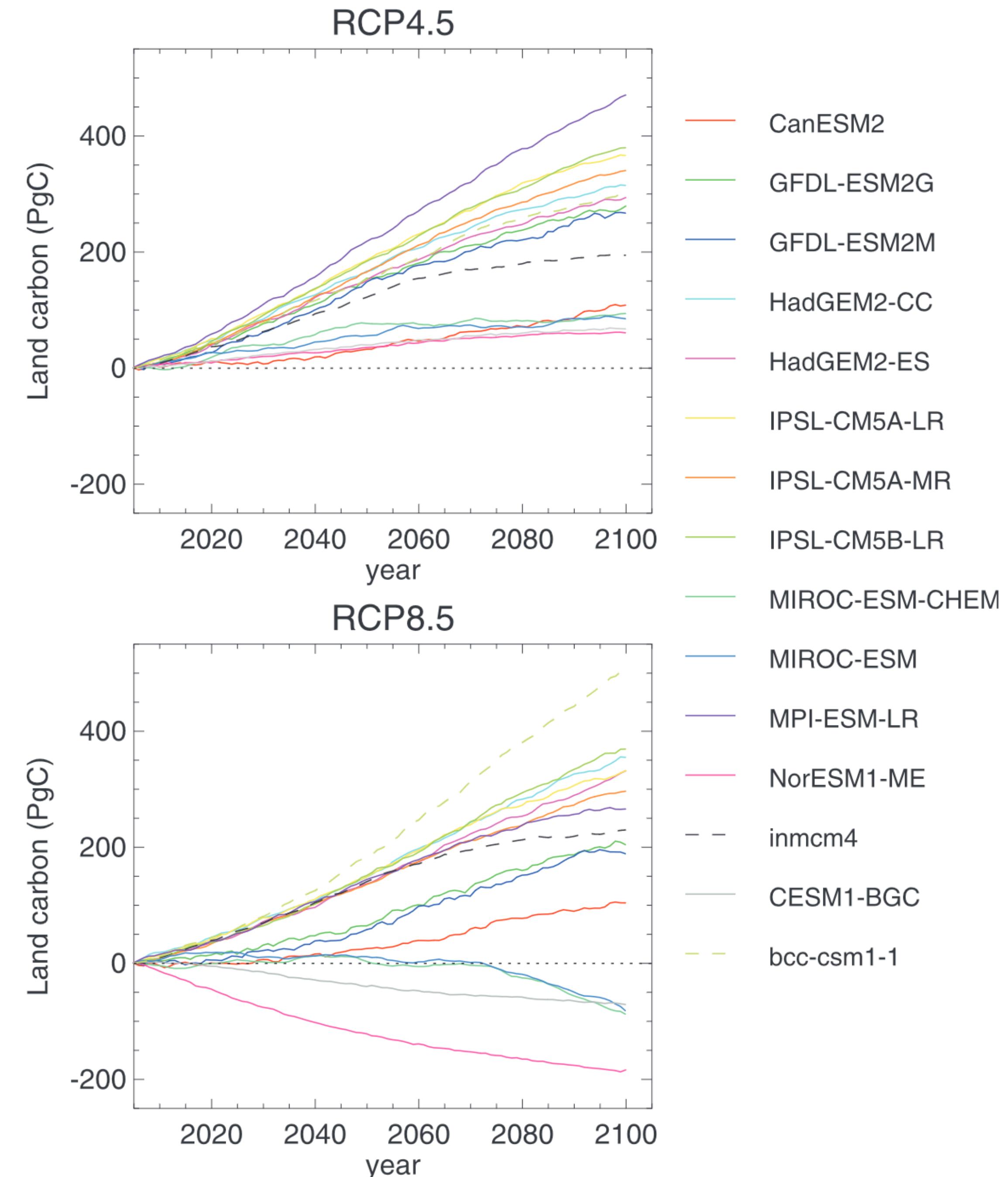


**Land takes up  
25% of emitted  
CO<sub>2</sub>, but we do  
not know how  
much nature  
can help in the  
future**



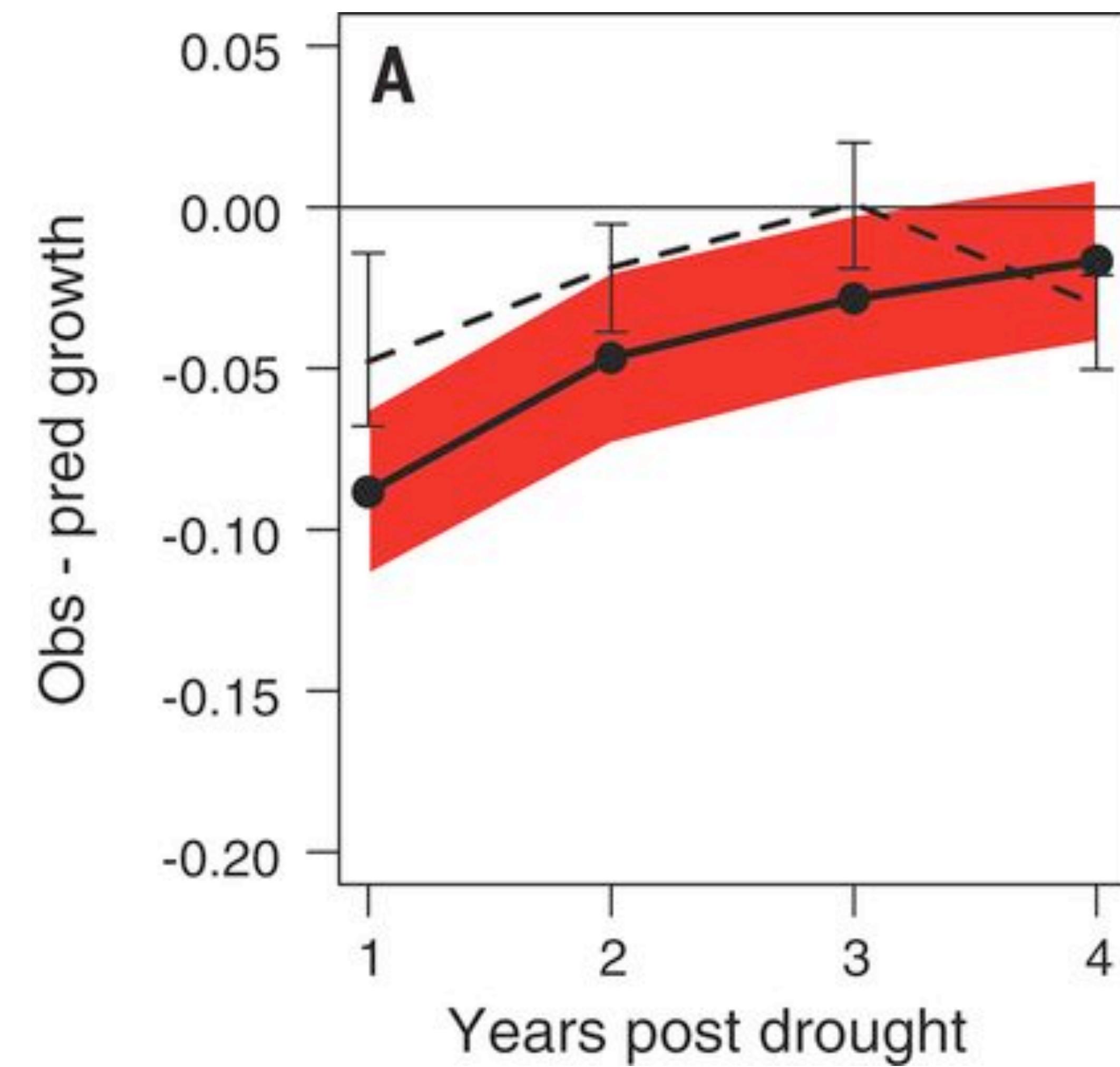


# Climate models differ in their projections of land carbon sink strength, even in the directions

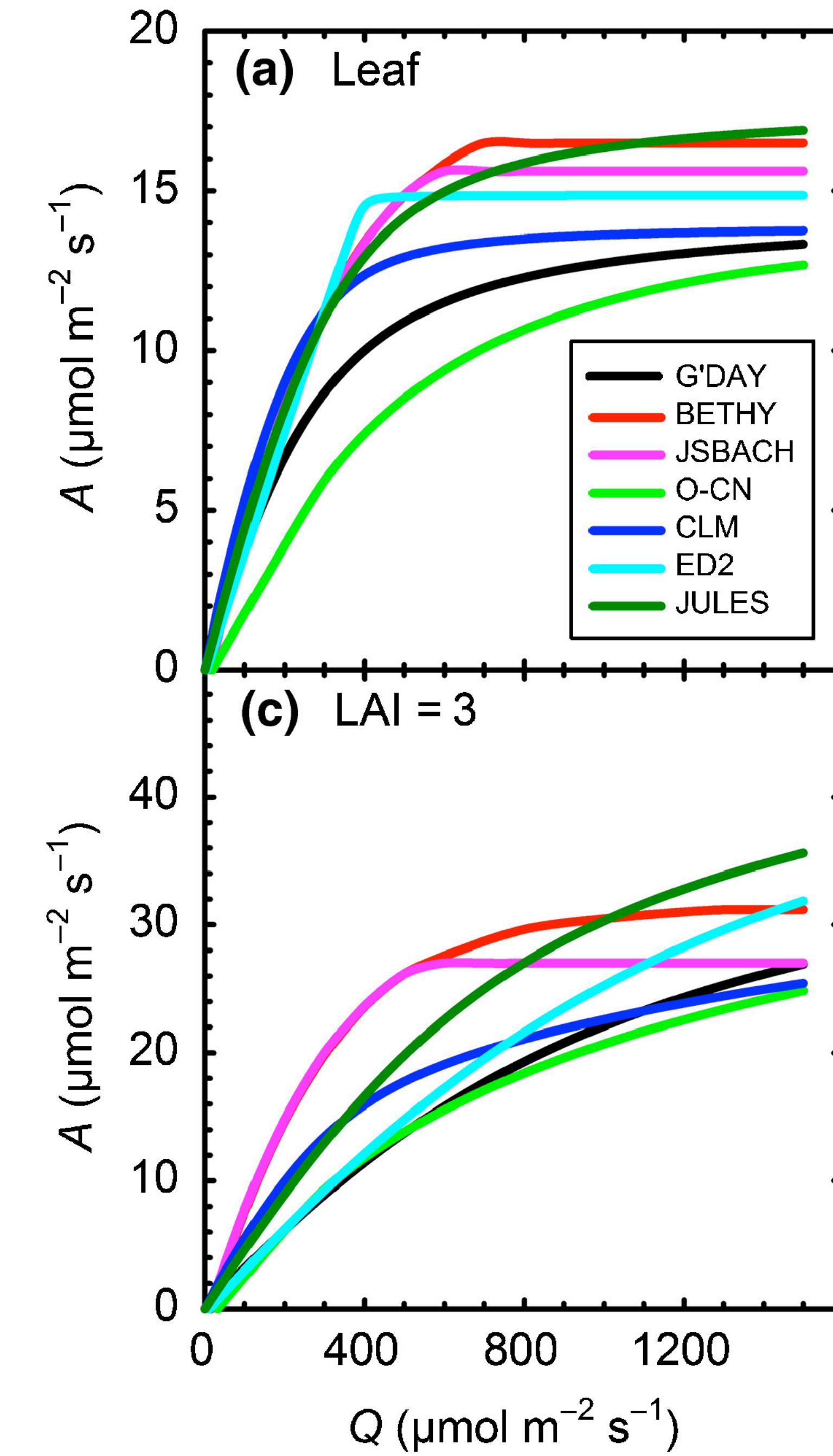


# Potential Reasons

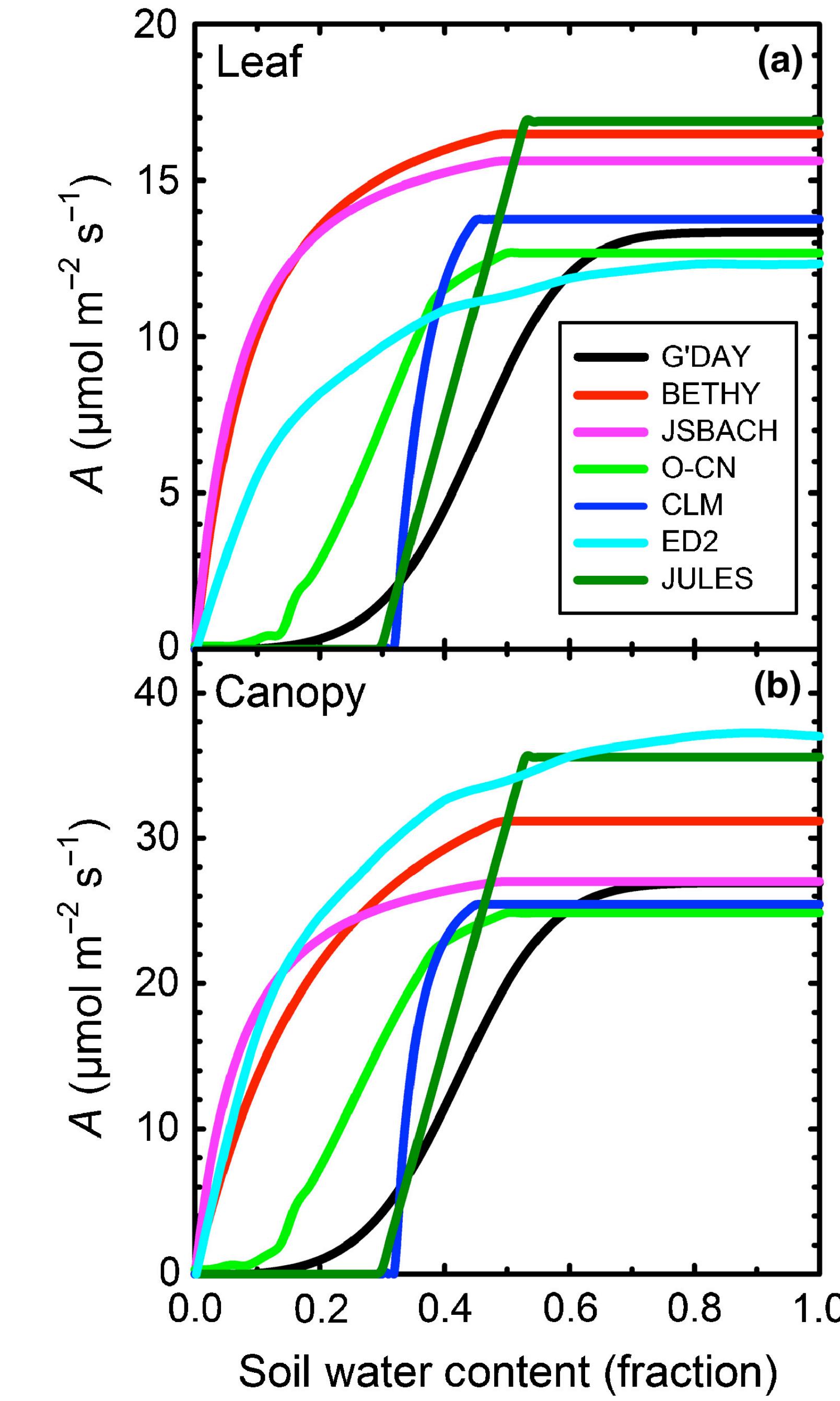
1. Lack physiological representations



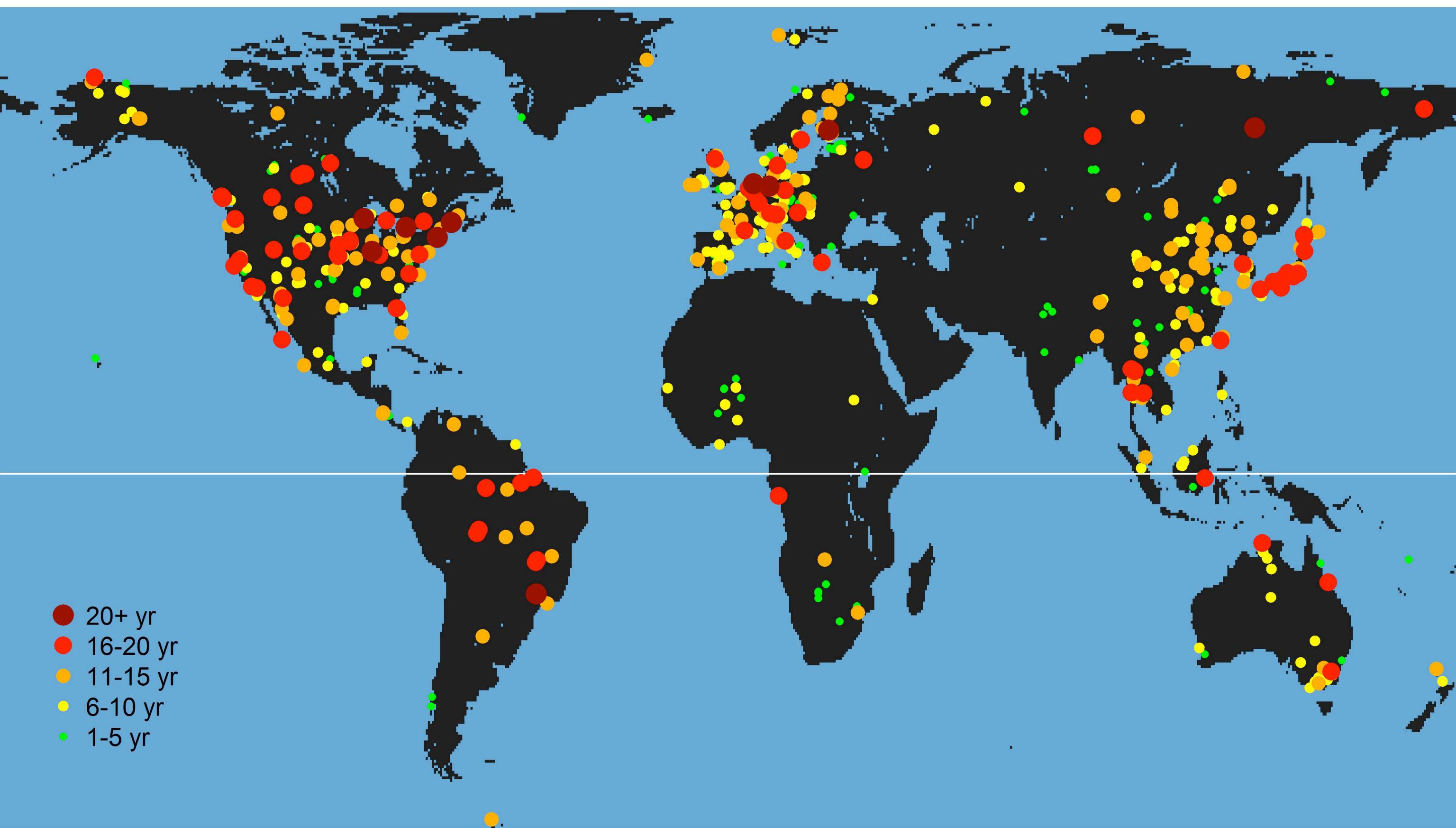
## 2. Contrasting model parameterization



## 2. Contrasting model parameterization



### 3. Limited data to calibrate the model



### 3. Limited data to calibrate the model



	Site ID	Policy 	Data Product  (Variables) 	1990	1995	2000	2005	2010	2015	2020
	<input checked="" type="checkbox"/> BR-CST	C	AmeriFlux BASE (32) AmeriFlux FLUXNET						✓ ✓	✓ ✓
	<input checked="" type="checkbox"/> BR-Sa1	C	AmeriFlux BASE (17)				✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓			
	<input checked="" type="checkbox"/> BR-Sa3	L	AmeriFlux BASE (26)			✓ ✓ ✓ ✓ ✓				
	<input checked="" type="checkbox"/> CA-Ca1	C	AmeriFlux BASE (33)		✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓					
	<input checked="" type="checkbox"/> CA-Ca2	C	AmeriFlux BASE (28)		✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓					
	<input checked="" type="checkbox"/> CA-Ca3	C	AmeriFlux BASE (39)		✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓

# Challenges



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## 1. Schemes

**Improve model representation of soil-plant-air continuum**

## 2. Setups

**Advance model parameters configuration**

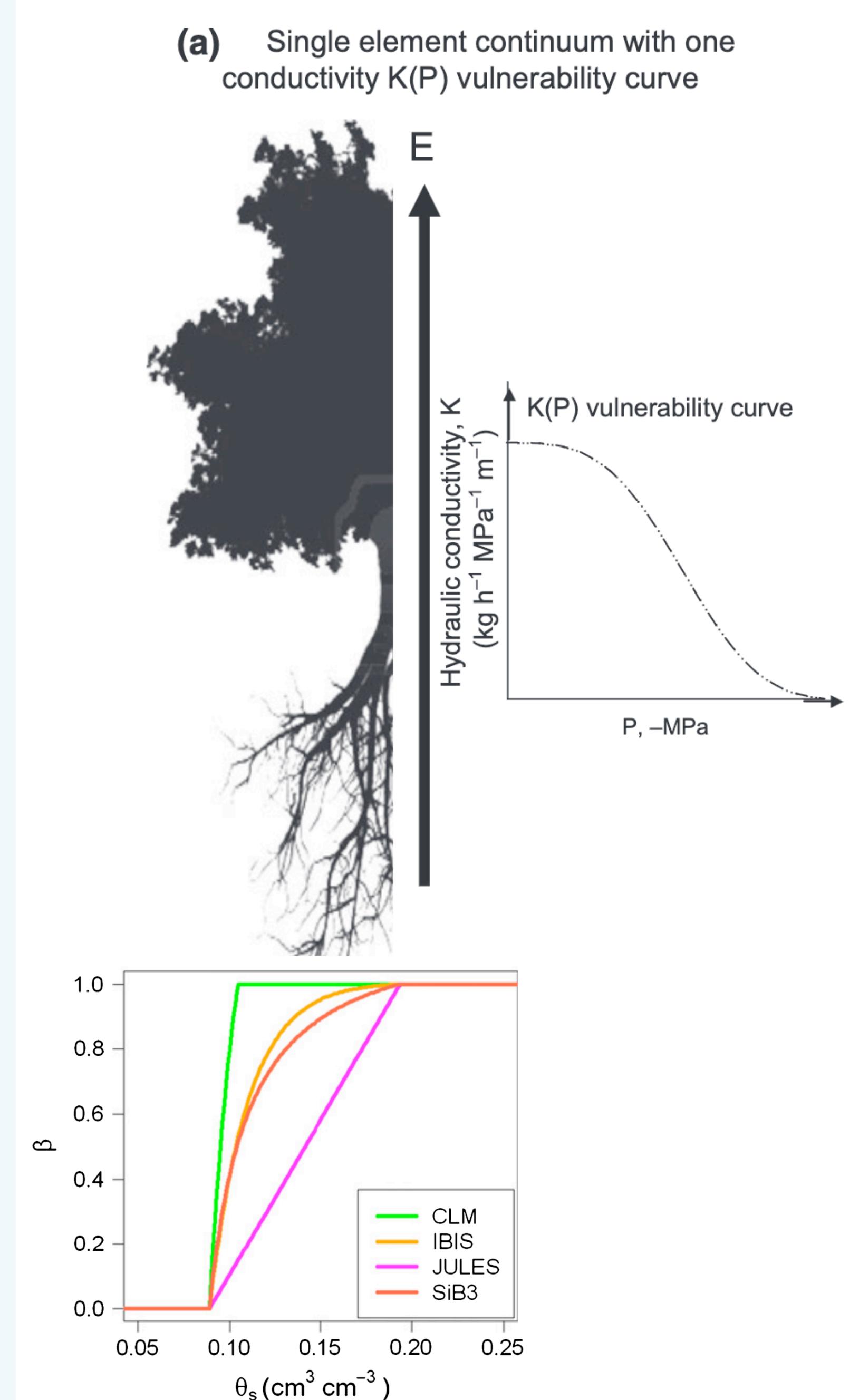
## 3. Calibration

**Use more data to calibrate the models**



## 1. Schemes

### Improve model representation of plant water relations

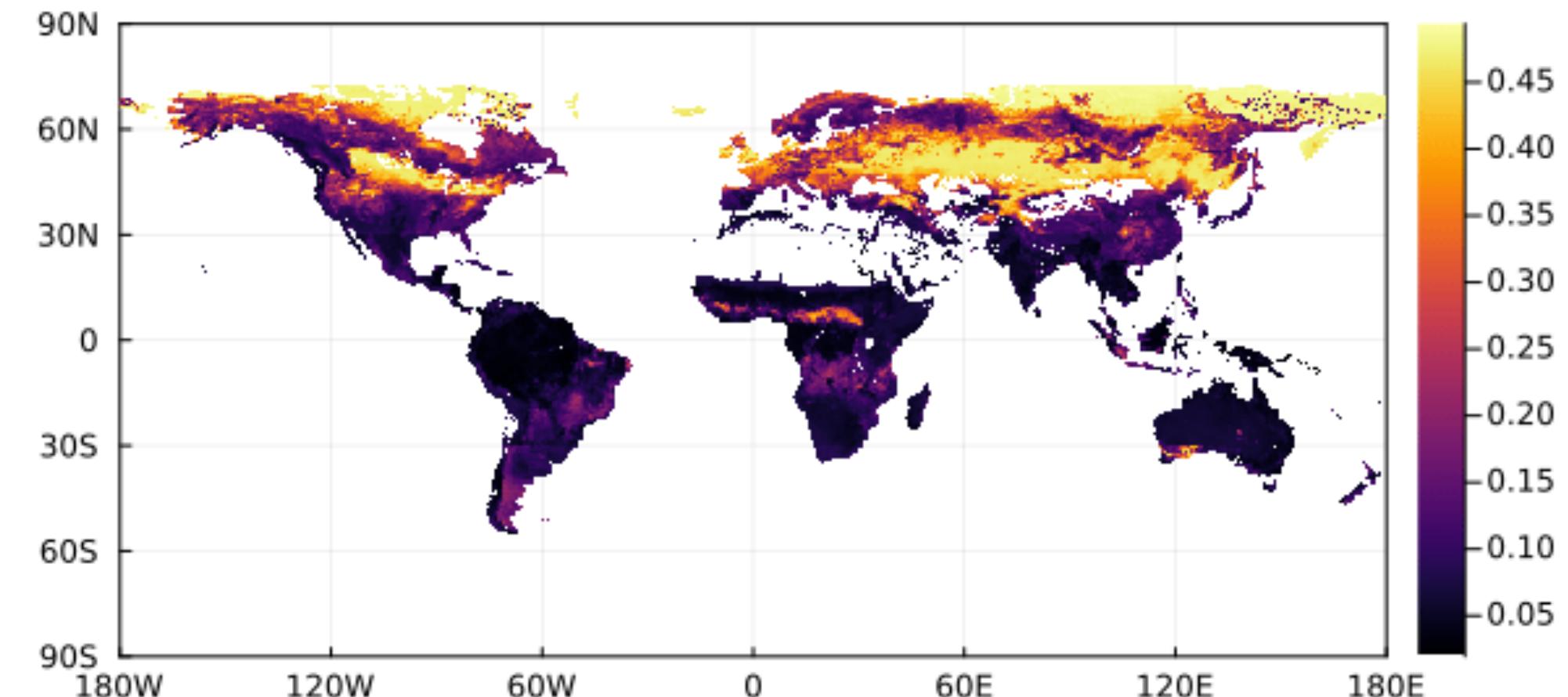




## 2. Setups

**Advance model  
parameter  
configuration  
for leaf traits**

Plant Functional Type	$\chi_L$	$\alpha_{vis}^{leaf}$	$\alpha_{nir}^{leaf}$	$\alpha_{vis}^{stem}$	$\alpha_{nir}^{stem}$	$\tau_{vis}^{leaf}$	$\tau_{nir}^{leaf}$
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

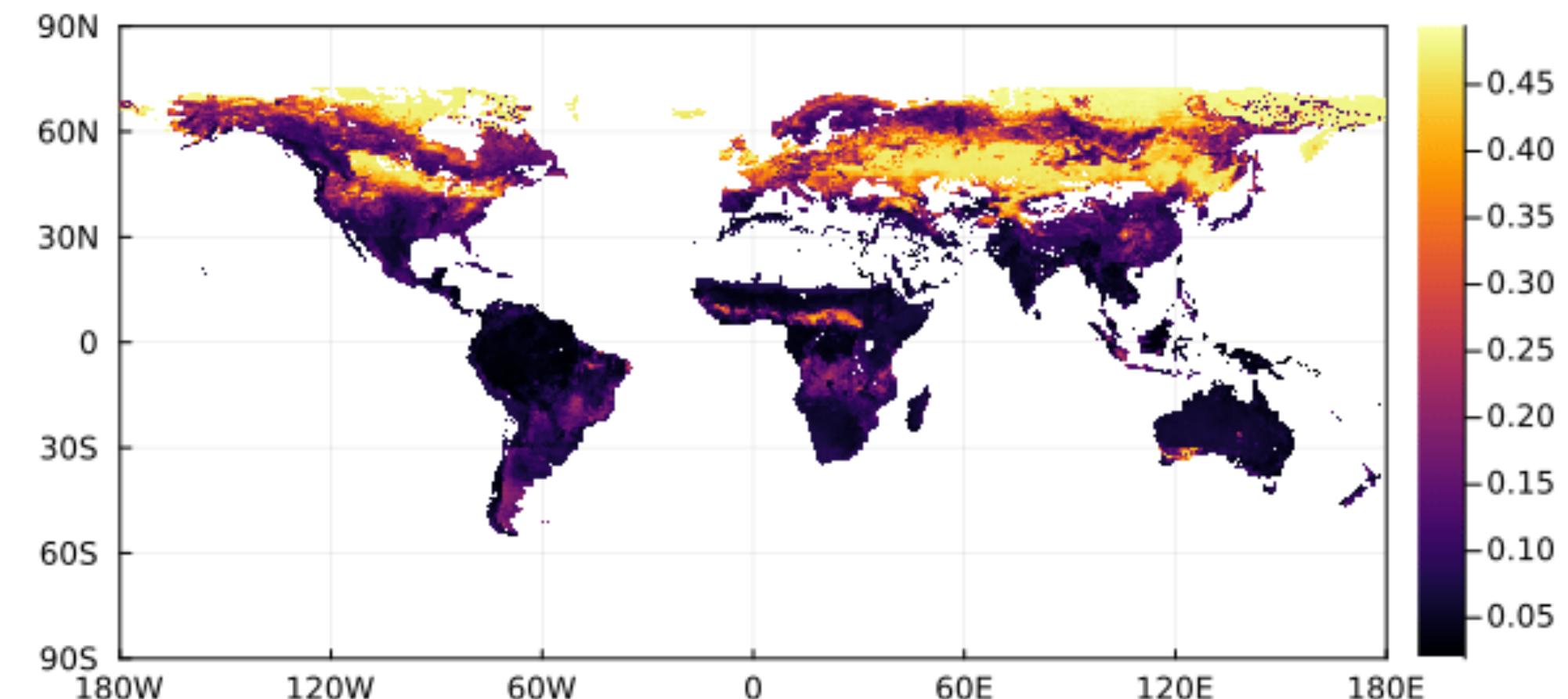




## 2. Setups

**Advance model  
parameter  
configuration  
for leaf traits**

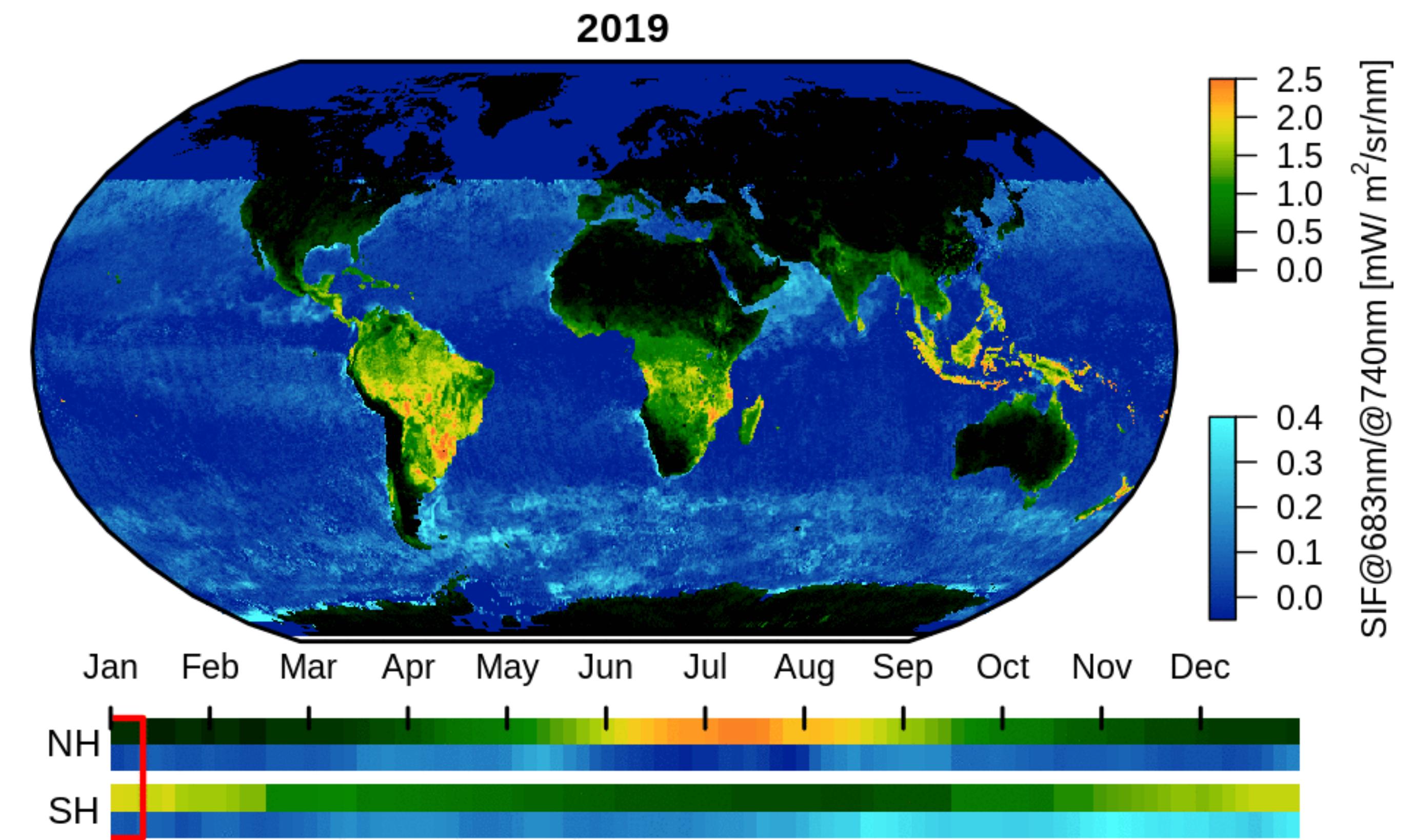
Plant Functional Type	$\chi_L$	$\alpha_{vis}^{leaf}$	$\alpha_{nir}^{leaf}$	$\alpha_{vis}^{stem}$	$\alpha_{nir}^{stem}$	$\tau_{vis}^{leaf}$	$\tau_{nir}^{leaf}$
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BDT tropical	0.01	0.10	0.45	0.16	0.39	0.05	0.25
BDT temperate	0.25	0.10	0.45	0.16	0.39	0.05	0.25
BDT boreal	0.25	0.10	0.45	0.16	0.39	0.05	0.25





### 3. Calibration

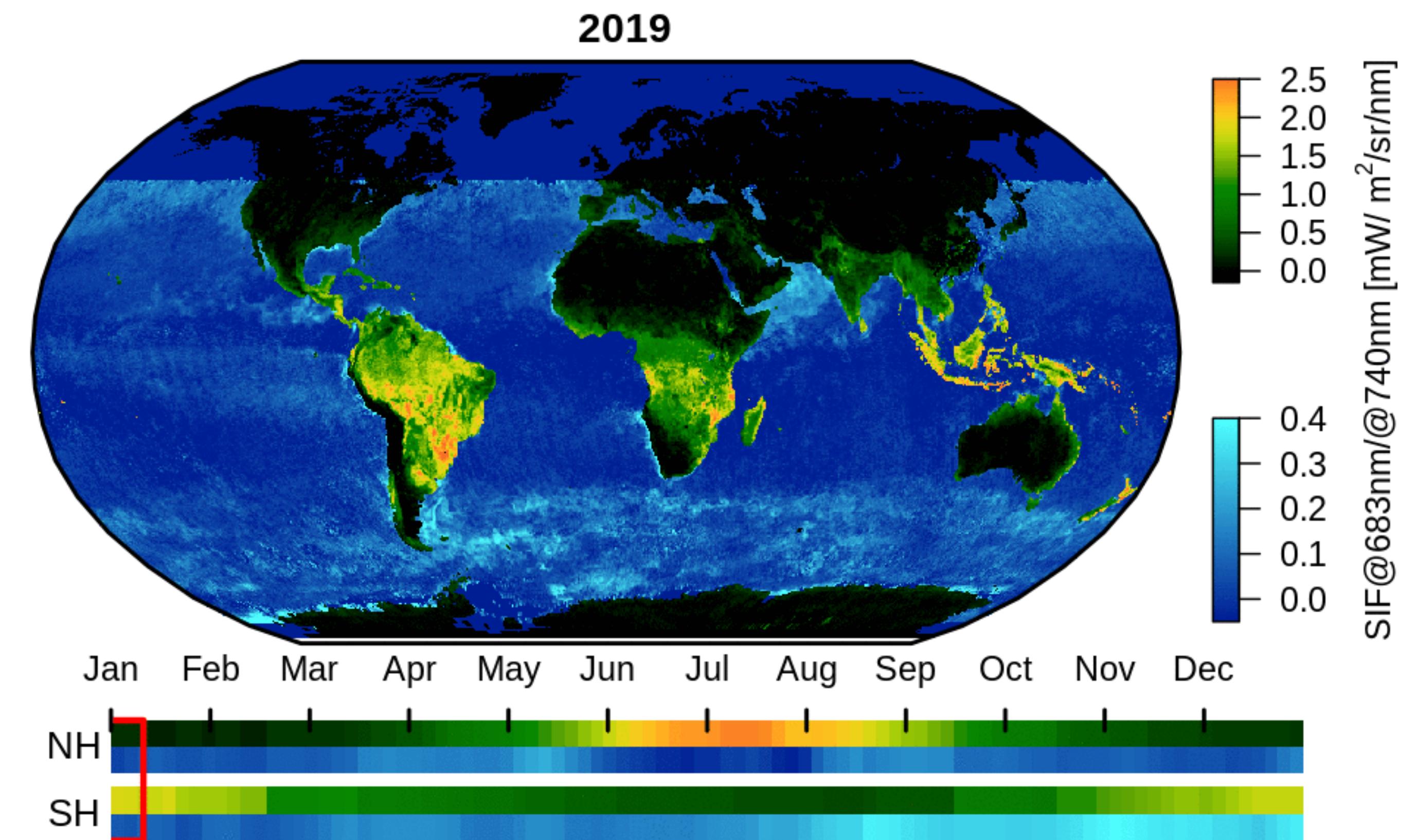
**Use remote sensing data to calibrate the models**





### 3. Calibration

**Use remote sensing data to calibrate the models**



# 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

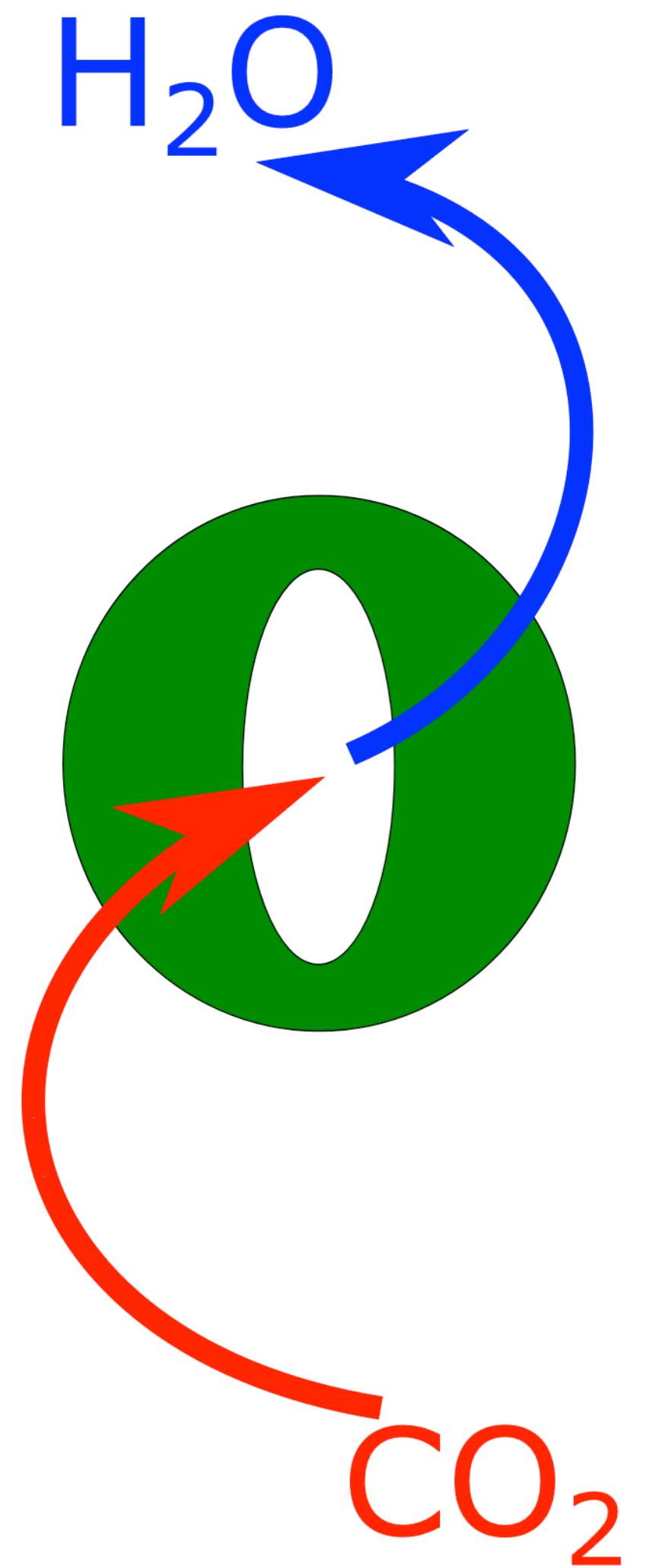
## 3. Calibration

Use more data to calibrate the models



## Physiology

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

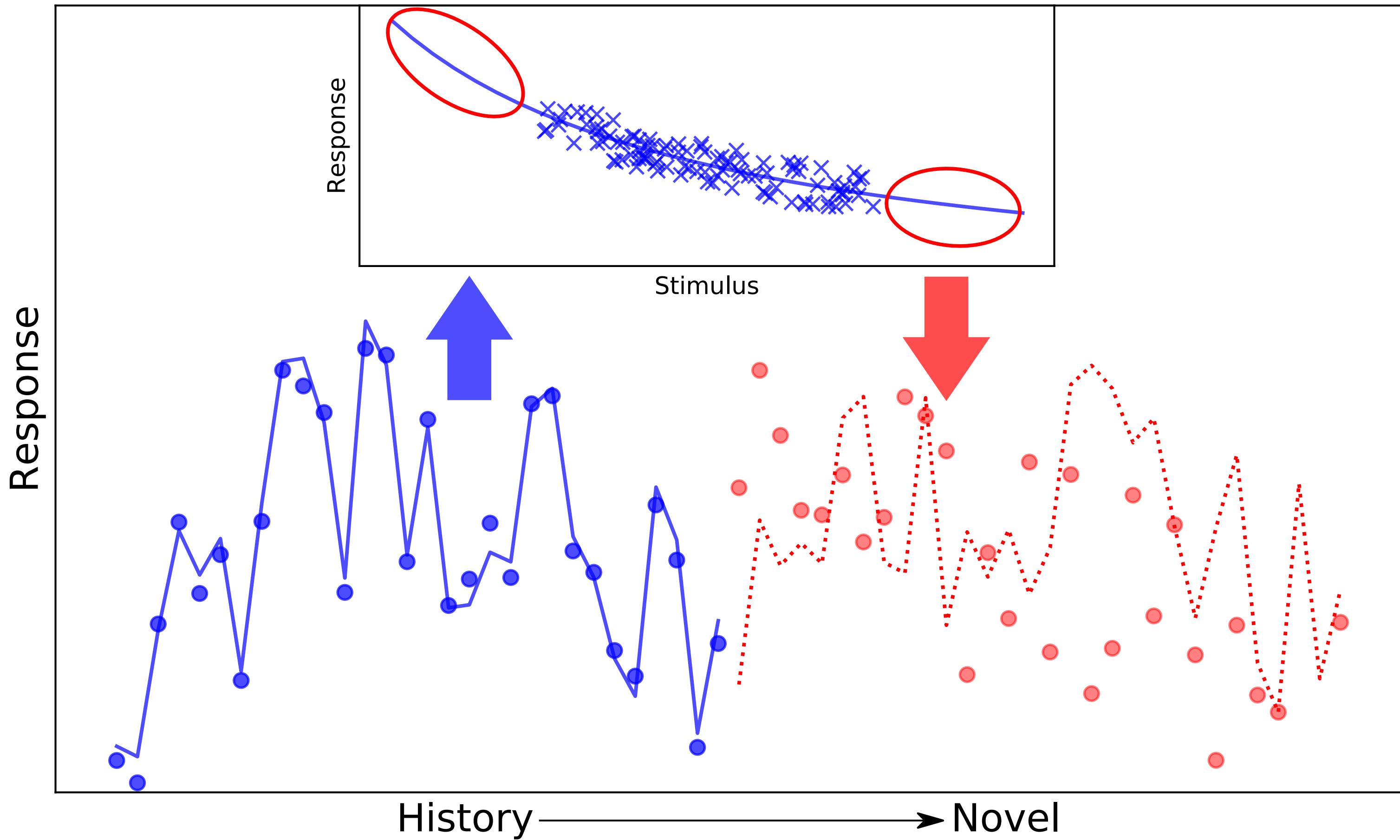


## Environment

- Atmospheric CO<sub>2</sub>
- Air humidity
- Air temperature
- Radiation
- Wind speed
- Soil moisture

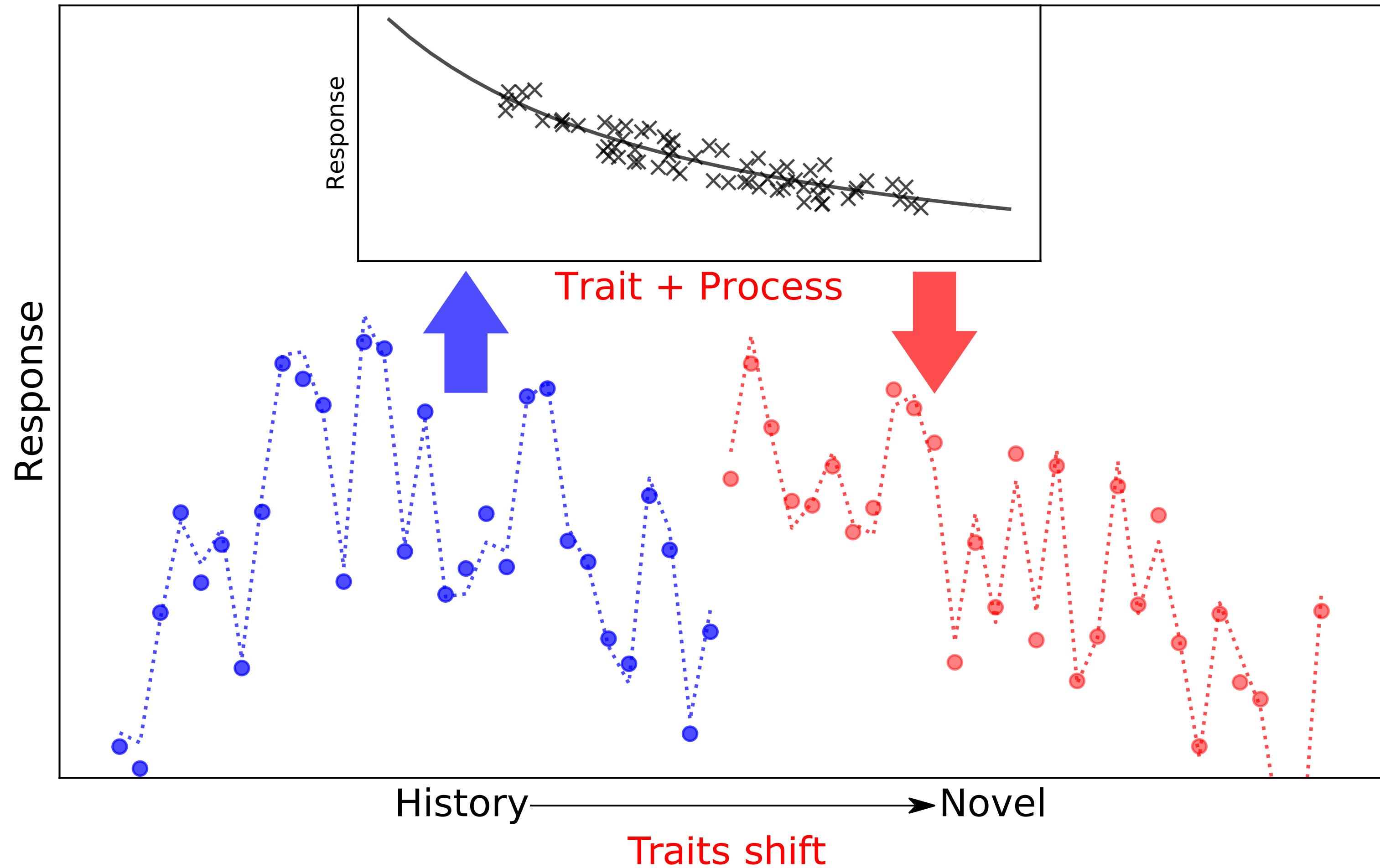


**Statistical models are efficient, but cannot well capture the responses to novel environment**





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

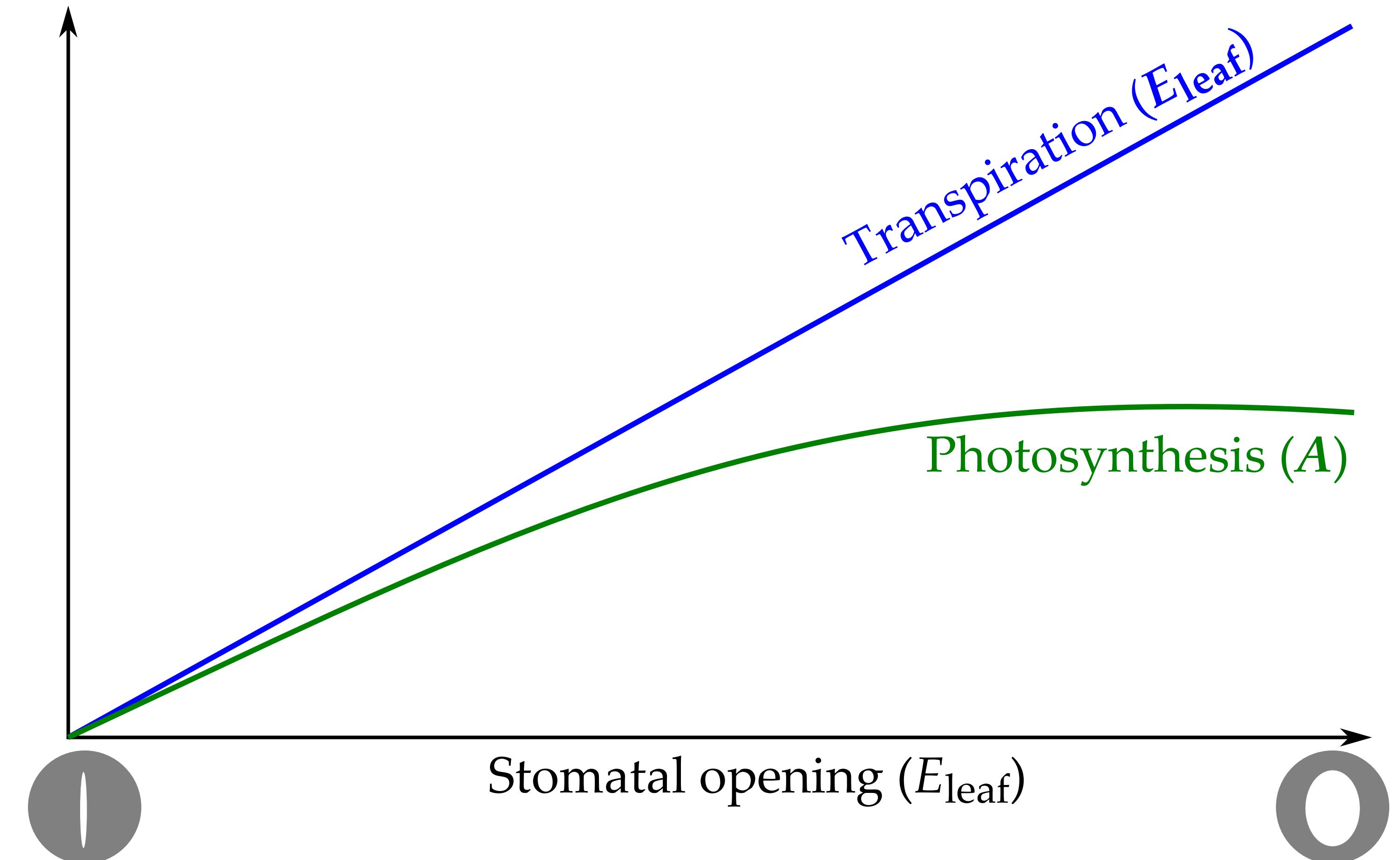




## Optimality

Maximize the difference between gain and cost

Gain:  $A(E_{leaf})$

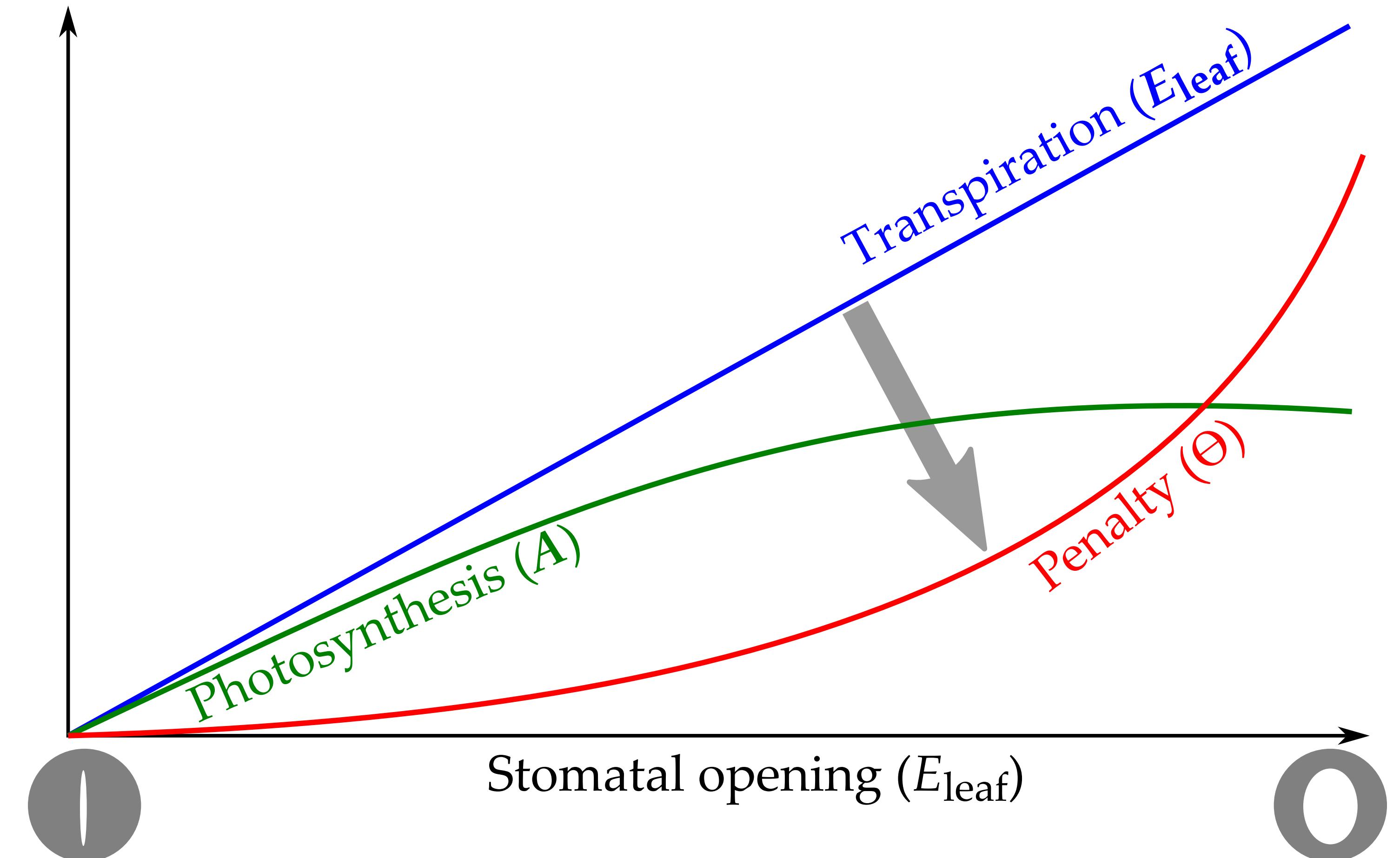




## Optimality

Maximize the difference between gain and cost

Risk:  $\Theta(E_{leaf})$

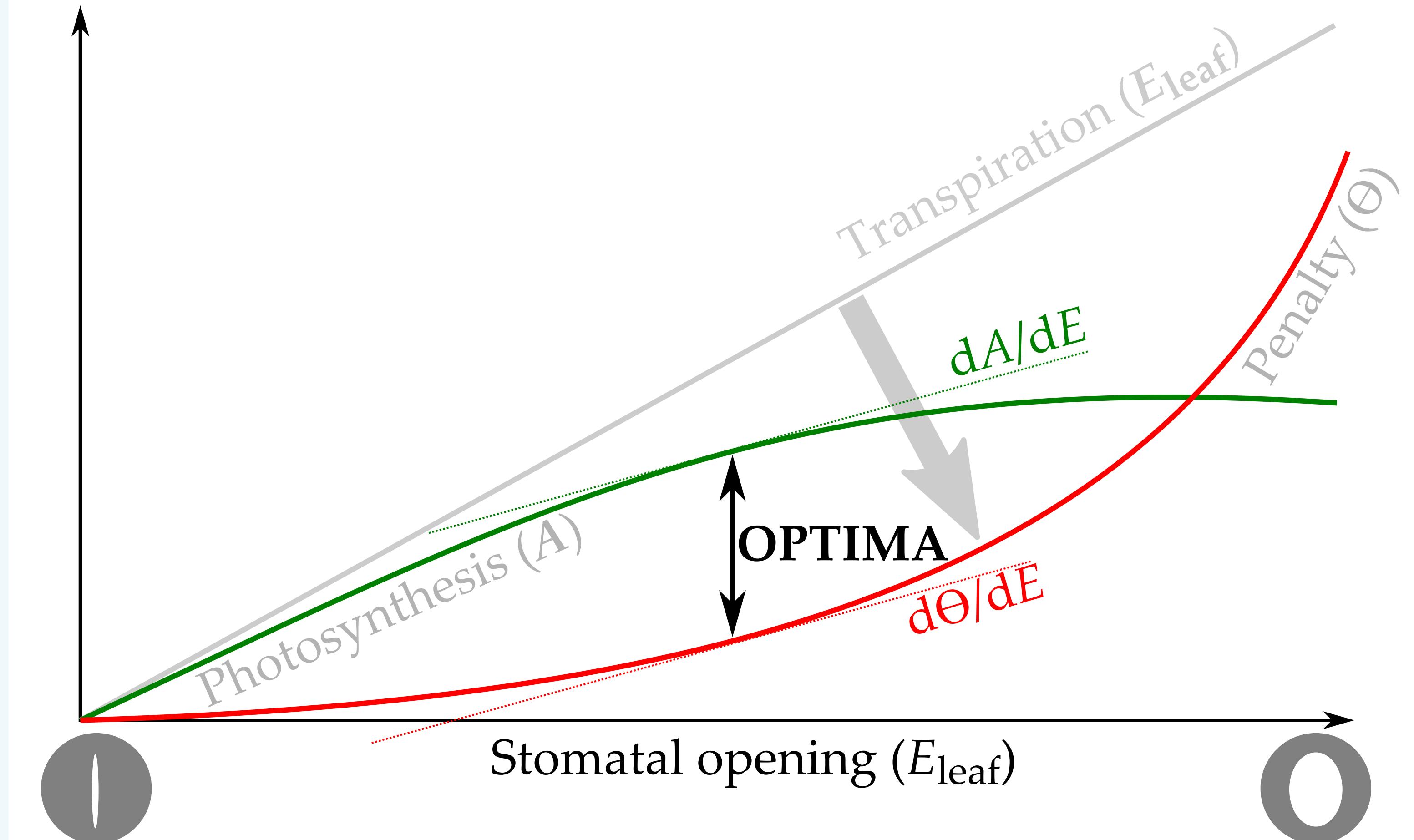




## Optimality

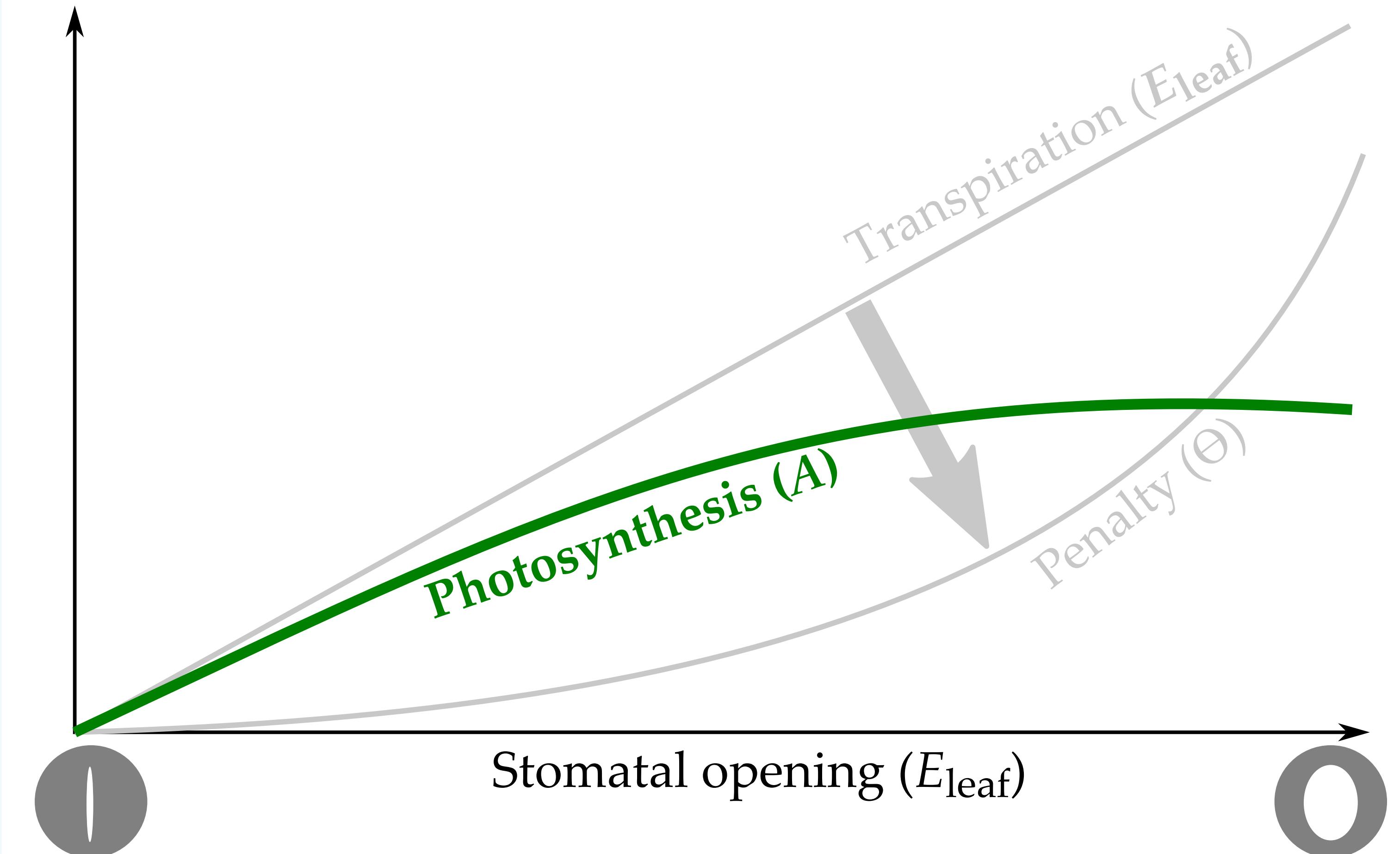
Maximize the difference between gain and cost **when**

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



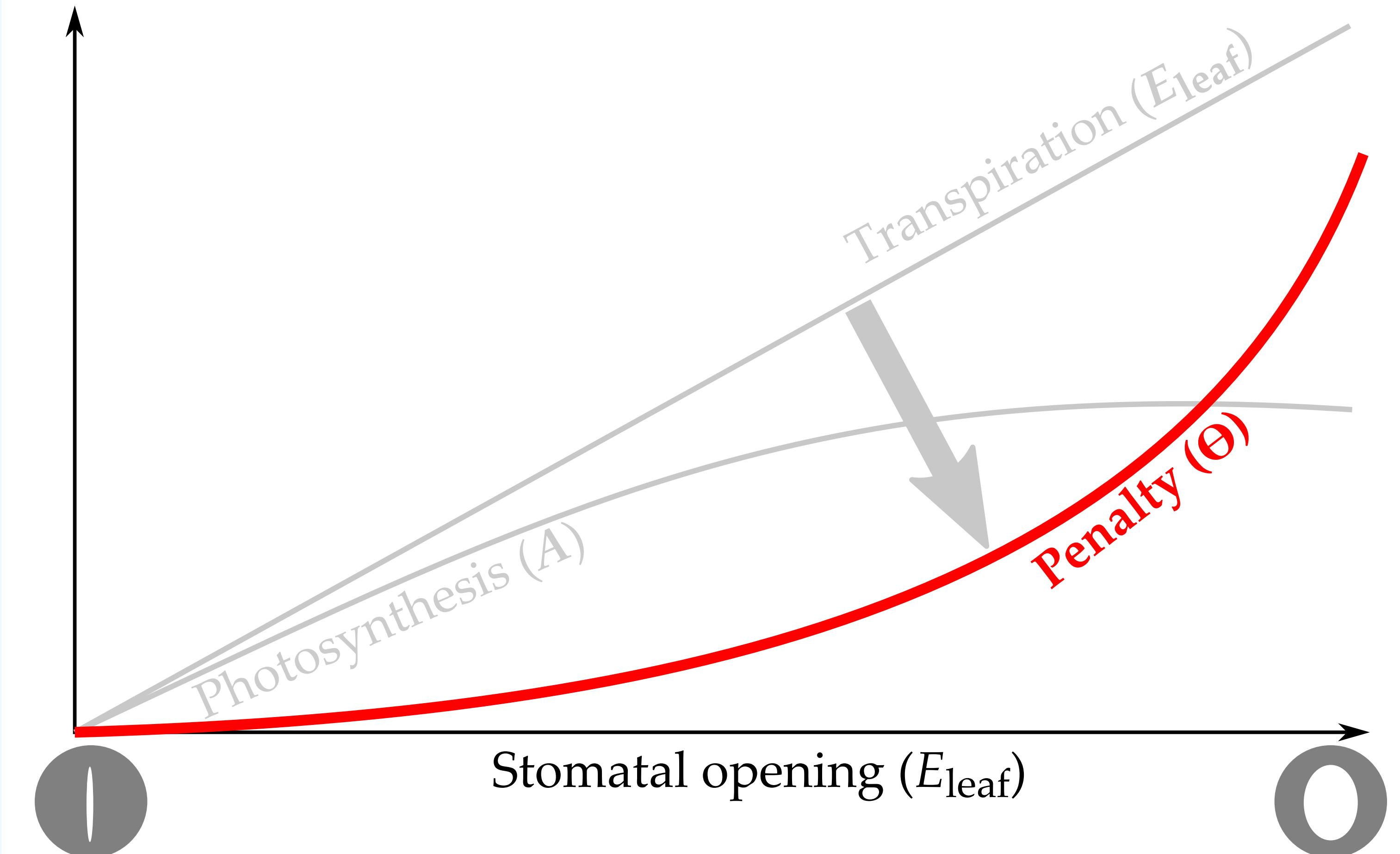


## Gain Function Instantaneous photosynthetic rate





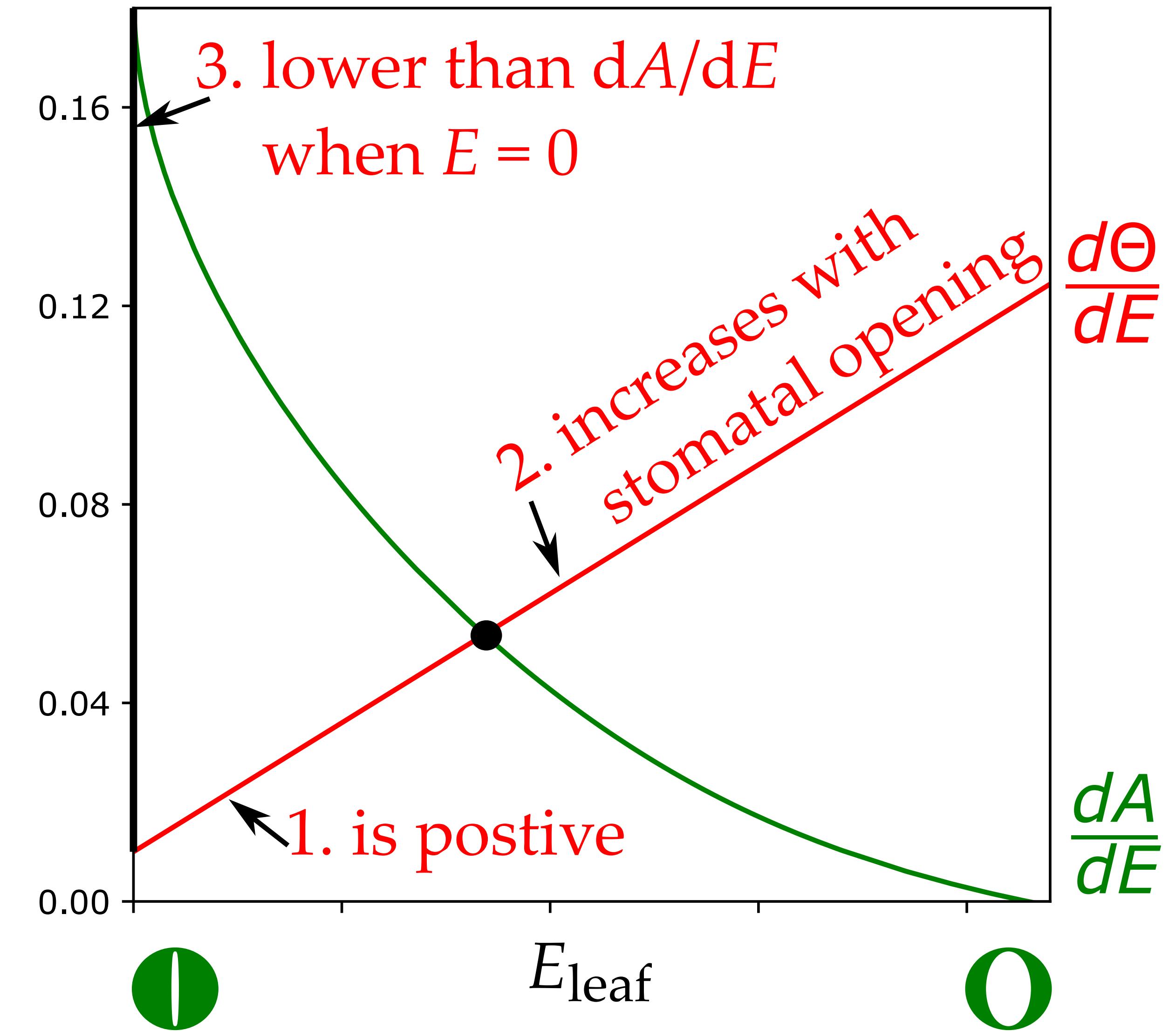
**Risk Function**  
**No direct  
measures**





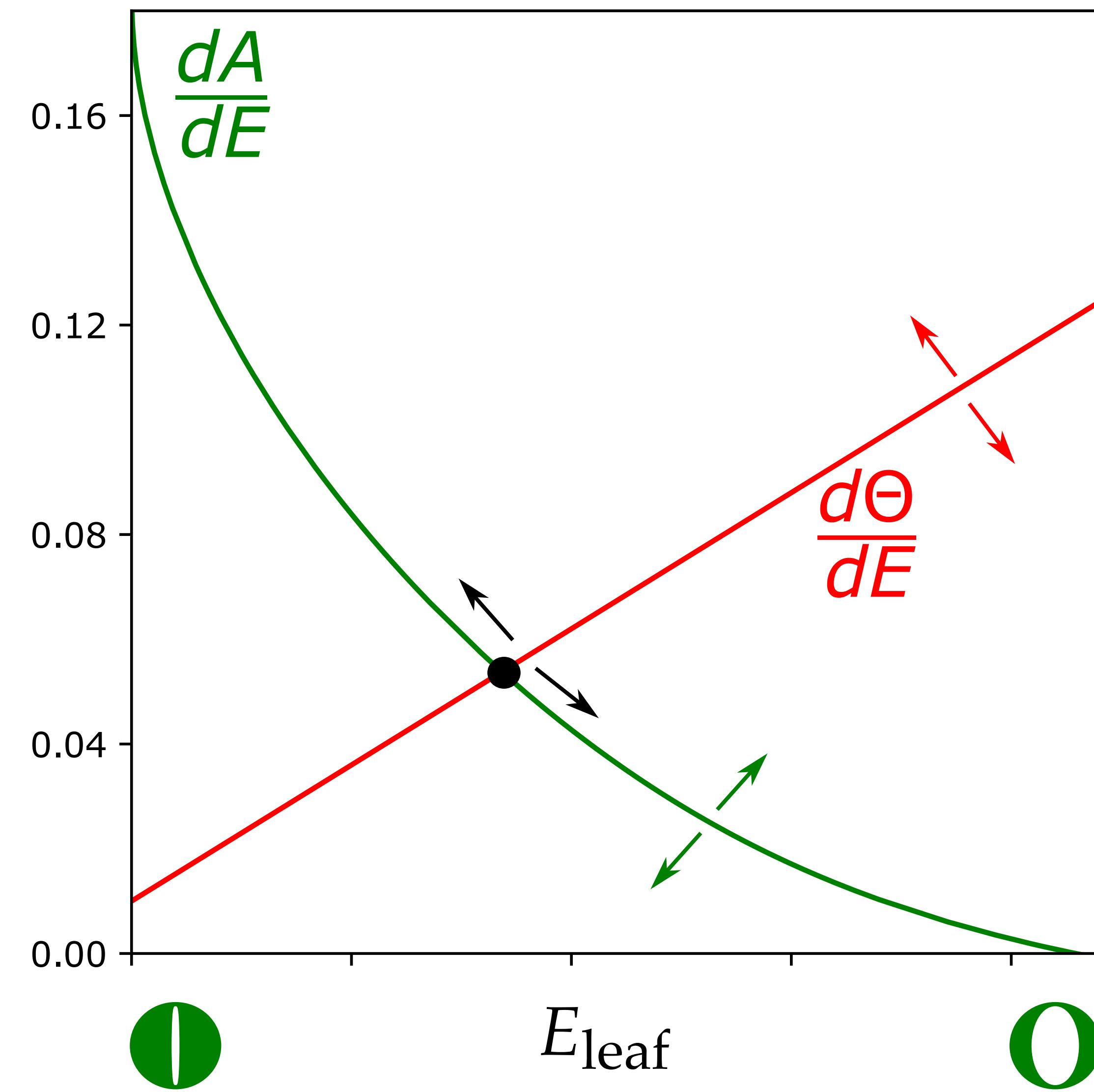
## Criteria

1. Positive
2. Increase with E
3. Lower than gain  
when  $E = 0$





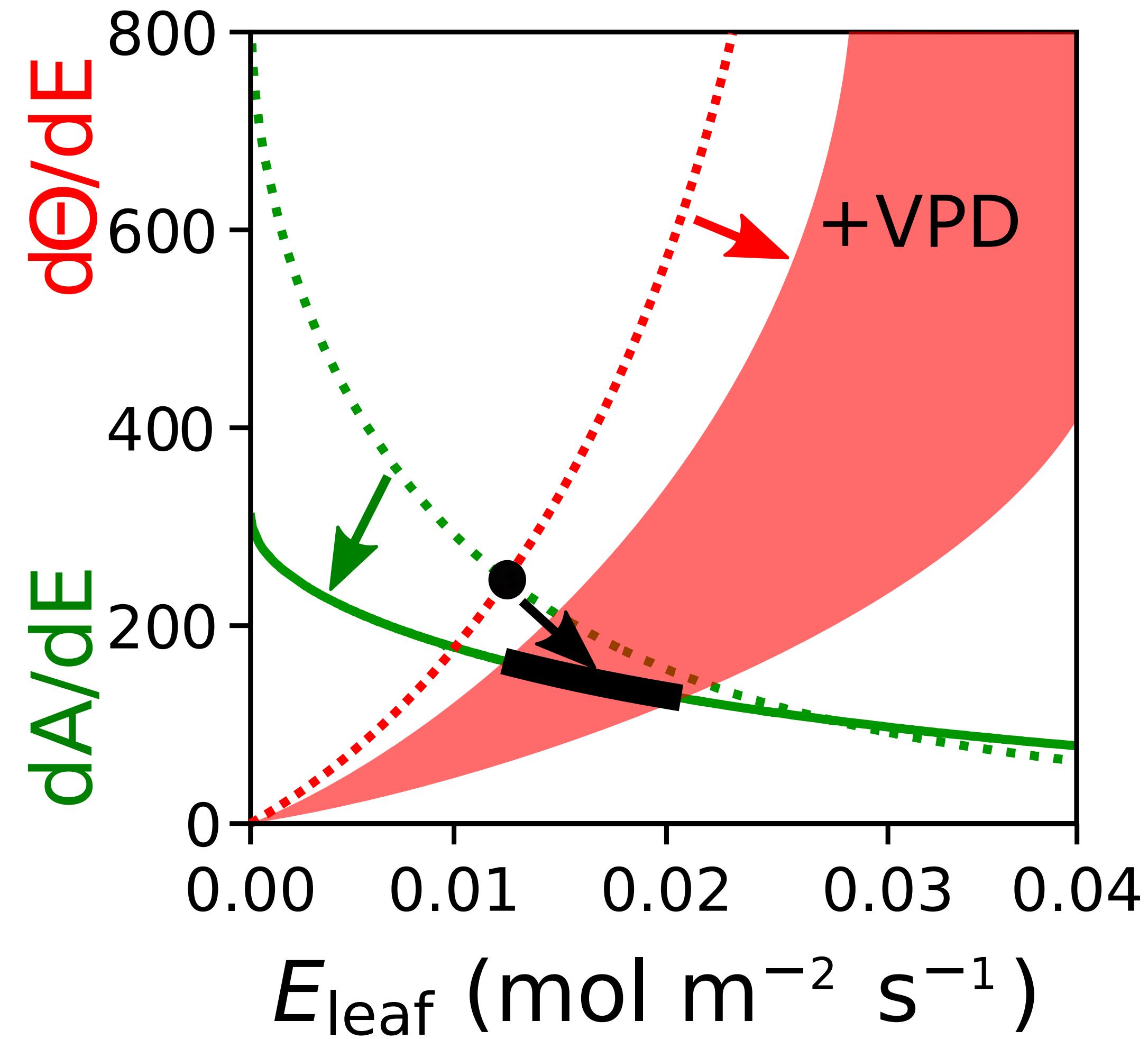
## Criteria

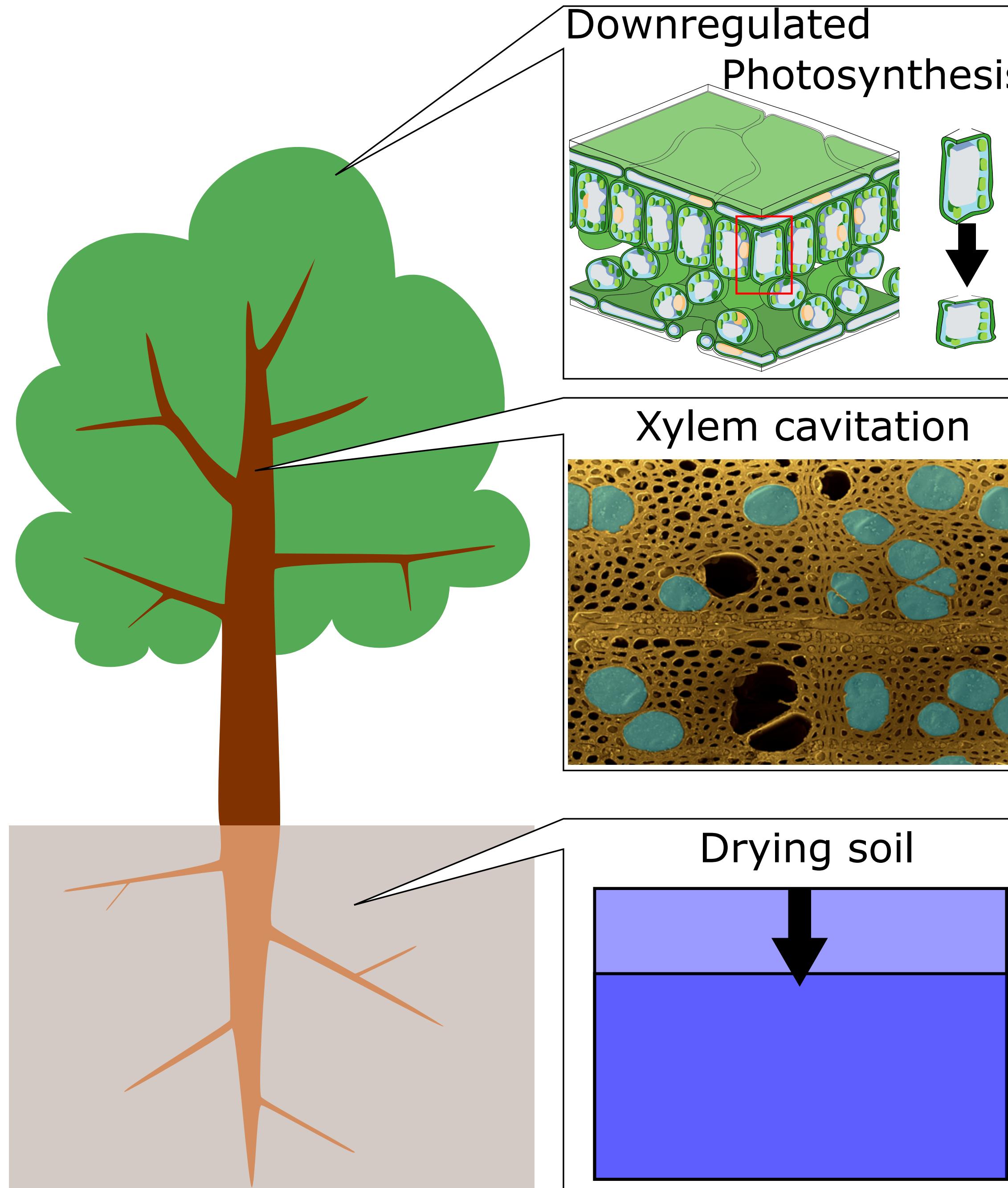




## Criteria

4. Decrease with VPD
5. Increase with  $\text{CO}_2$
6. Increase with drought
7. Increase with drought history





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)

... ...



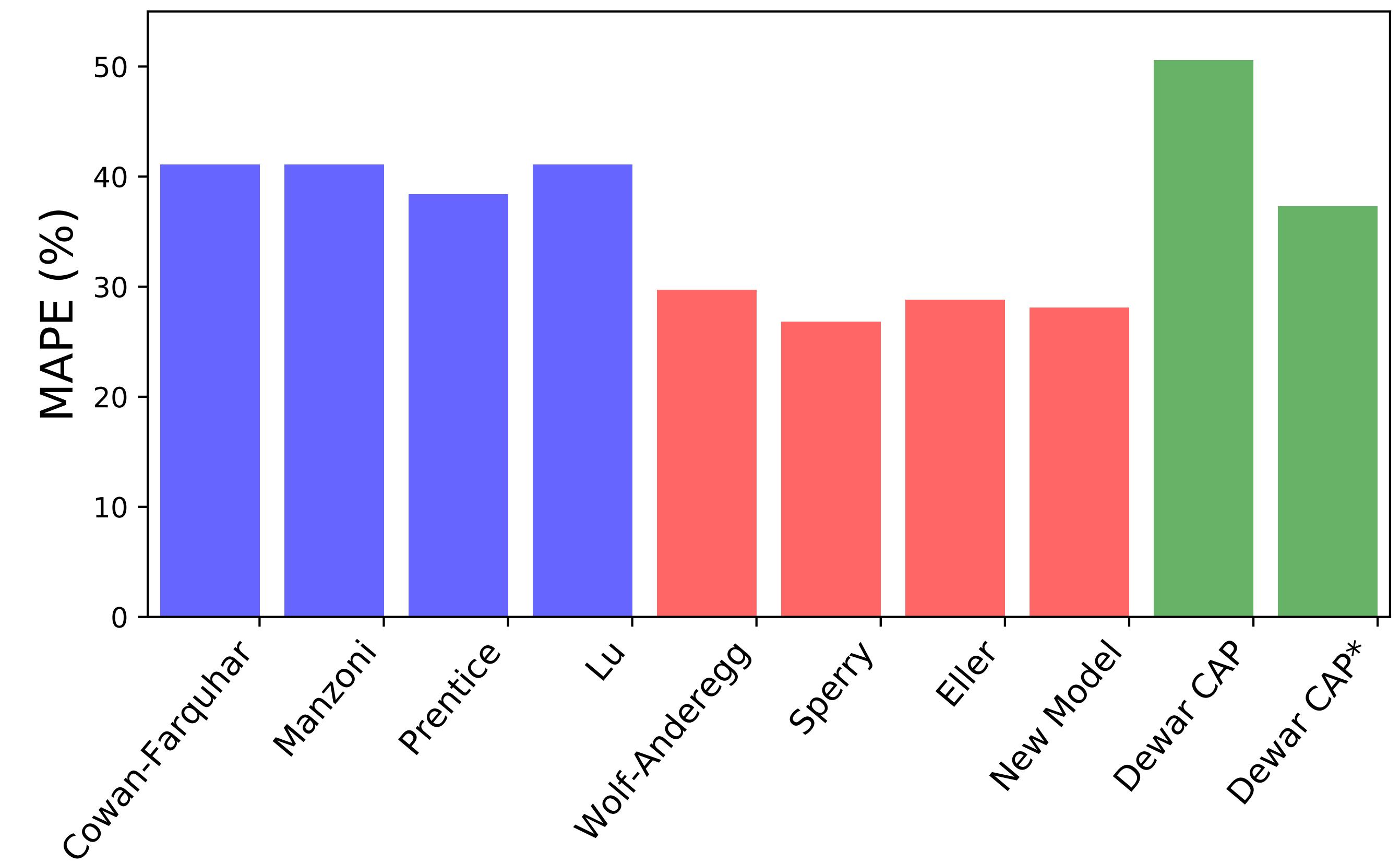
Model	Reference	Water Penalty ( $\Theta$ or $\Theta'$ )	Marginal Penalty ( $d\Theta/dE$ or $d\Theta'/dE$ )	Response	
				Criteria I–III	Criteria IV–VII DCPK
Cowan-Farquhar	(Cowan and Farquhar, 1977)	$\Theta = \frac{E_{\text{leaf}}}{\lambda}$	$\frac{d\Theta}{dE} = \frac{1}{\lambda}$	YNN	NNNN
Manzoni	(Manzoni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



## Birch dataset

### Growth chamber

- CO<sub>2</sub>
- Air humidity
- Soil moisture

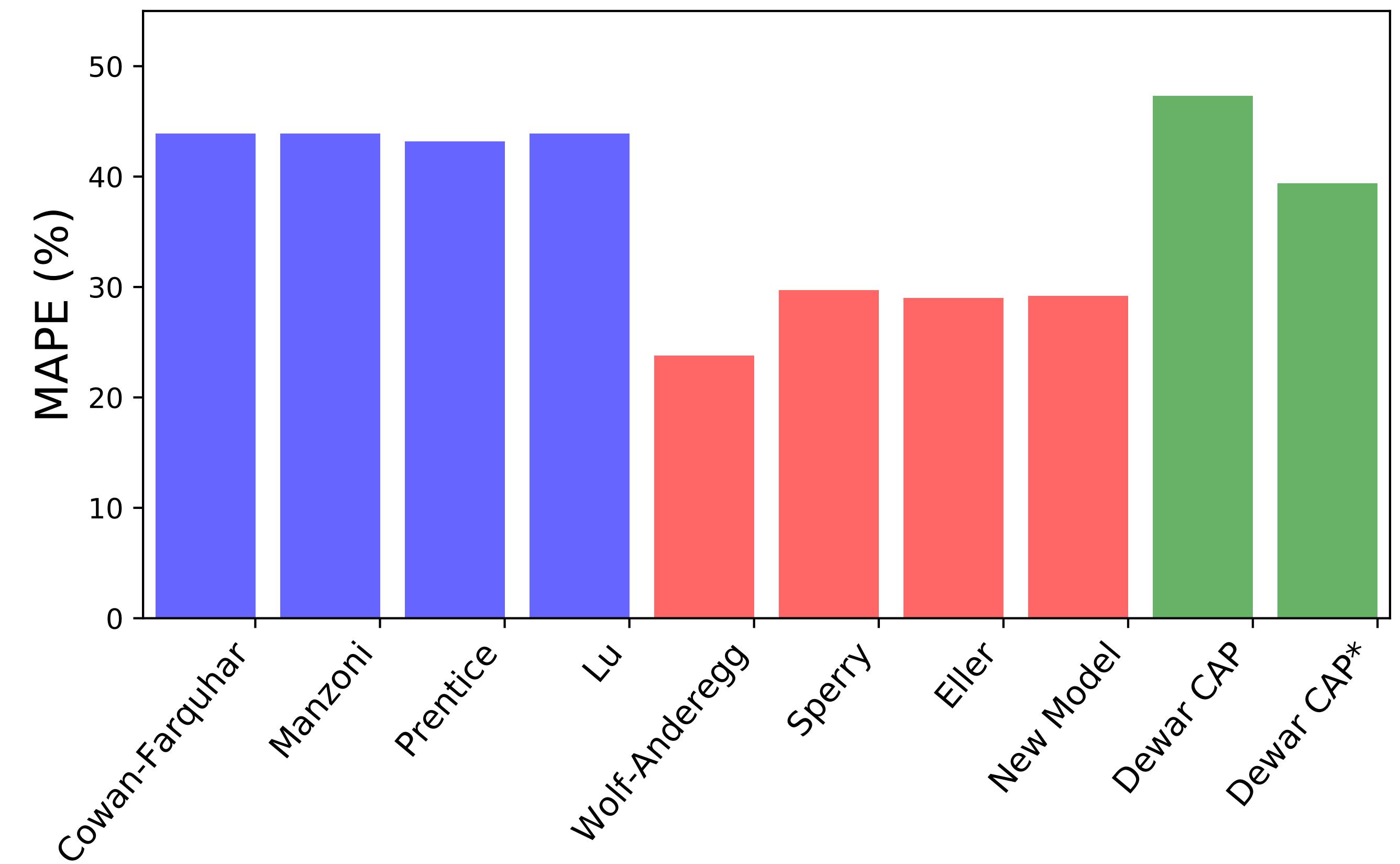




## Aspen dataset

### Research garden

- Soil moisture
- Air humidity\*

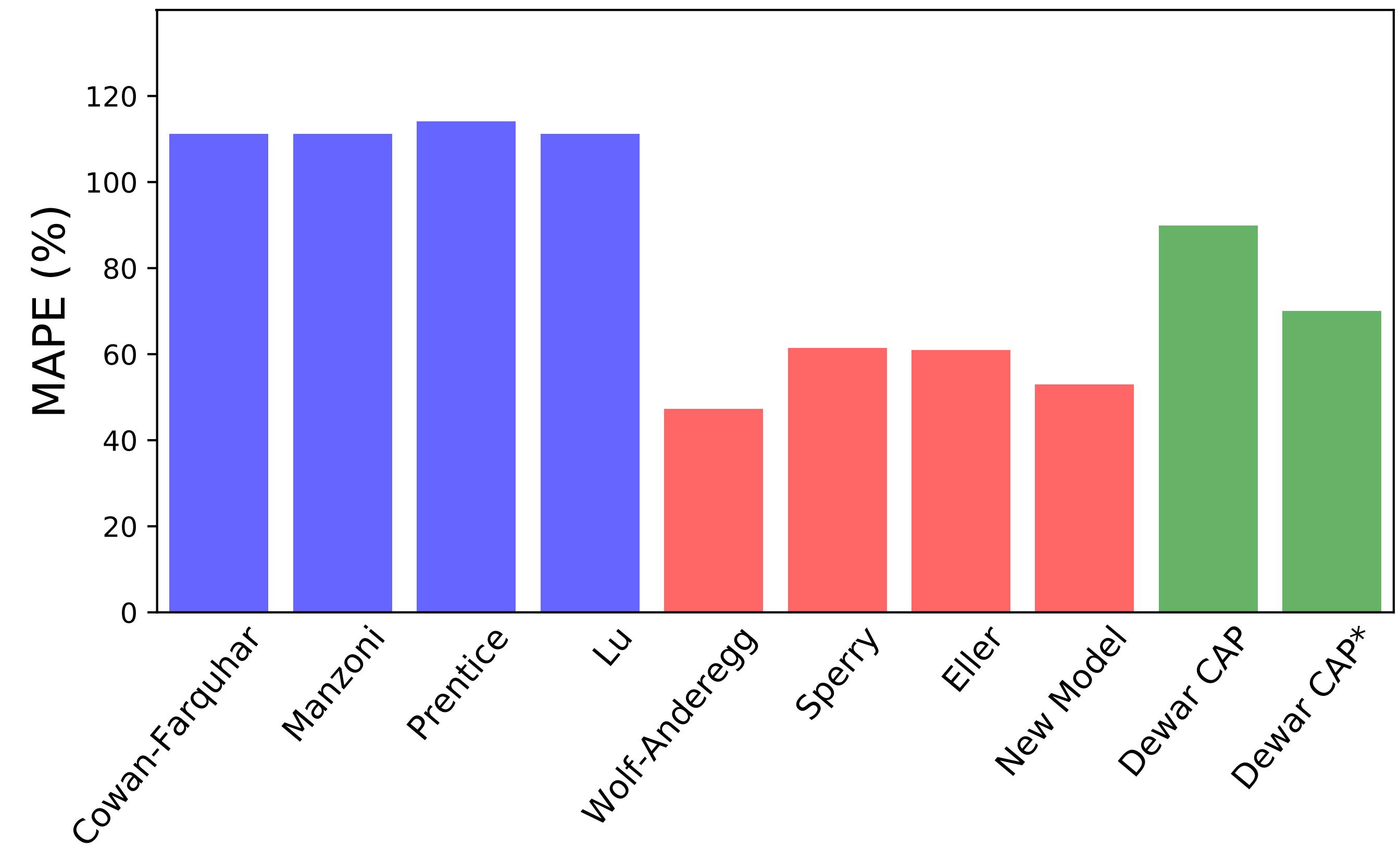
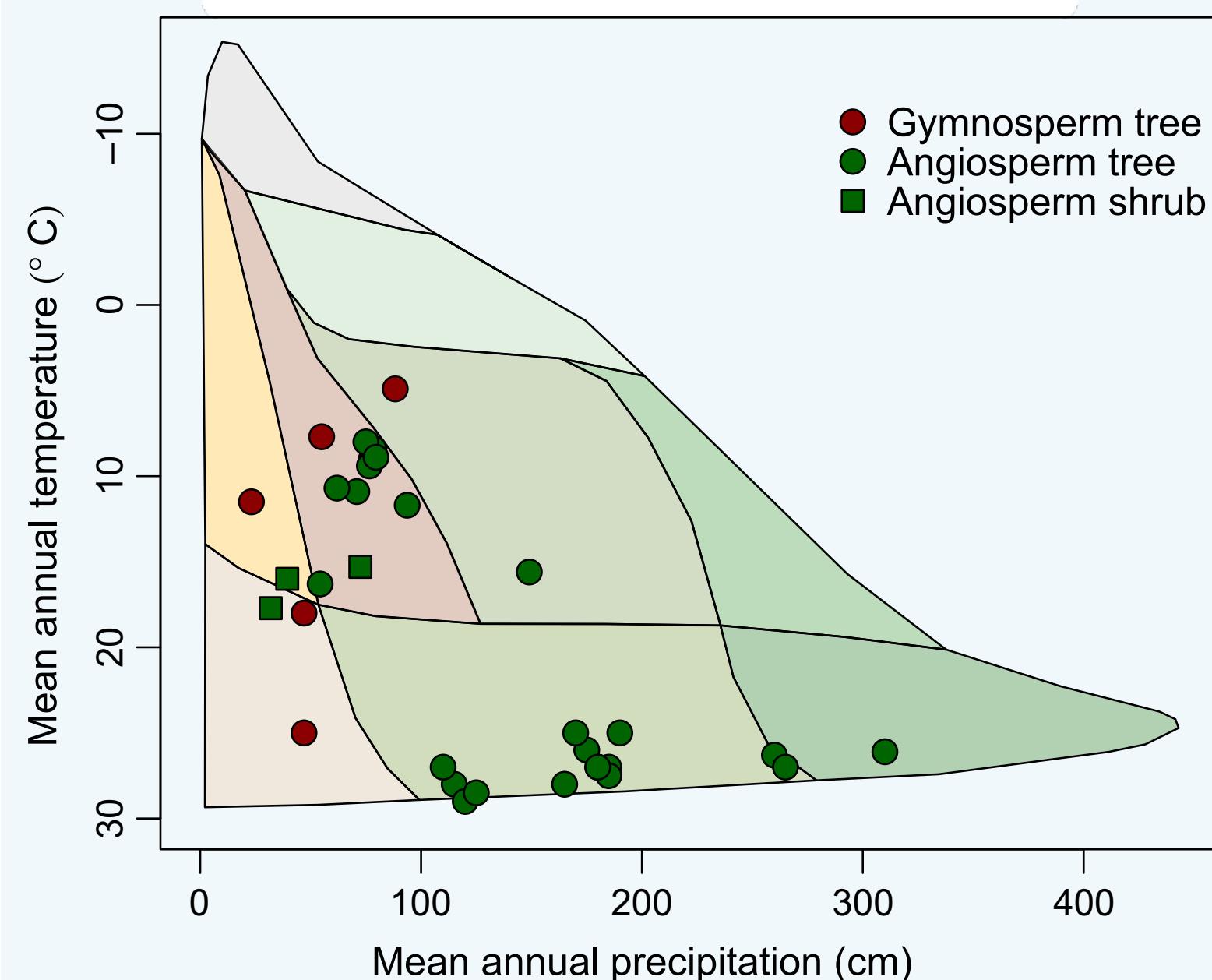




## Compiled dataset

### Natural forests

- Soil moisture\*
- Air humidity\*





Model	Reference	Water Penalty ( $\Theta$ or $\Theta'$ )	Marginal Penalty ( $d\Theta/dE$ or $d\Theta'/dE$ )	Response	
				I–III	Criteria IV–VII DCPK
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Prentice	(Prentice et al., 2014)	$\Theta = A \cdot \left(1 - \frac{1}{c_E E_{\text{leaf}} + c_V V_{\text{cmax}}} \right)$	$\frac{d\Theta}{dE} = \frac{A}{E_{\text{leaf}} + \frac{c_V}{c_E} V_{\text{cmax}}}$	YNY	YYNN
Lu	(Lu et al., 2016)	$\Theta = \frac{E_{\text{leaf}}}{\lambda}$	$\frac{d\Theta}{dE} = \frac{1}{\lambda}$	YNN	NNNN
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Sperry	(Sperry et al., 2017)	$\Theta = A_{\text{max}} \cdot \left(1 - \frac{K}{K_{\text{max}}} \right)$	$\frac{d\Theta}{dE} = -\frac{dK}{dE} \cdot \frac{A_{\text{max}}}{K_{\text{max}}}$	YYY	YYYY
Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\text{max},0}} \right)$	$\frac{d\Theta}{dE} = -\frac{dK}{dE} \cdot \frac{A}{K}$	YYY	YYYN
New Model		$\Theta = A \cdot \frac{E_{\text{leaf}}}{E_{\text{crit}}}$	$\frac{d\Theta}{dE} = \frac{A}{E_{\text{crit}} - E_{\text{leaf}}}$	YYY	YYYY
Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{\text{ww}} \cdot \frac{\text{SC}}{\text{SC}_{\text{max}}}$	$\frac{d\Theta'}{dE} = \frac{A}{\text{SC}_{\text{max}} - \text{SC}} \cdot \frac{d\text{SC}}{dE}$	YYY	YYYY
Dewar CAP	(Dewar et al., 2018)	$\Theta' = A_{\text{ww}} \cdot \frac{P}{P_{\text{crit}}}$	$\frac{d\Theta'}{dE} = \frac{A}{K \cdot (P_{\text{crit}} - P)}$	YYY	YYYY

# 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



## Yes?

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

## No?

- **Less daytime photosynthetic gain**
- **Turgor maintenance**

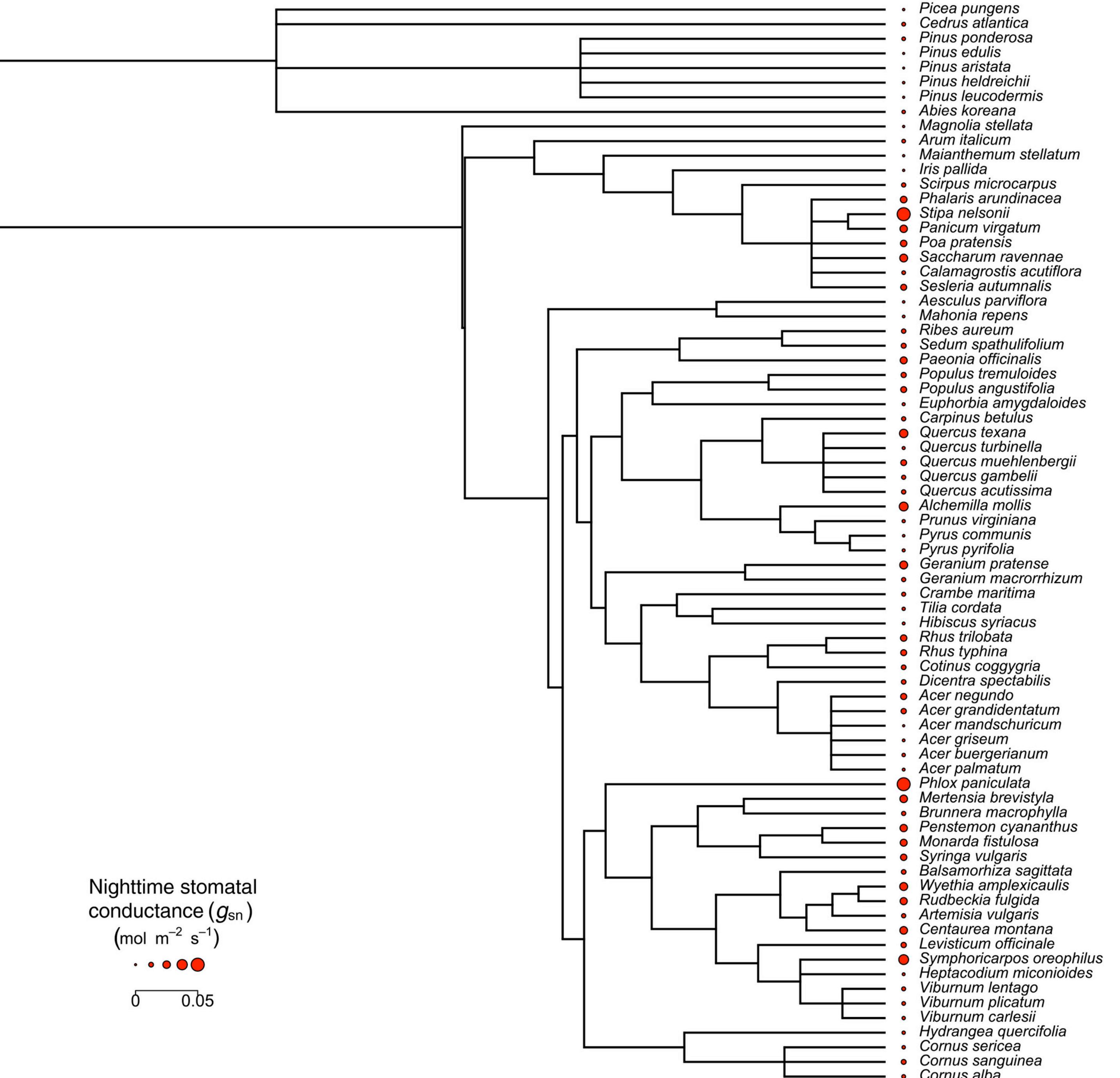


## Nighttime E

### Found in various species

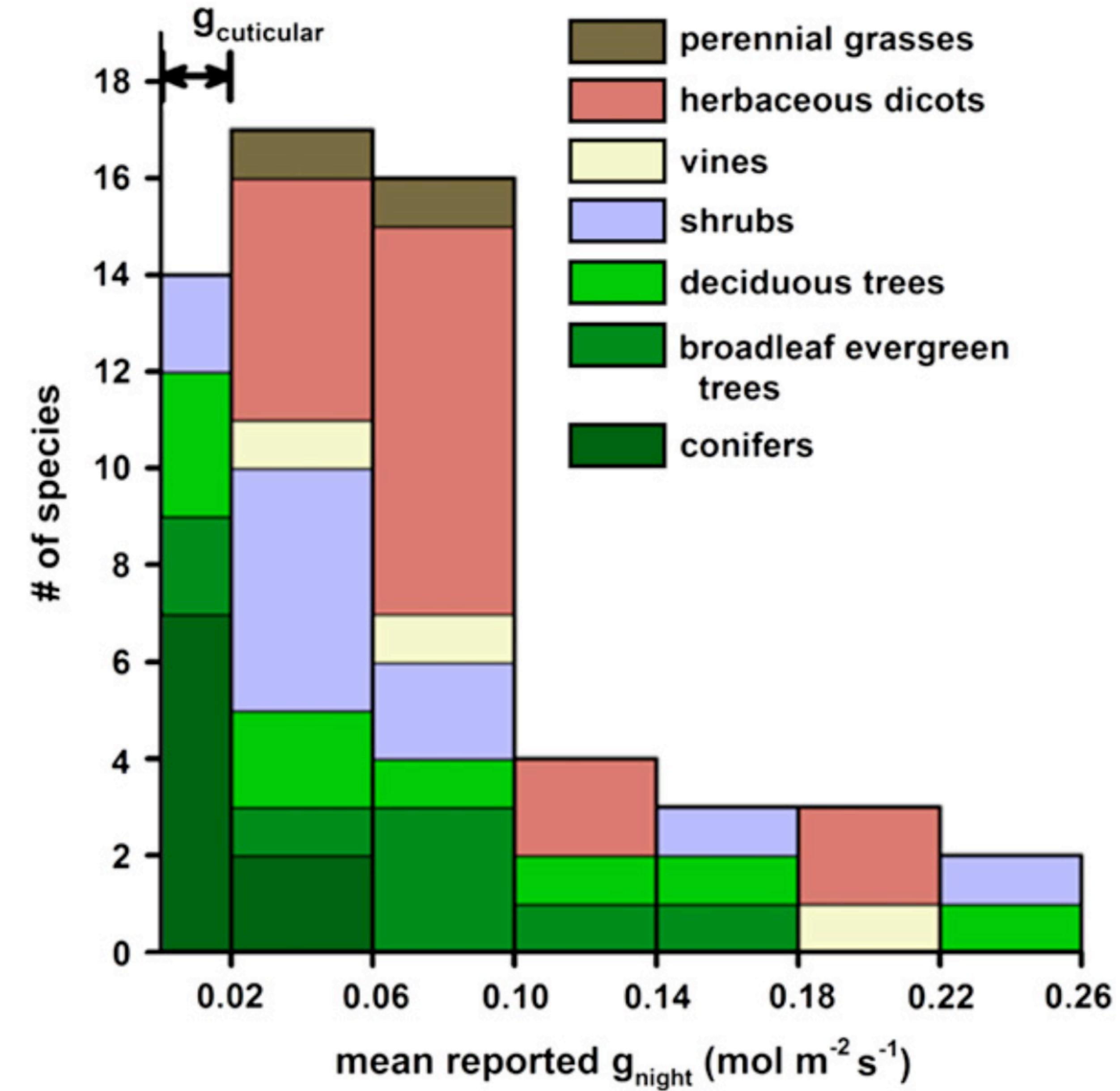
Nighttime stomatal conductance ( $g_{sn}$ )  
 $(\text{mol m}^{-2} \text{s}^{-1})$

0 0.05





Nighttime E  
About 10% to  
15% of the  
daytime E





## Major drivers?

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

## Responses to

- Air humidity
- CO<sub>2</sub>
- Soil moisture
- Leaf temperature
- Leaf respiration





## Optimality

**Maximize the difference between gain and cost**

## Gain

- All benefits

## Risk

- Daytime photosynthesis

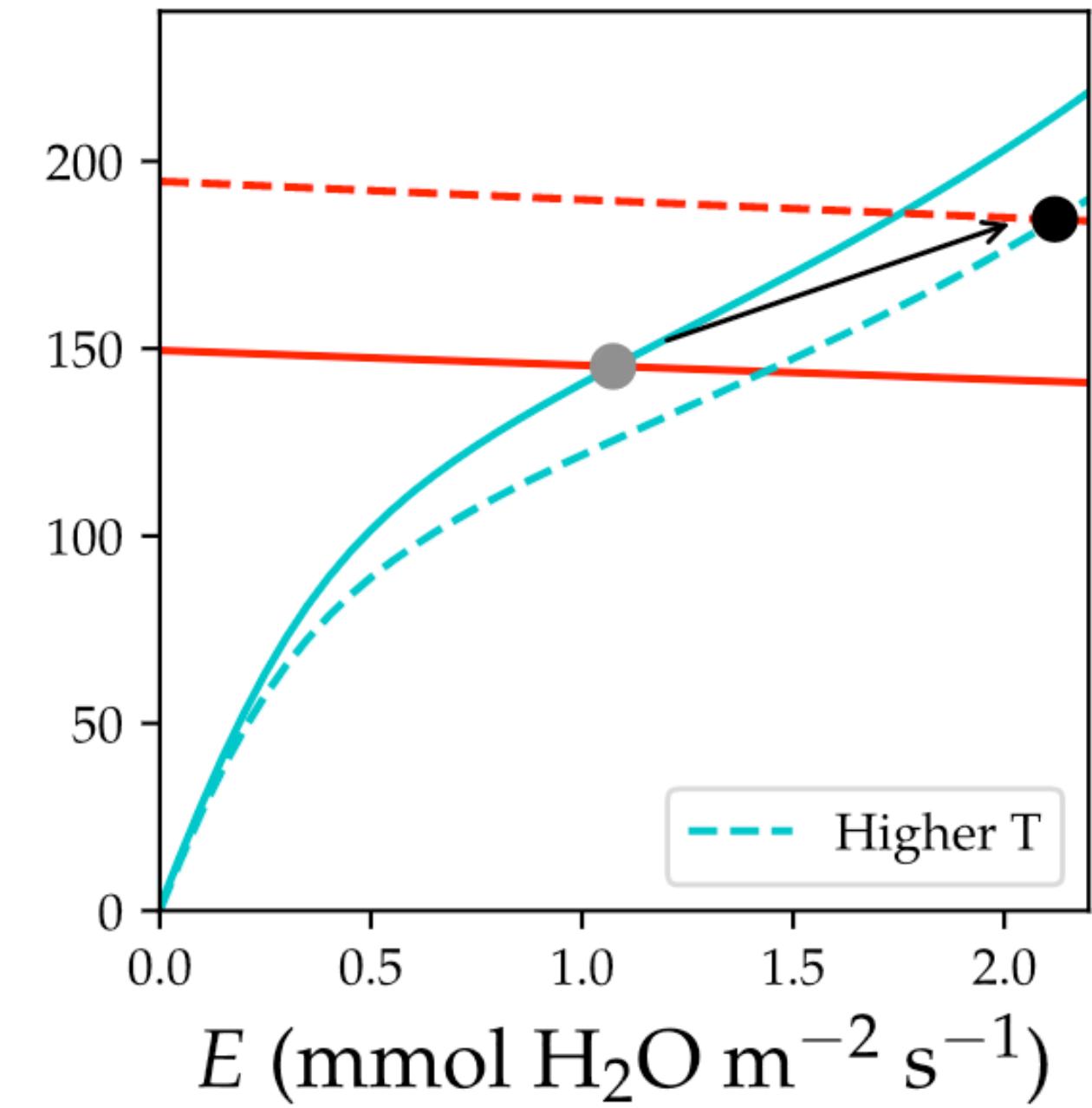
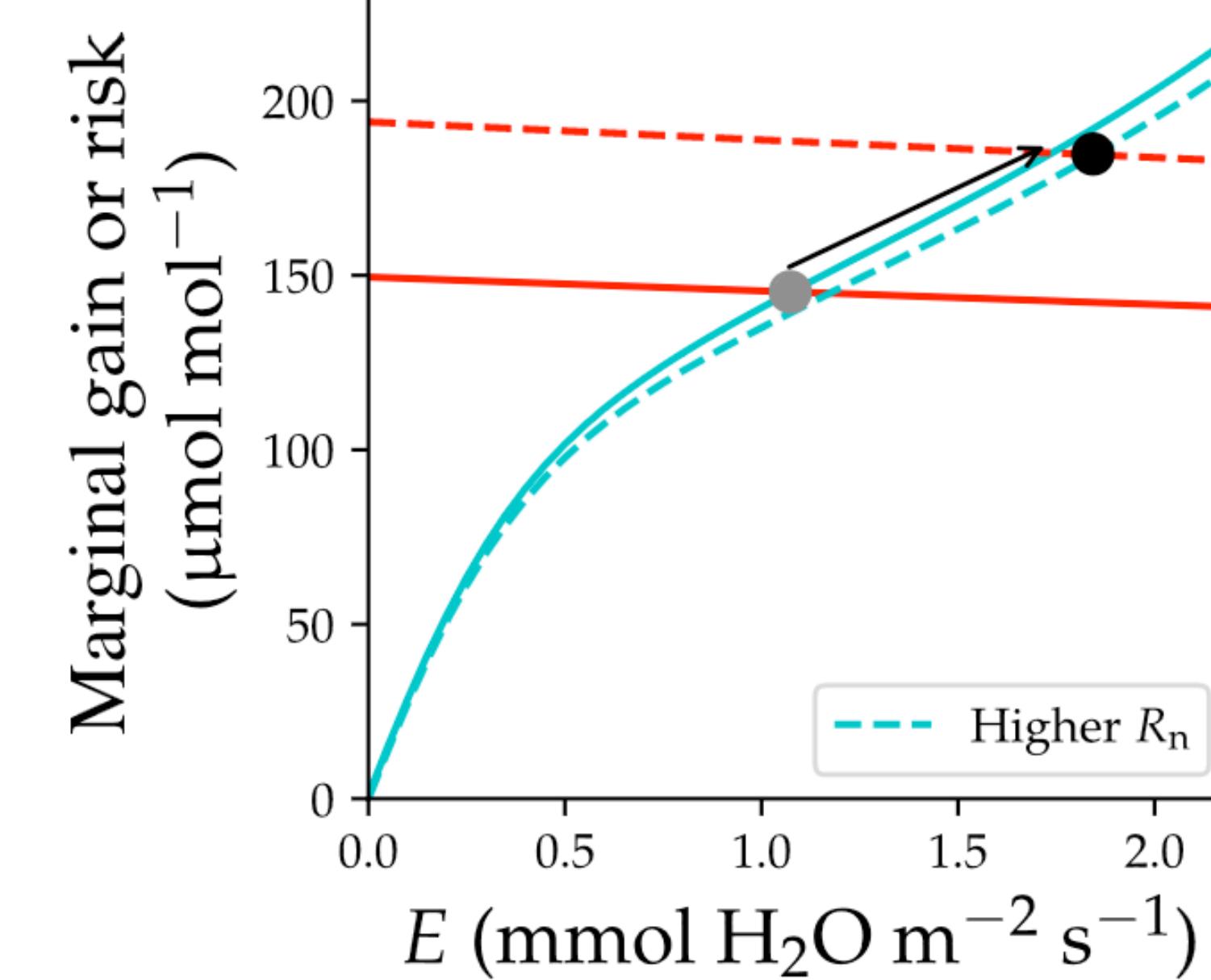




## Optimality

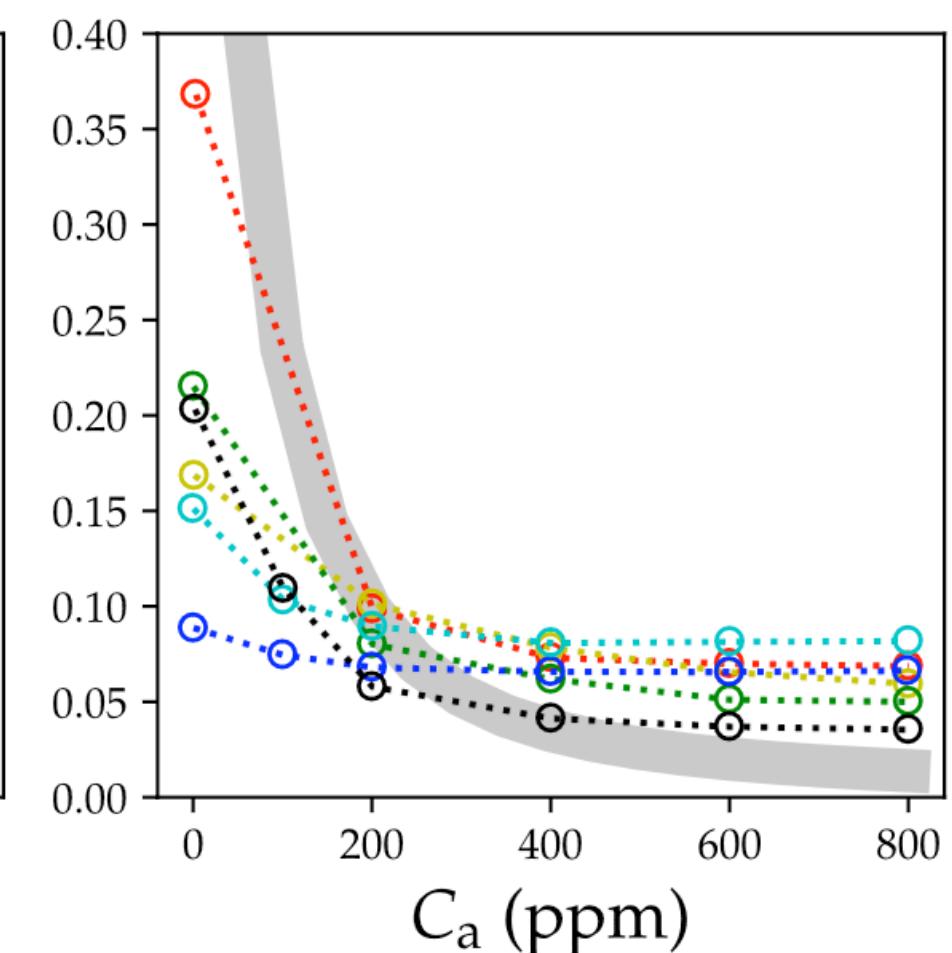
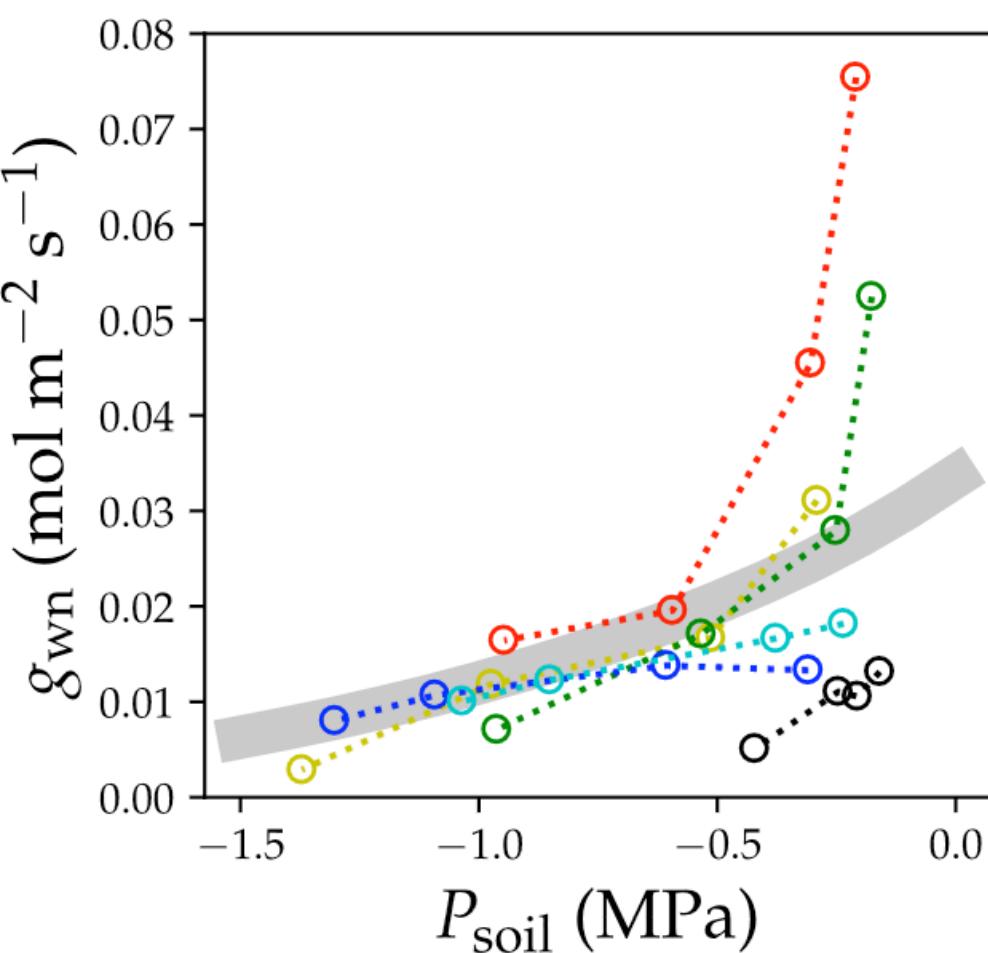
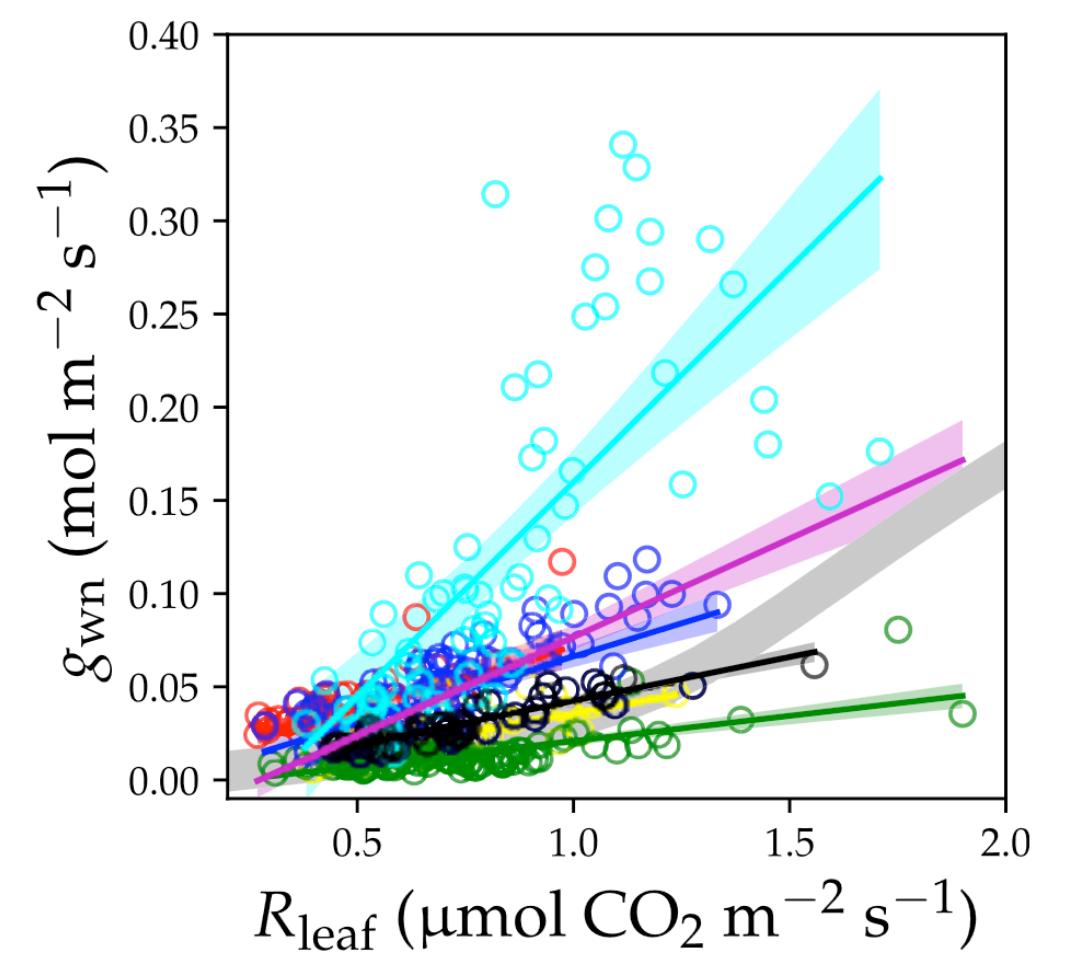
**Maximize the difference between gain and cost**

$$-\frac{\partial R_{\text{leaf}}}{\partial E_n} - f_f \cdot \frac{A_d(E_n)}{E_{\text{crit}} - E_n} = 0$$



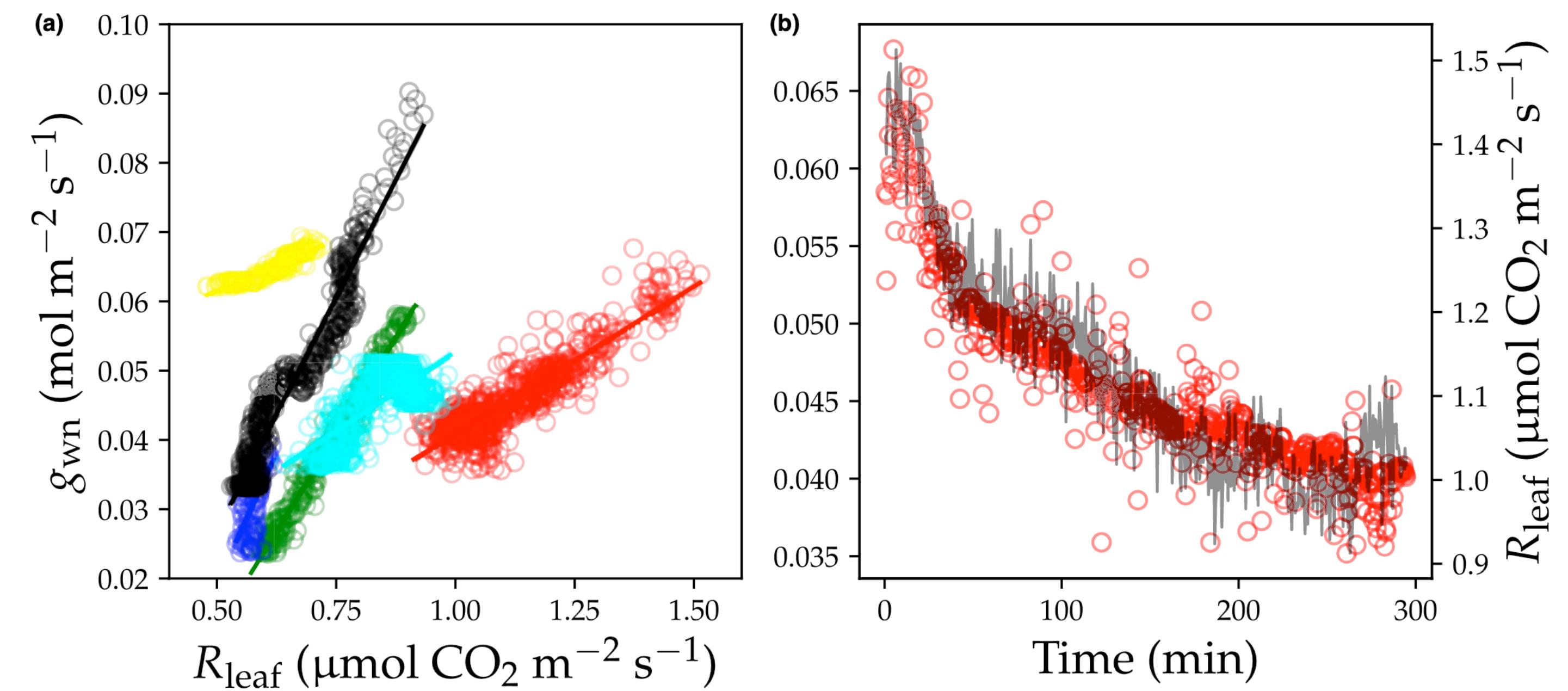
## Optimality

Maximize the difference between gain and cost





**Optimality**  
**Maximize the difference between gain and cost**



# 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

## Next generation

What make a  
next generation  
model?

### Learn from data

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

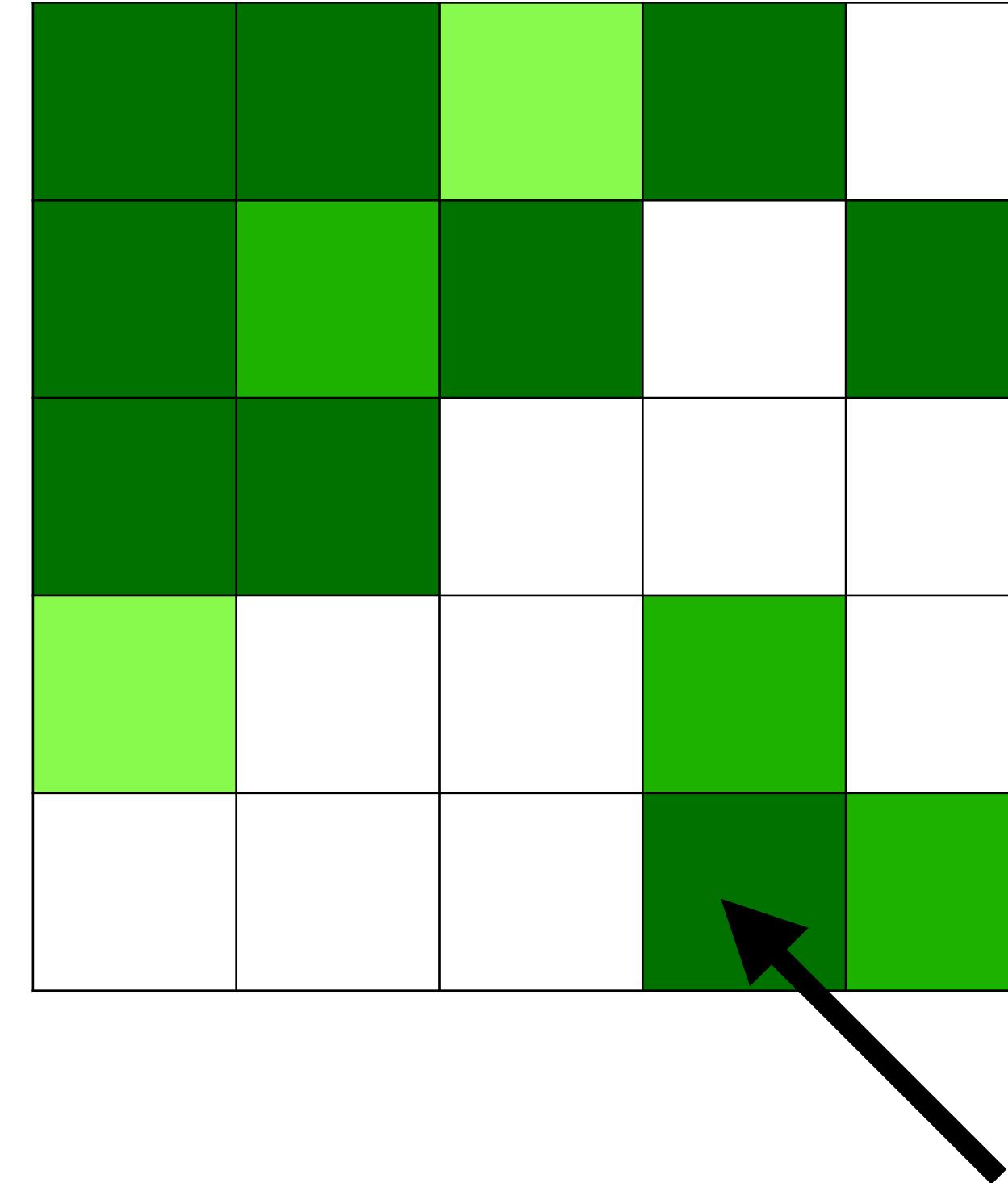
### Model framework

- **Modularity**
- **Scalability**
- **Architecture**
- **User friendly**

## Tradeoffs

- Complexity
- Accuracy
- Delivery
- Efficiency

Traits are what  
we need to learn



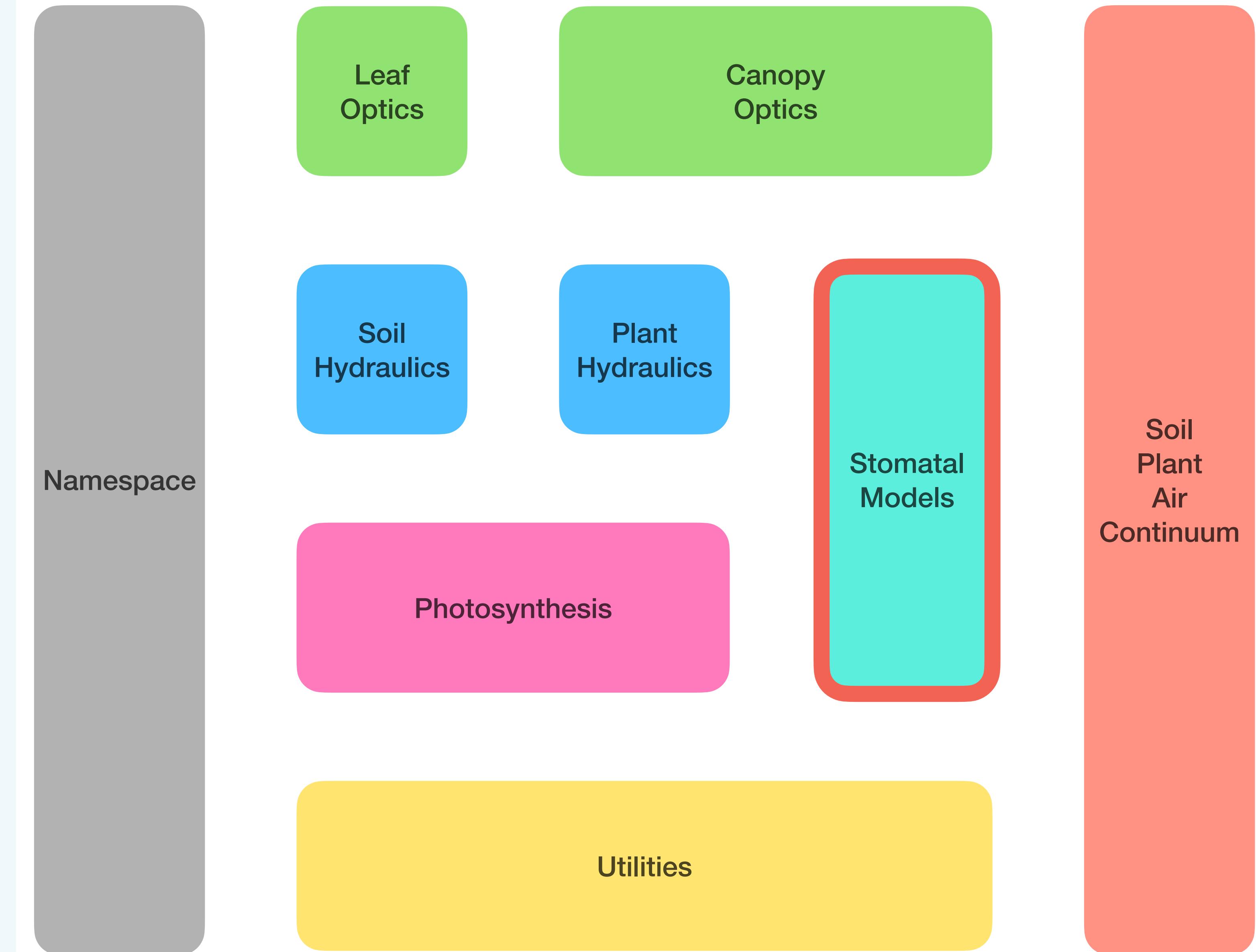
Minimum Element

Soil-plant-air continuum



## 1. Modularity

**Each module can be used as a **standalone** package**





## 1. Modularity

Each module  
can be used as  
a **standalone**  
package

```
wls = ClimaCache.WaveLengthSet{FT}();
bio = ClimaCache.HyperspectralLeafBiophysics{FT}();
lha = ClimaCache.HyperspectralAbsorption{FT}();
LeafOptics.leaf_spectra!(bio, wls, lha, FT(50));
```



## 2. User friendly Convenient functions to begin with

GUI on the way  
for teaching  
purpose

```
spac = MonoMLTreeSPAC{Float64}();
initialize!(spac);
update!(spac; cab = 40, car = 6);
soil_plant_air_continuum!(spac, 120.0);

@show TROPOMI_SIF740(spac.CANOPY);
@show MODIS_NIRv(spac.CANOPY);
@show OC02_SIF759(spac.CANOPY);
```



### 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

Soil  
Plant  
Air  
Continuum

Single elements  
Complex SPAC

#### Photosynthesis

Classic C3 model  
Classic C4 model  
New Cytochrome C3 model

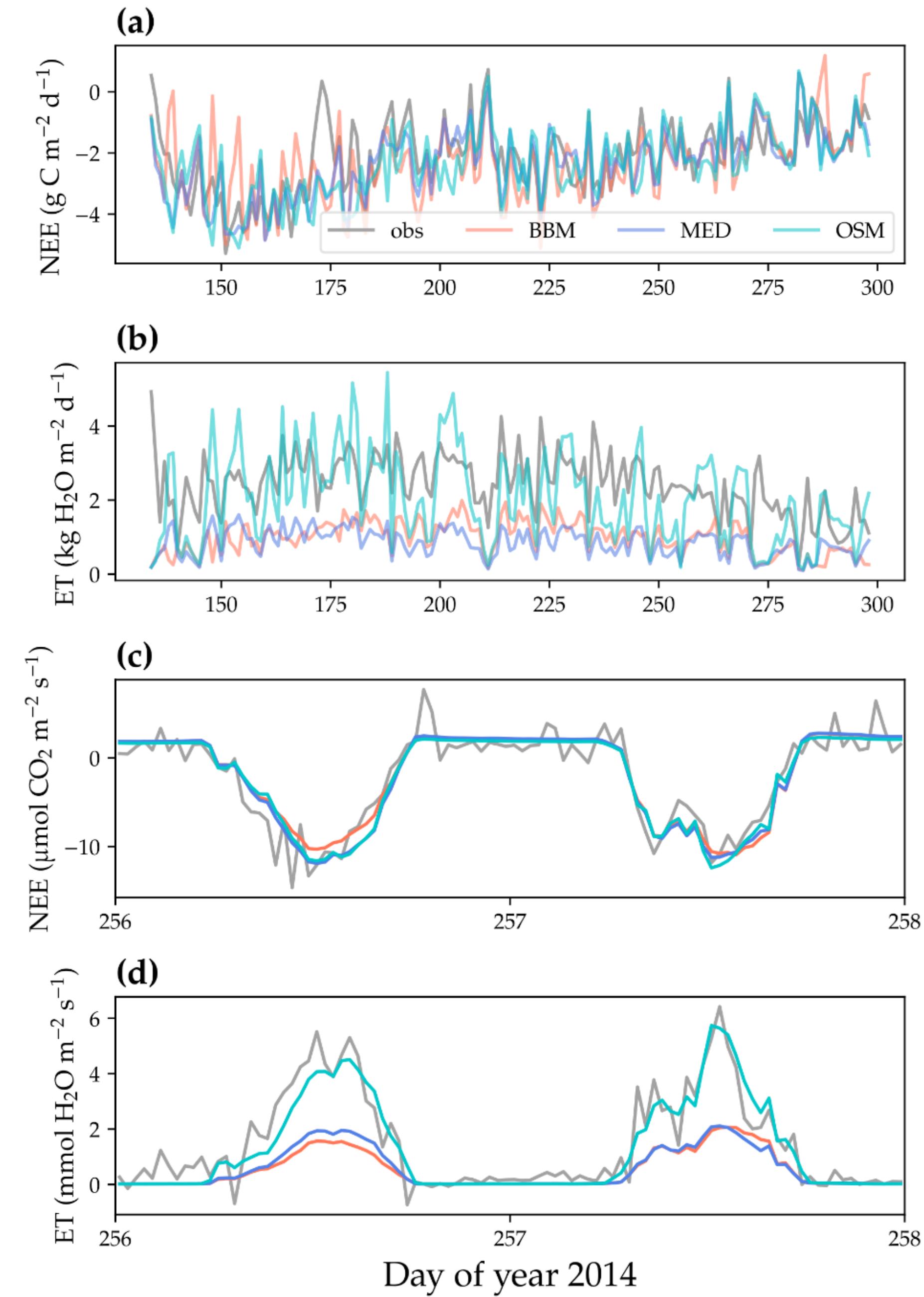
#### Utilities

Shared constants  
Solvers  
IO Tools



### 3. Freedom

**Example 1:**  
**Comparison of**  
**three stomatal**  
**models**

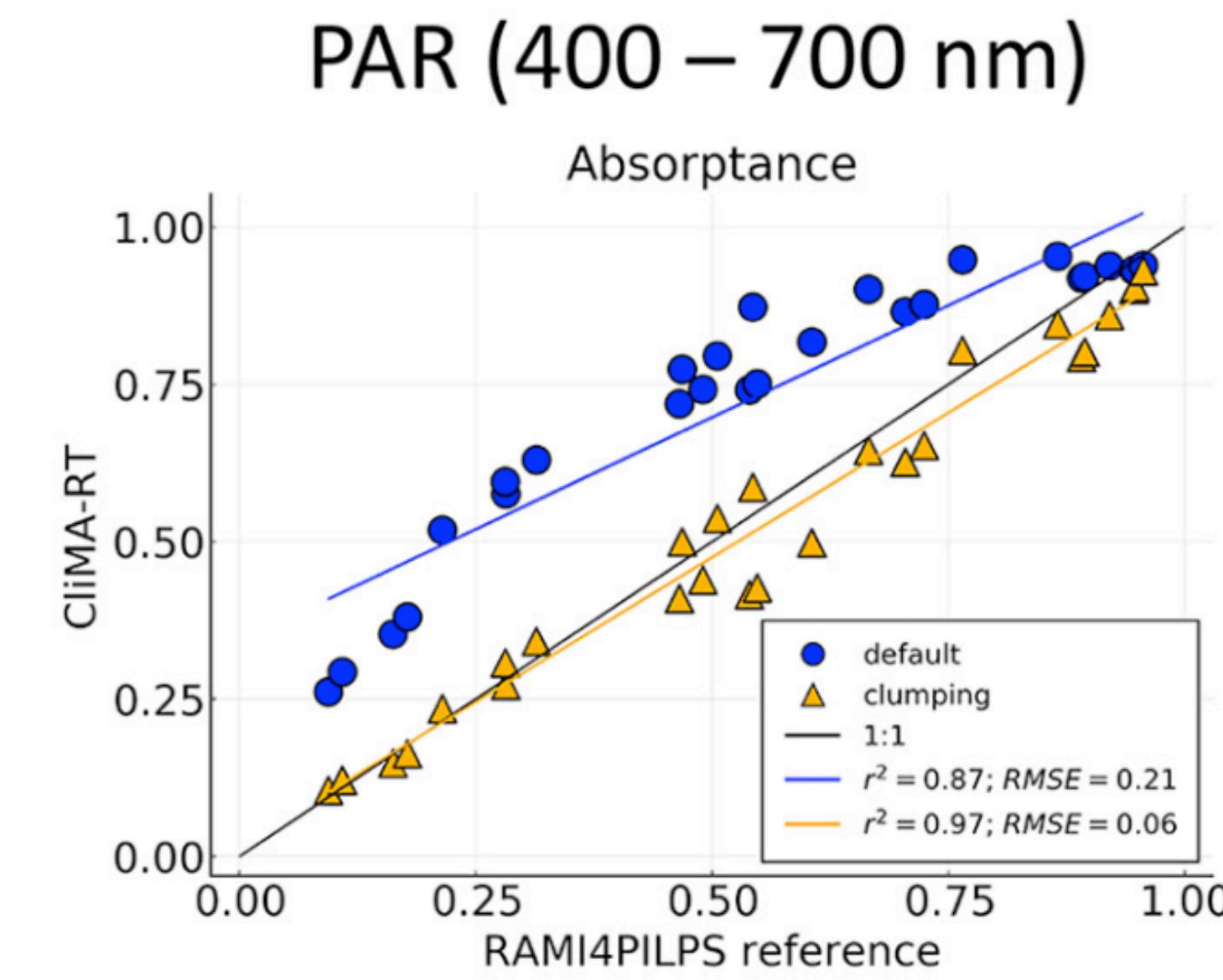
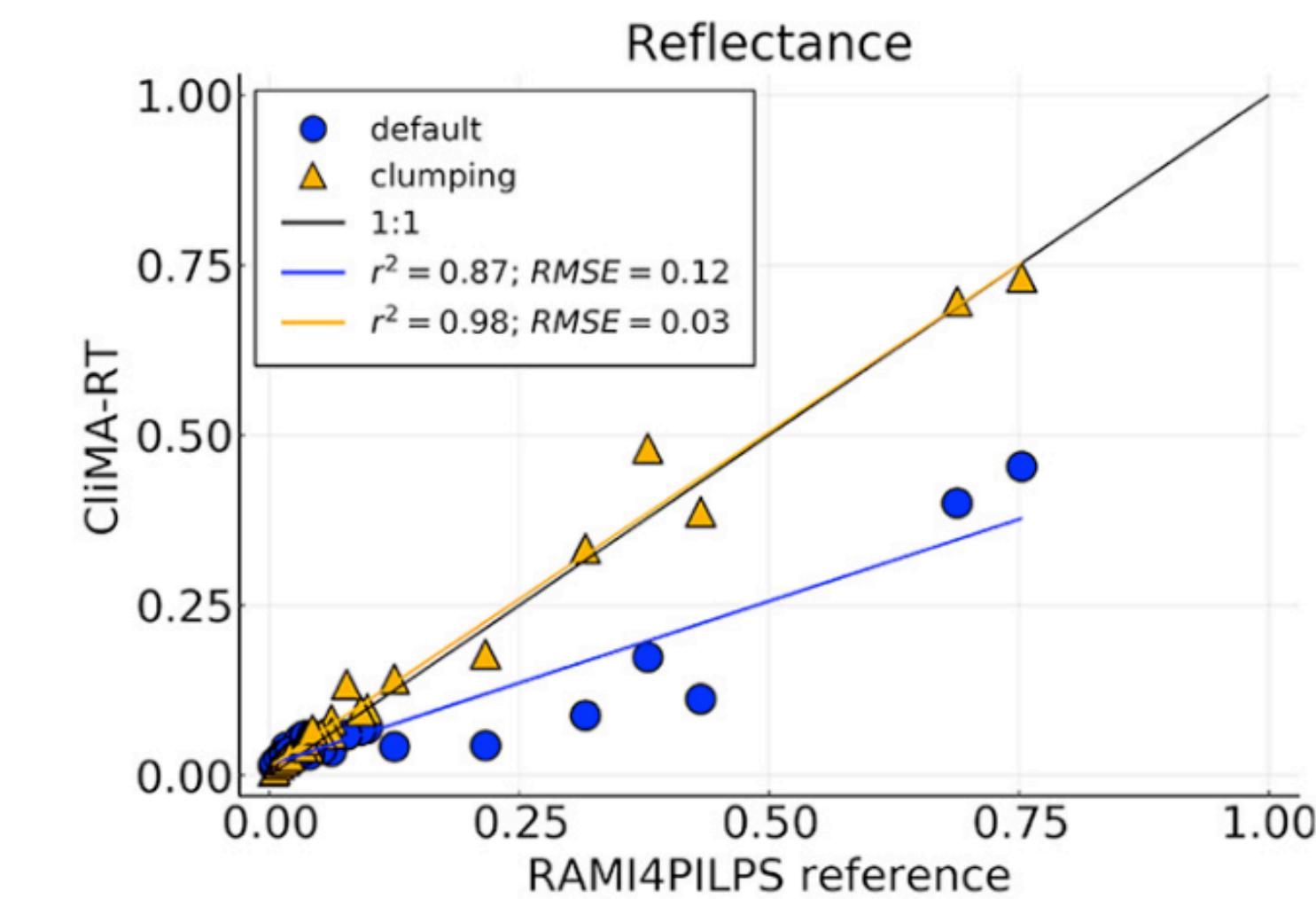


Day of year 2014



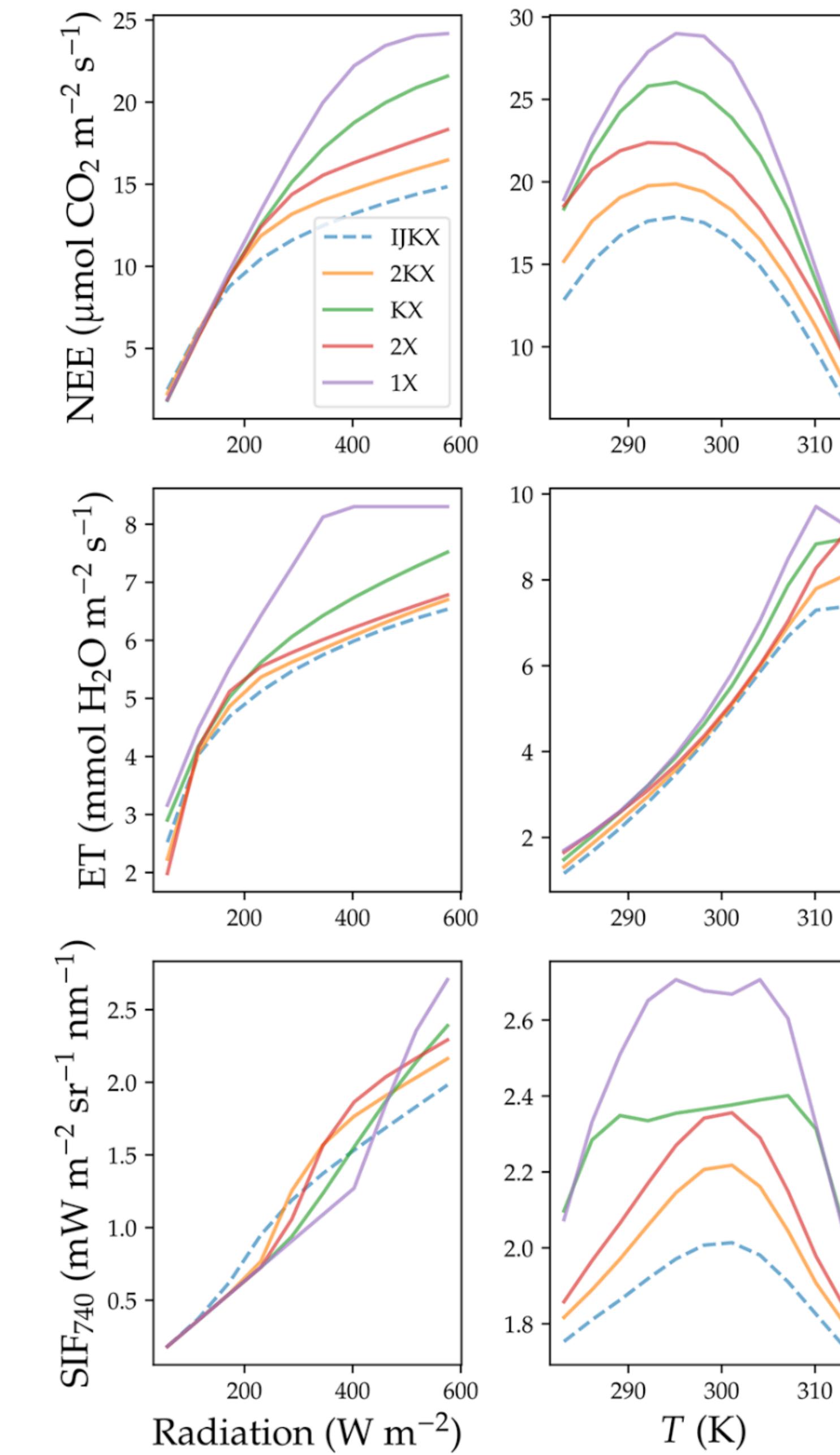
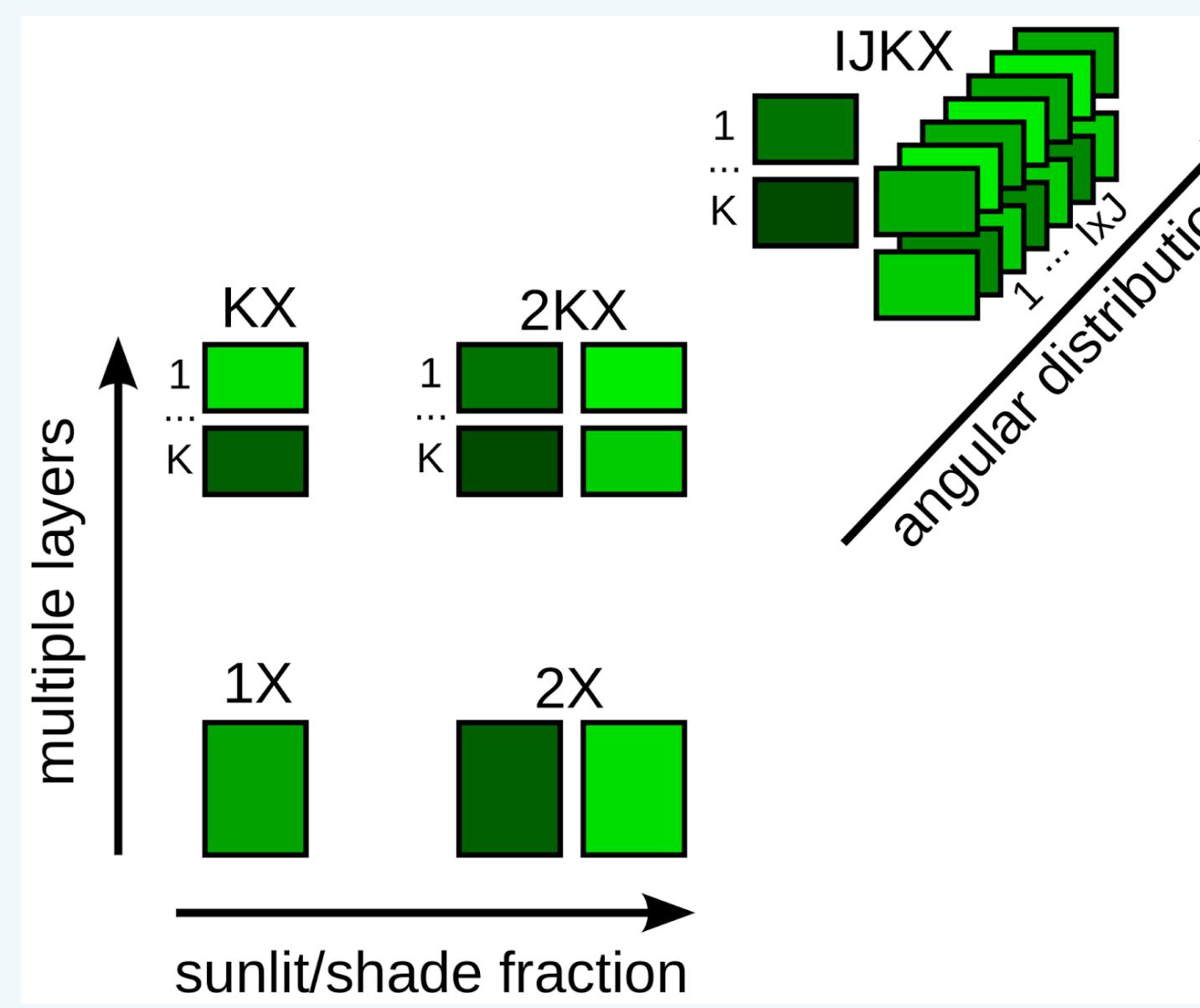
### 3. Freedom

**Example 2:**  
**Turn on/off**  
**clumping index**



### 3. Freedom

#### Example 3: Comparison of canopy complexity





# 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

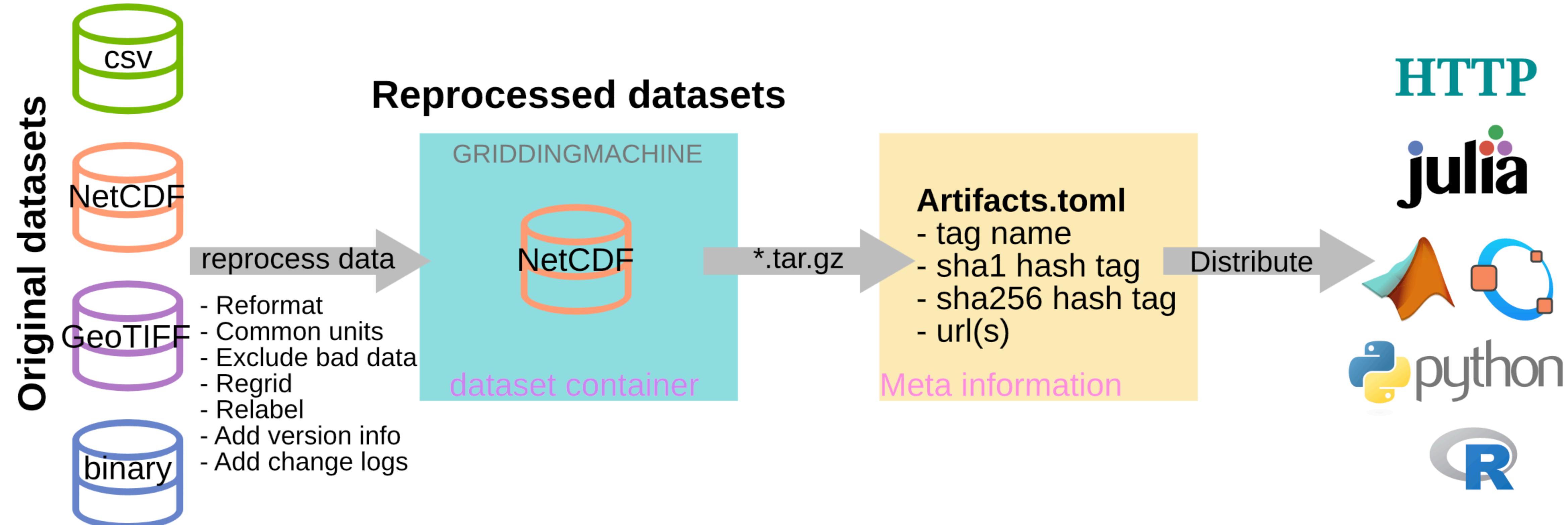
**Use more data to calibrate the models**

## 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



## GriddingMachine

### Testing modules

- Blender
- Fetcher
- Partitioner

## GriddingMachine.jl

### Collector.jl

Tool to manage our collection of datasets locally

### Indexer.jl

Tool to read the datasets locally

### Requestor.jl

Tool to request data for a given latitude and longitude from the server

### GriddedCollection

Data struct that contains information of the collection, such as supported data versions

### query\_collection

Function to locate the local dataset; if file does not exist, download it automatically

### clean\_collection!

Function to clean up the collection, such as out-of-dated collections

### read\_LUT

Function to read the data full or in part data from local files

### request\_LUT

Function to request data in part from a server, rather than from locally downloaded file



## 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", 28.6, -81.2);
```

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



# 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**

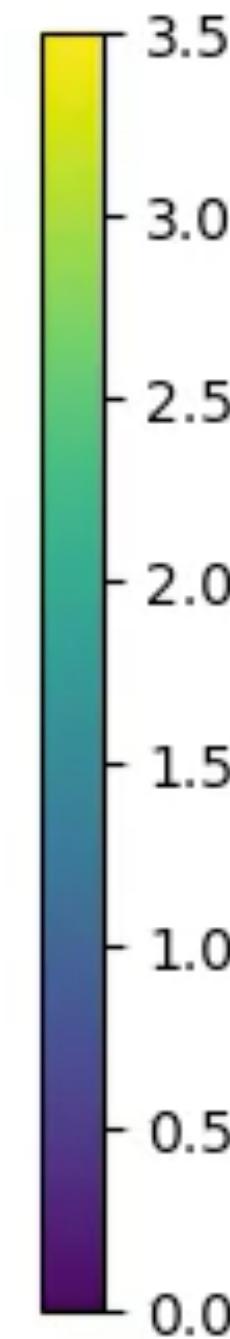
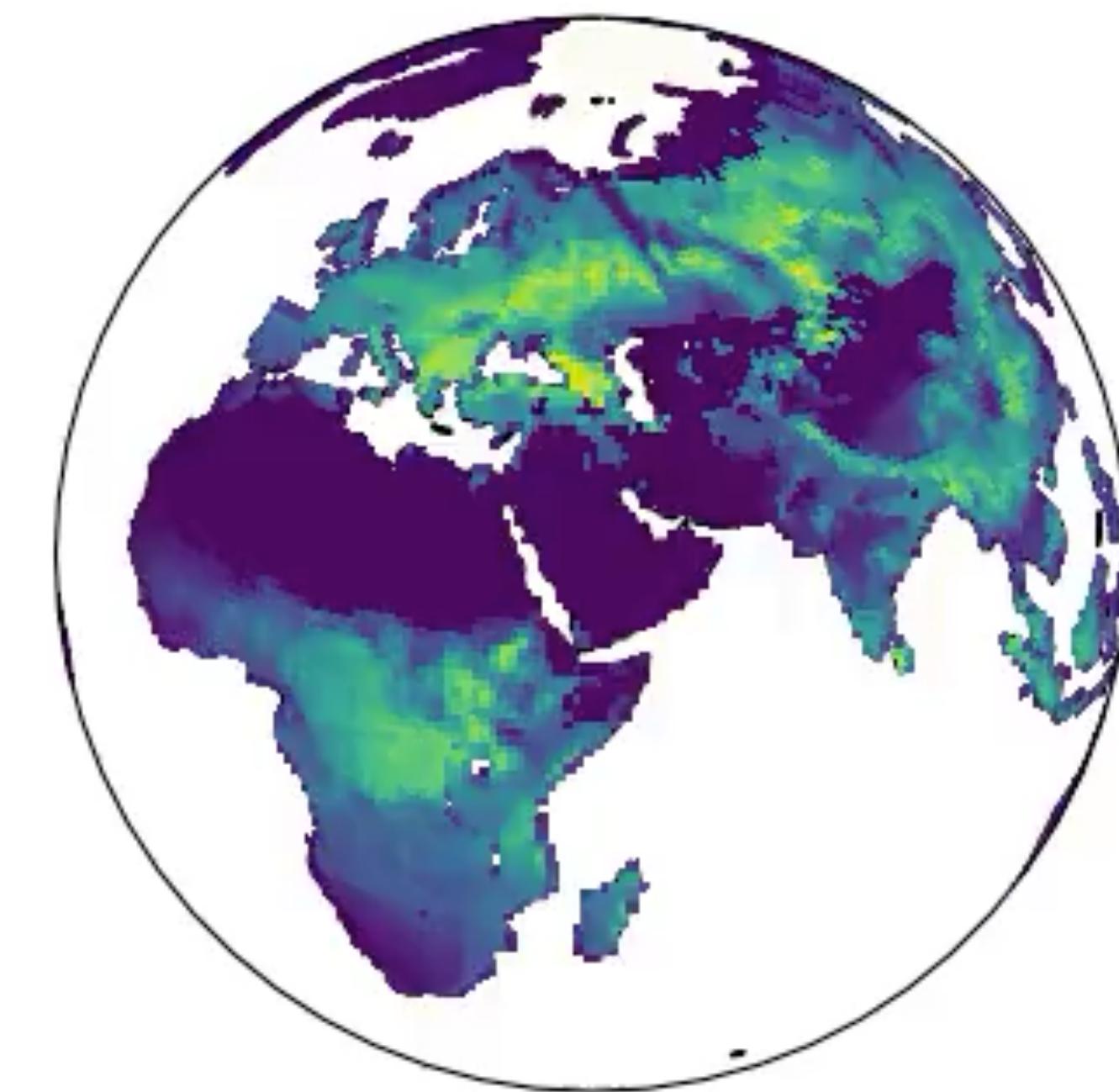
# First global scale simulation of CliMA Land

## Configurations

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

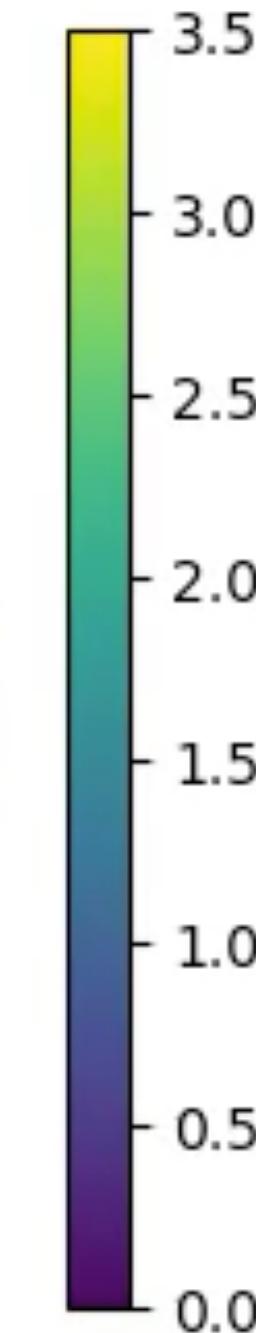
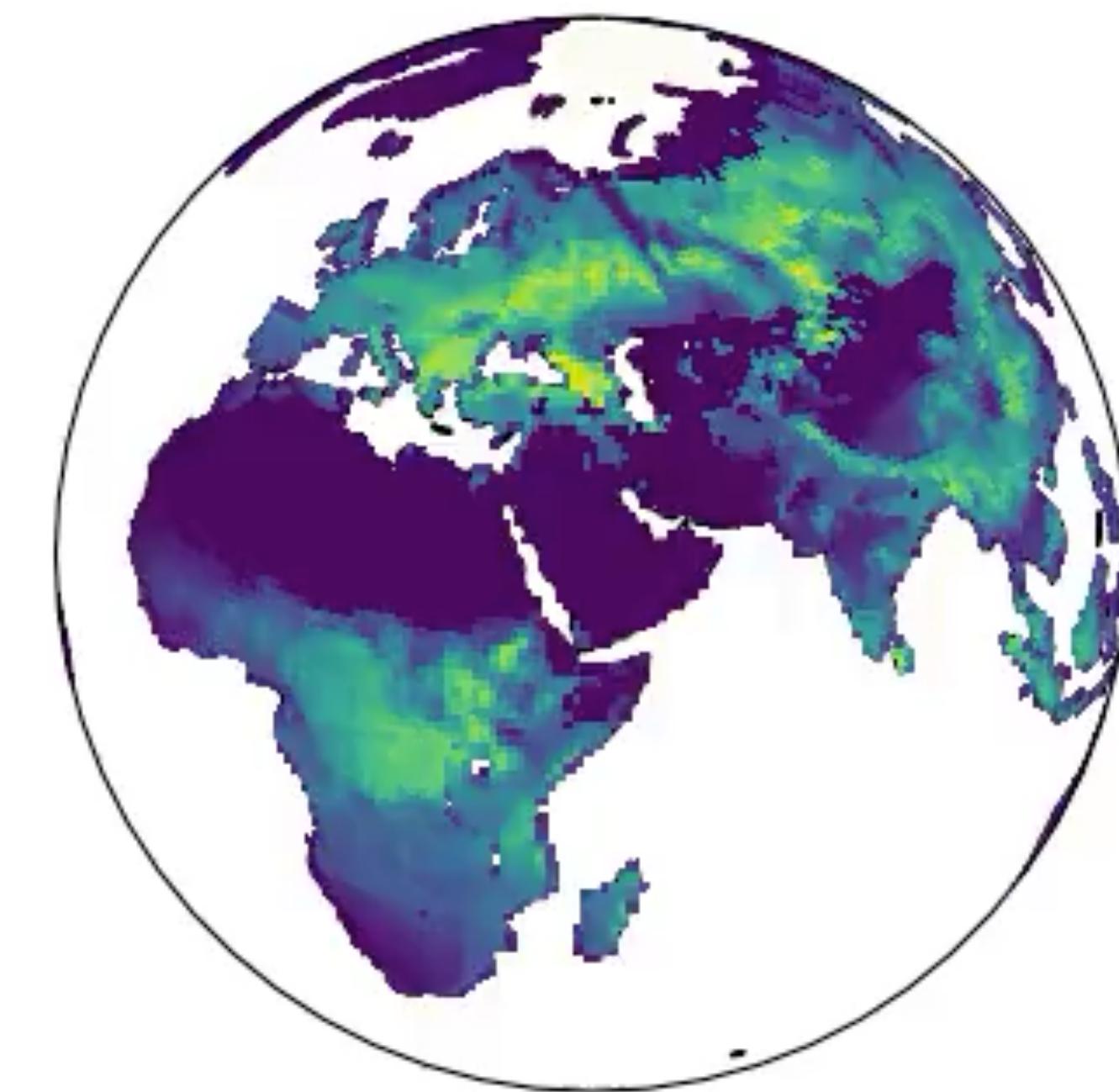
**~2 h for annual simulation on  
hourly time step on 160 cores!**

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

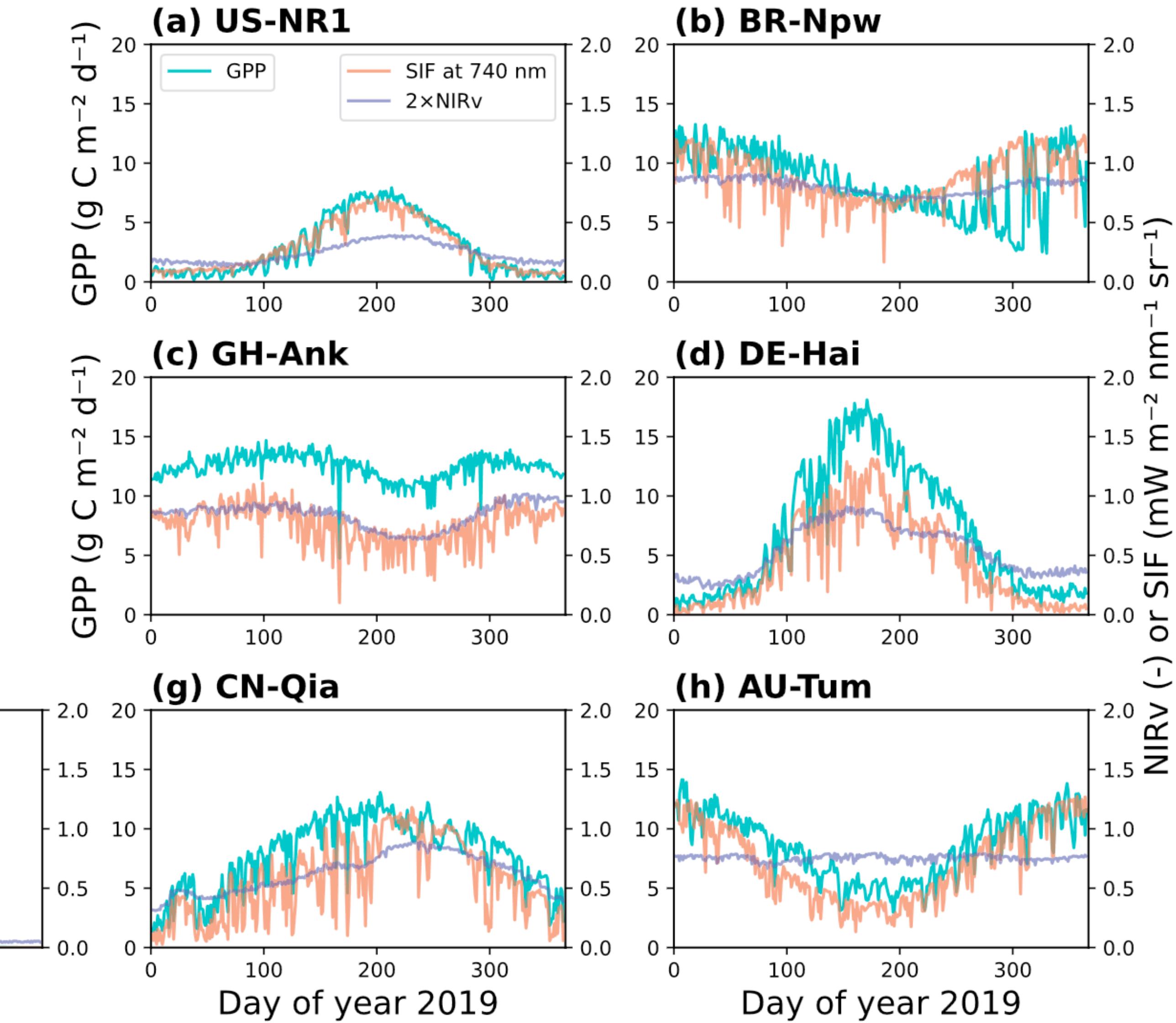
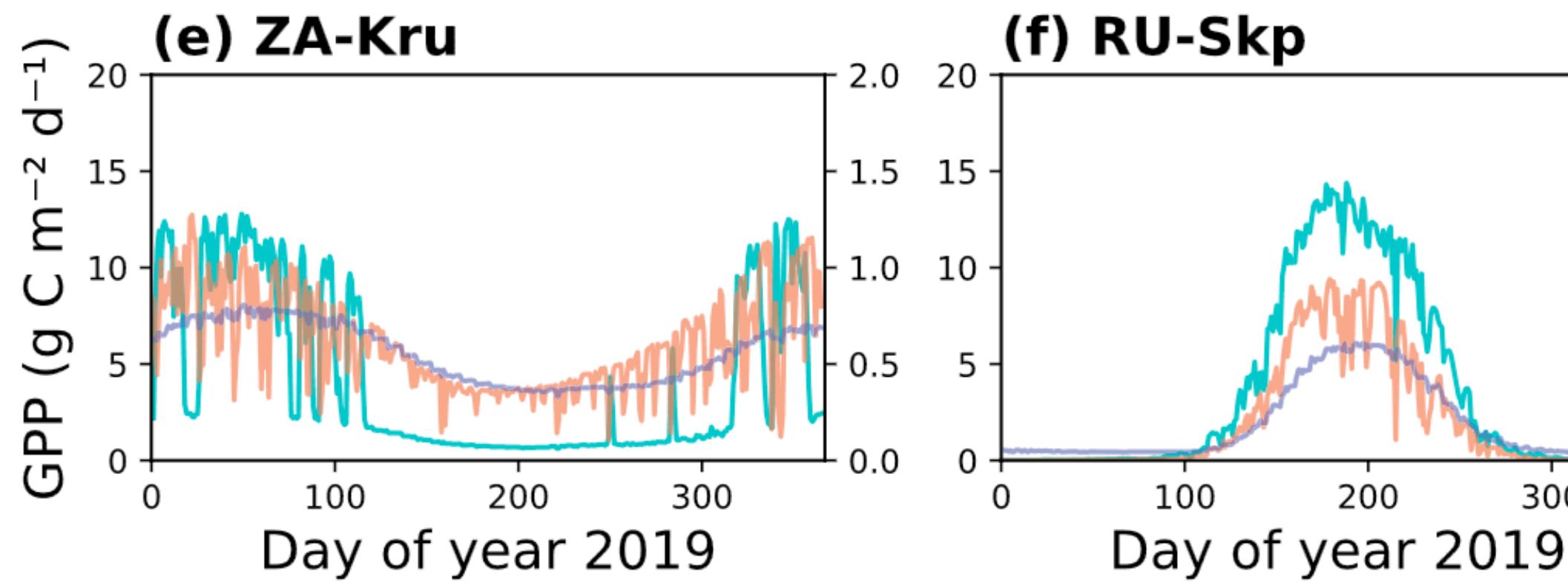


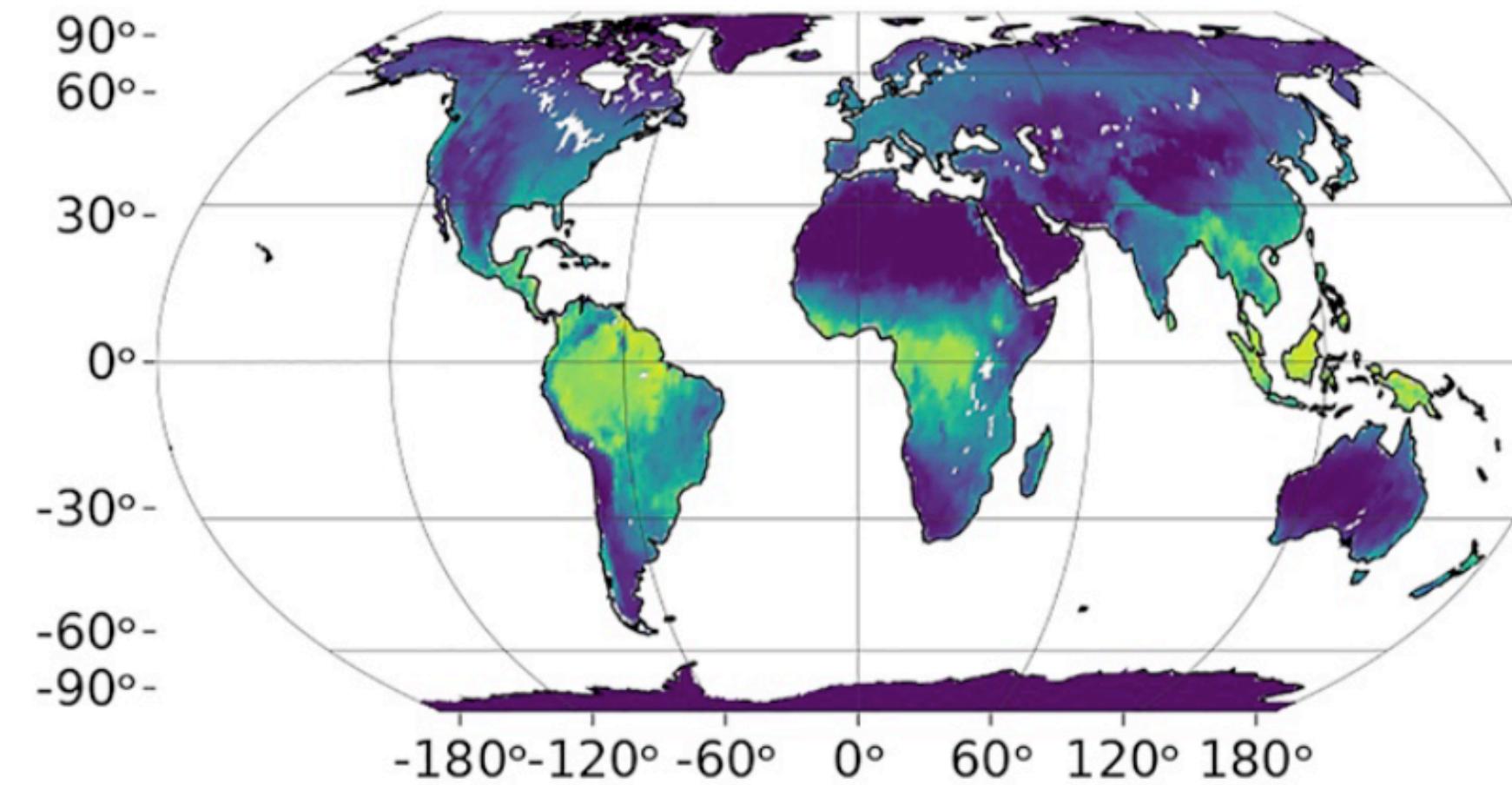
CliMA Land SIF @ 740 nm

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

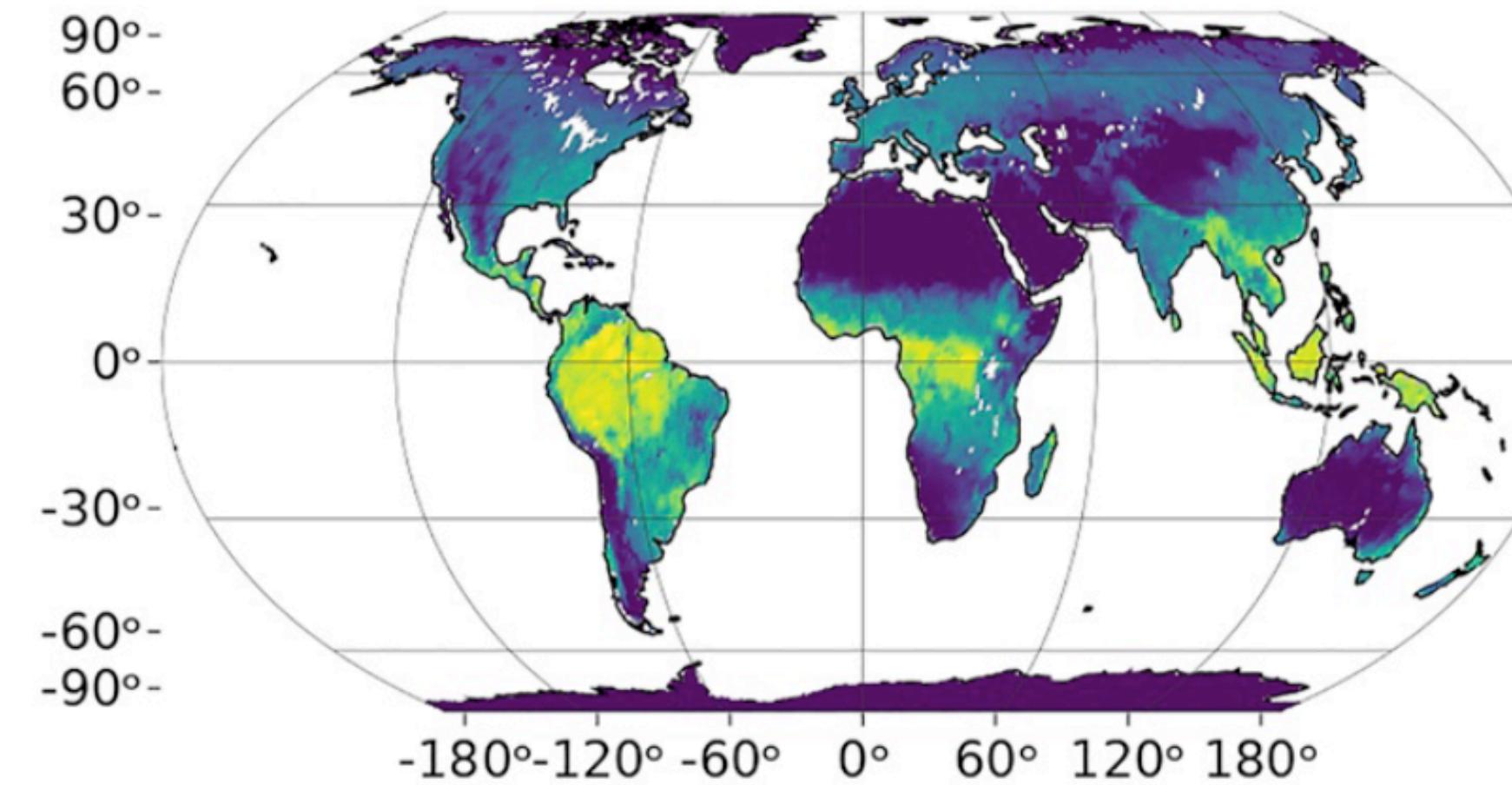


CliMA Land SIF @ 740 nm

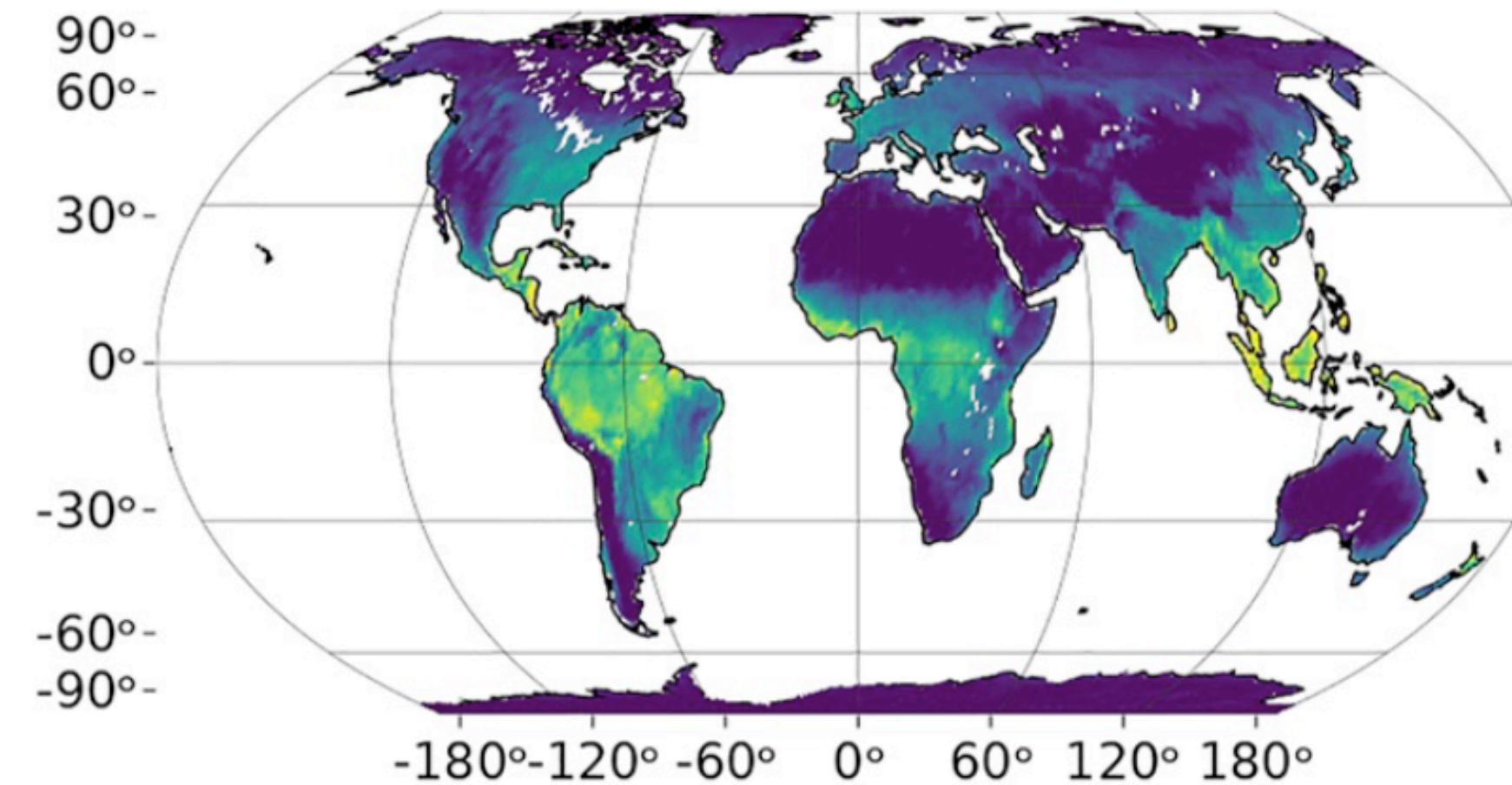




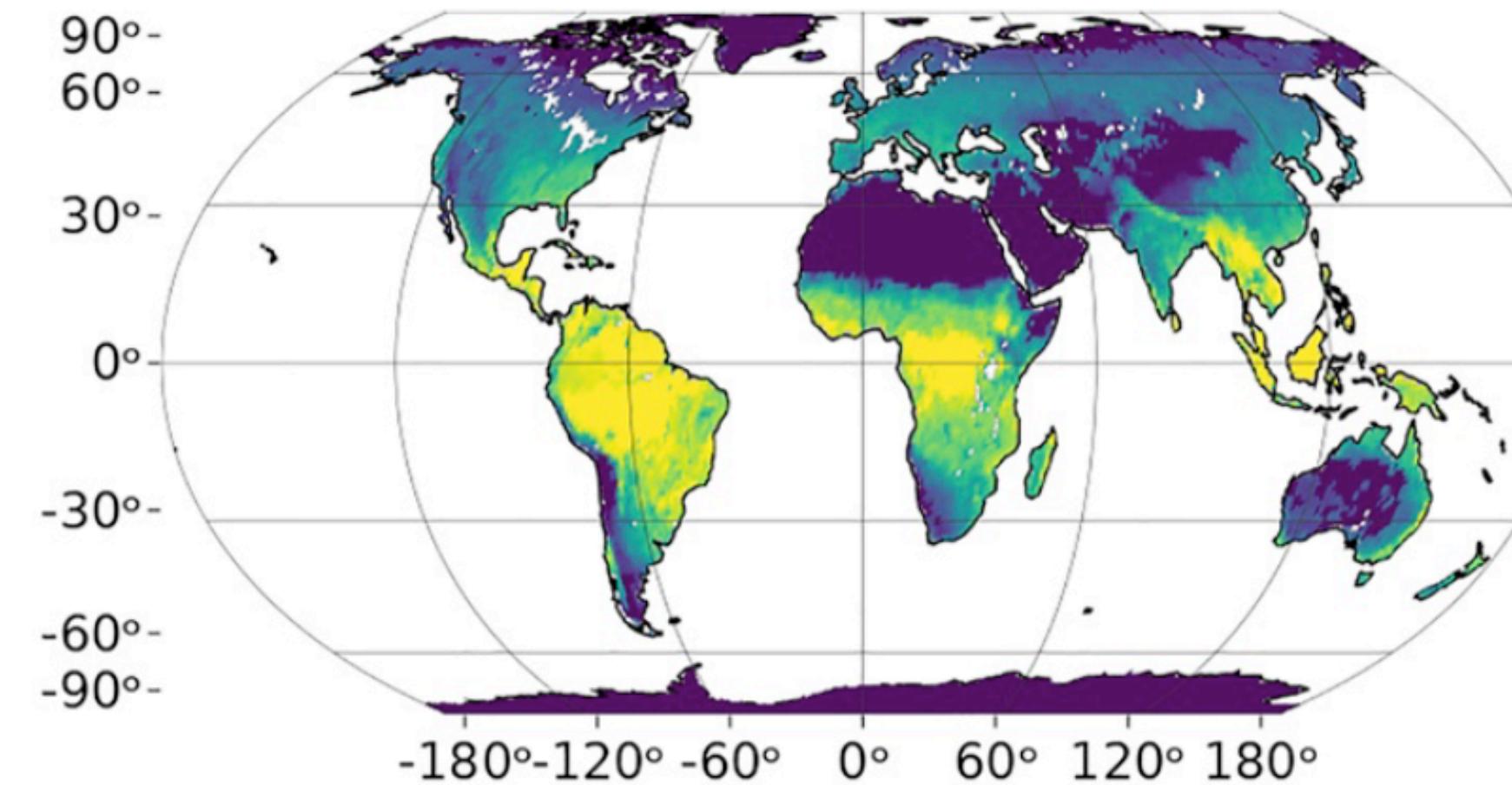
8  
6  
4  
2  
0  
MPI RS GPP  
( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )



15  
10  
5  
0  
CliMA GPP  
( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )

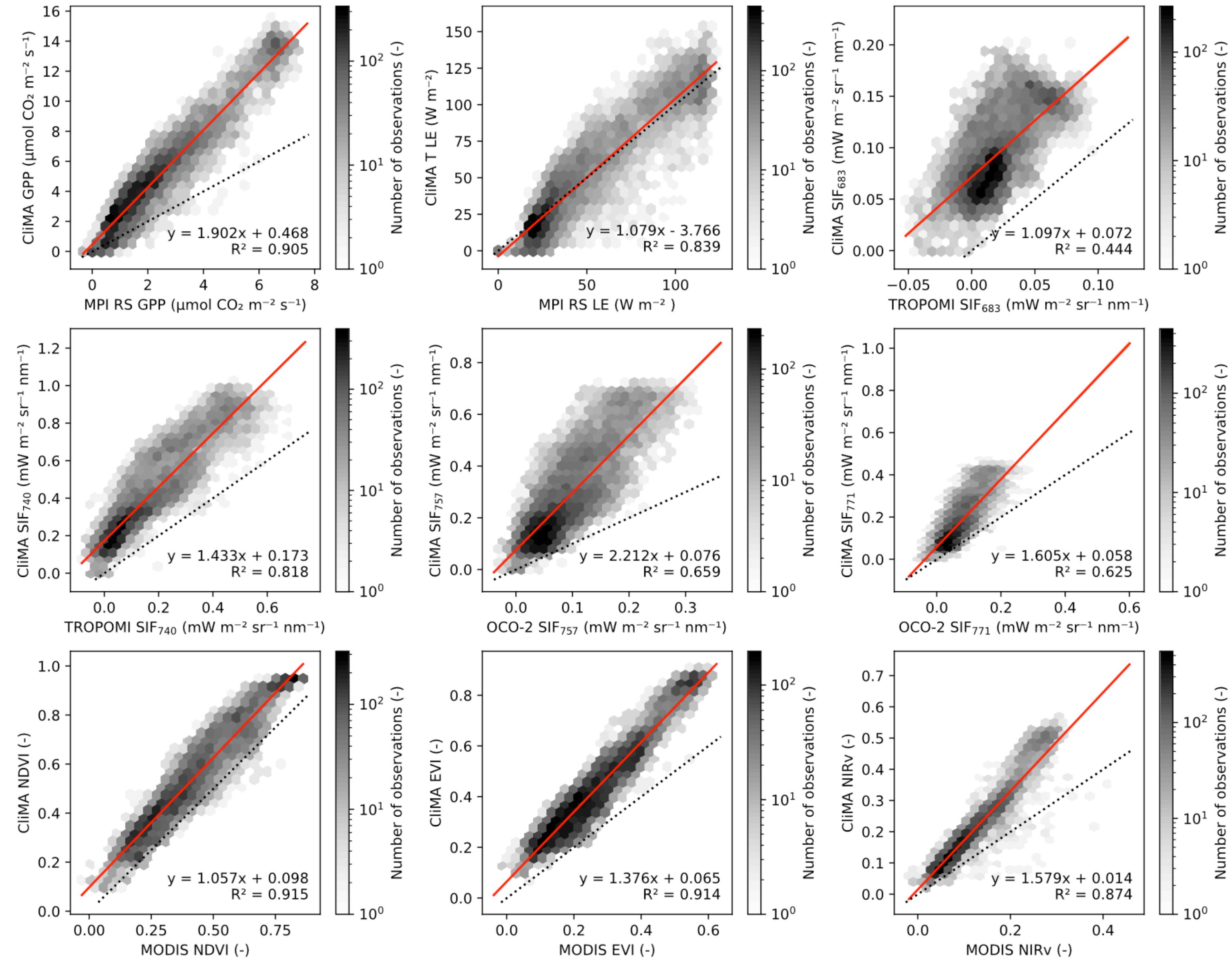


0.6  
0.5  
0.4  
0.3  
0.2  
0.1  
0.0  
TROPOMI SIF<sub>740</sub>  
( $\text{mW m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$ )

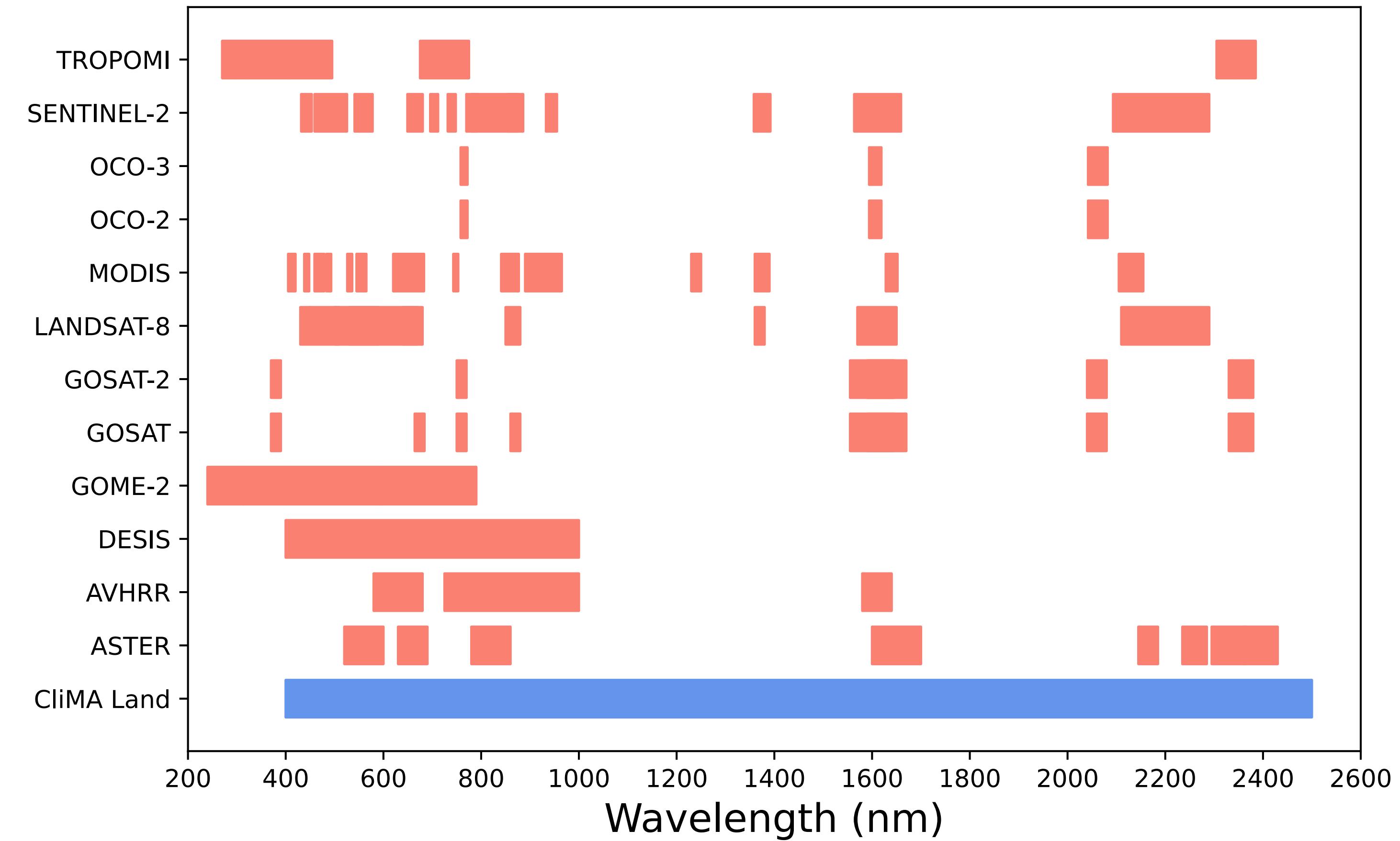


0.8  
0.6  
0.4  
0.2  
0.0  
CliMA SIF<sub>740</sub>  
( $\text{mW m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$ )

# CiMA Land performs well for simulated quantities without any calibrations



**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 light
- Account for carbon cost in reproduction
- Add more species in the SPAC system
- Make model ready to study competition
- ....

# Future research plans

Caltech



CliMA

CLIMATE MODELING ALLIANCE



## 2. Setups Advance model parameters configuration

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

# 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
- Explore nature based solutions against climate change



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