

植物生理生态学与陆面模式

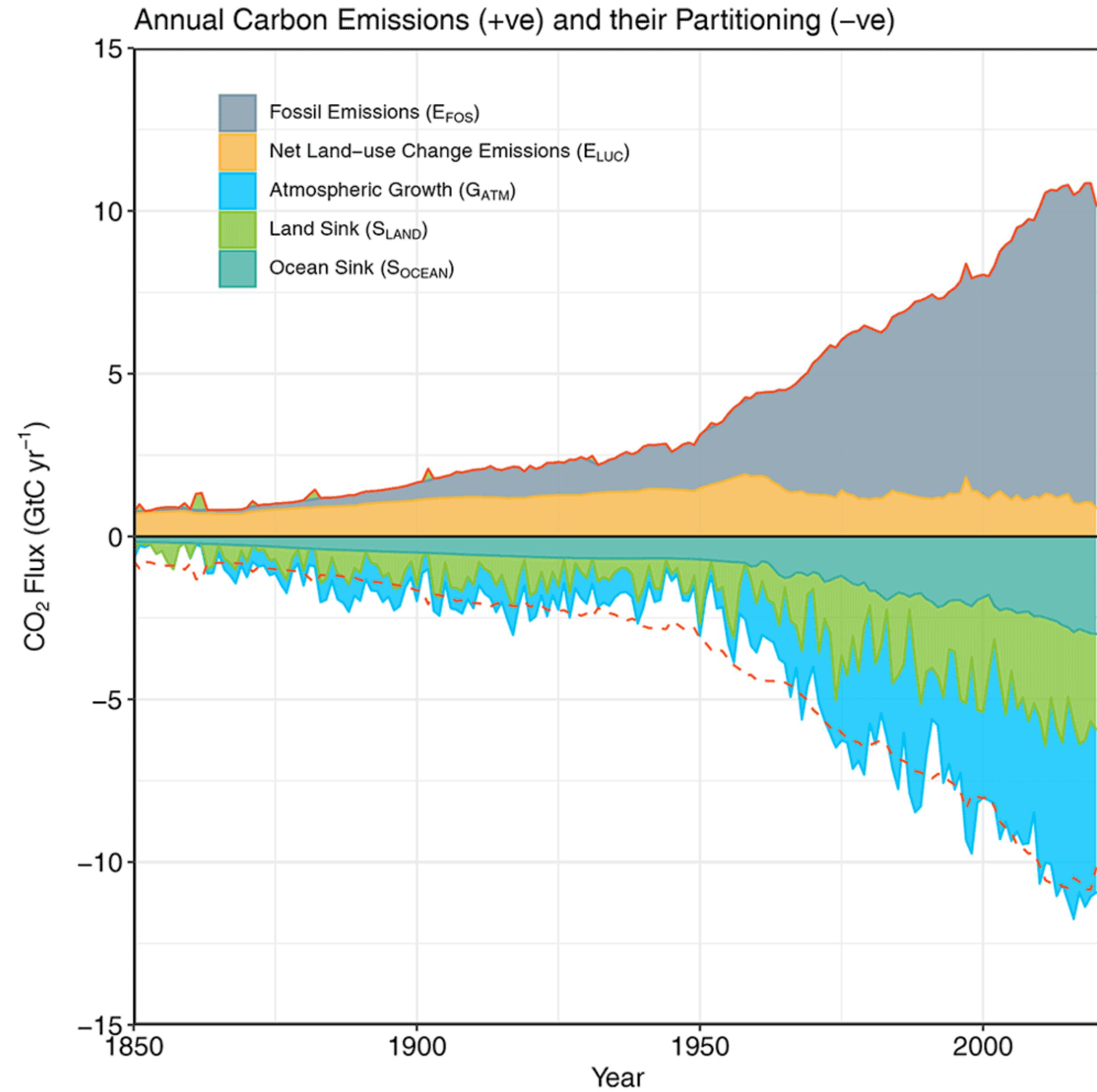
王玉杰

中国科学技术大学/地球和空间科学学院

3/21/2025 华南植物园

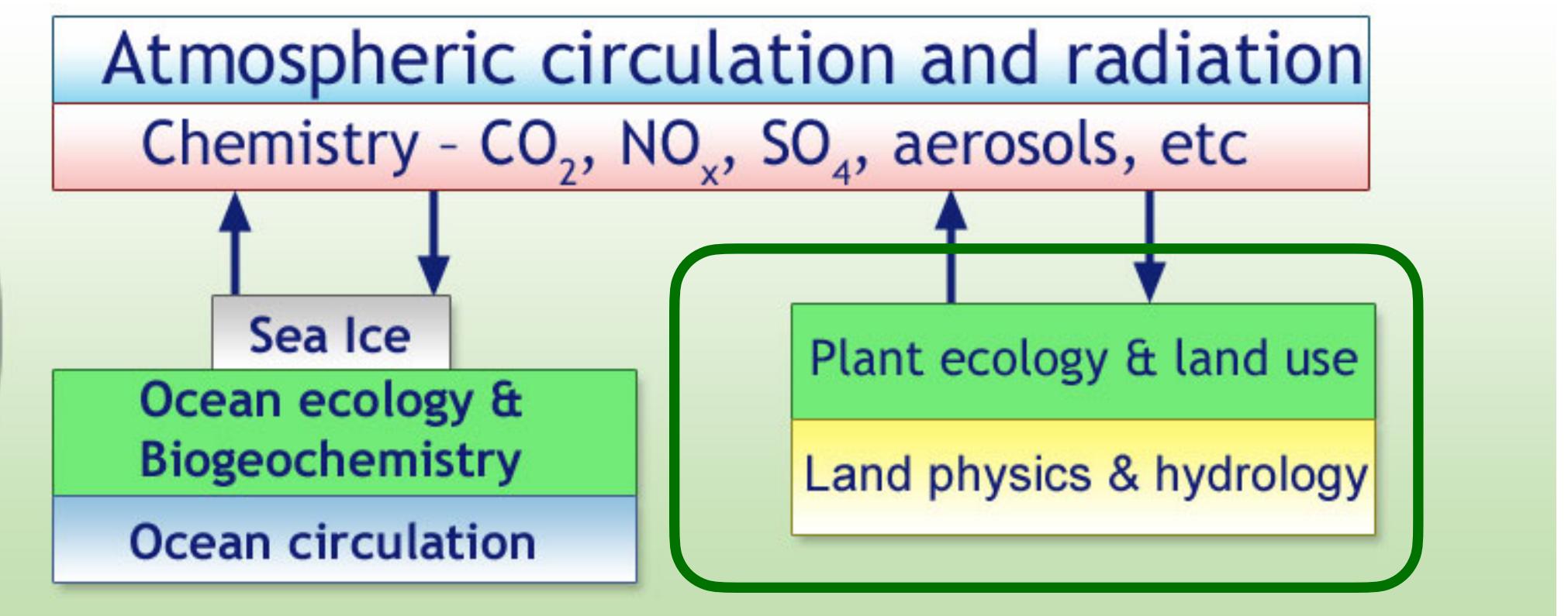


陆地吸收了25%
的碳排放，是实
现碳中和不可或
缺的部分。



气候模式

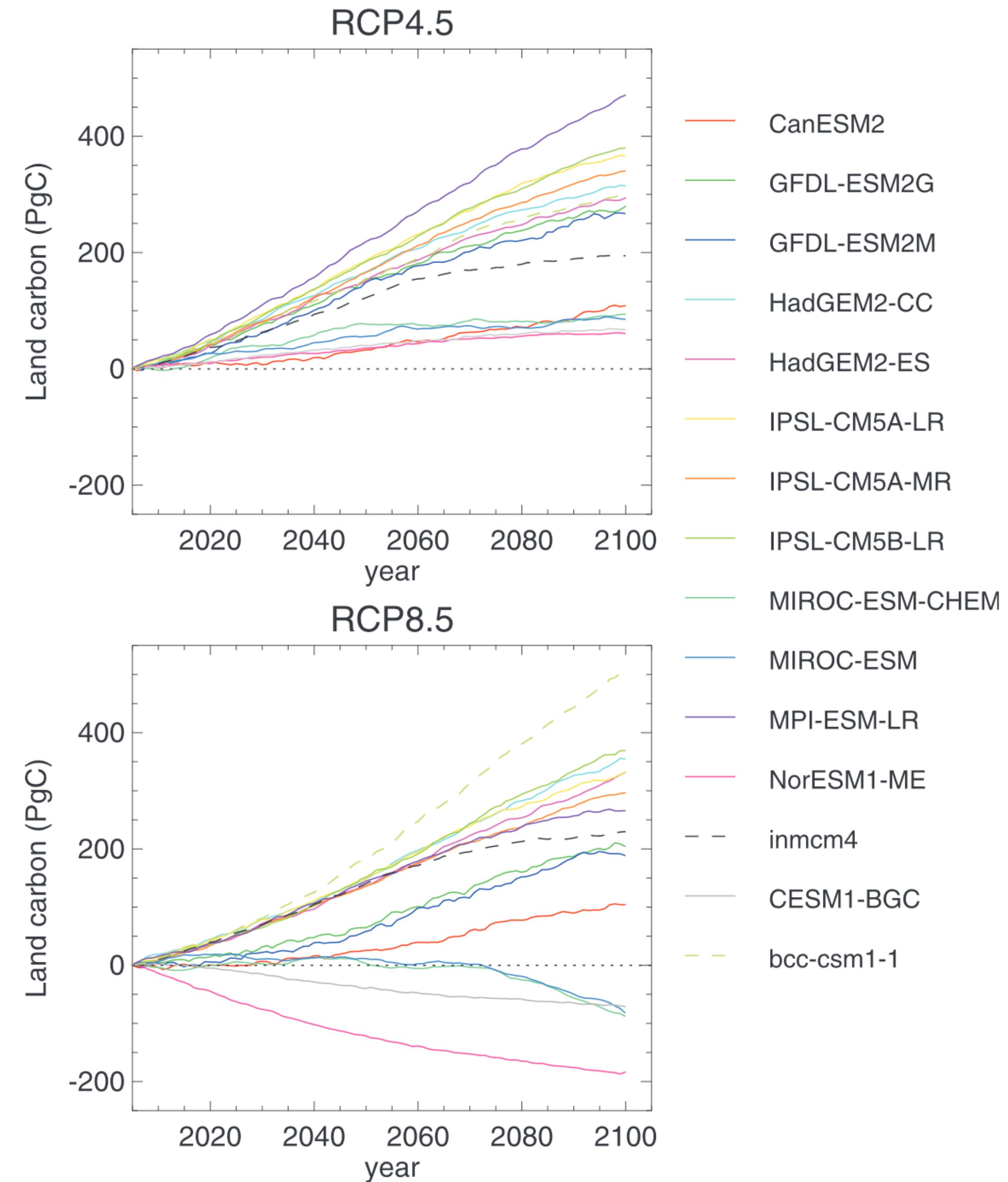
地球系统模式

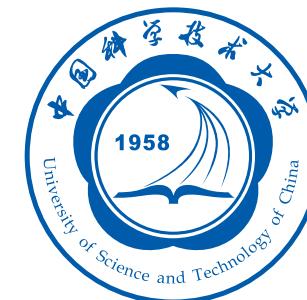


陆面模式

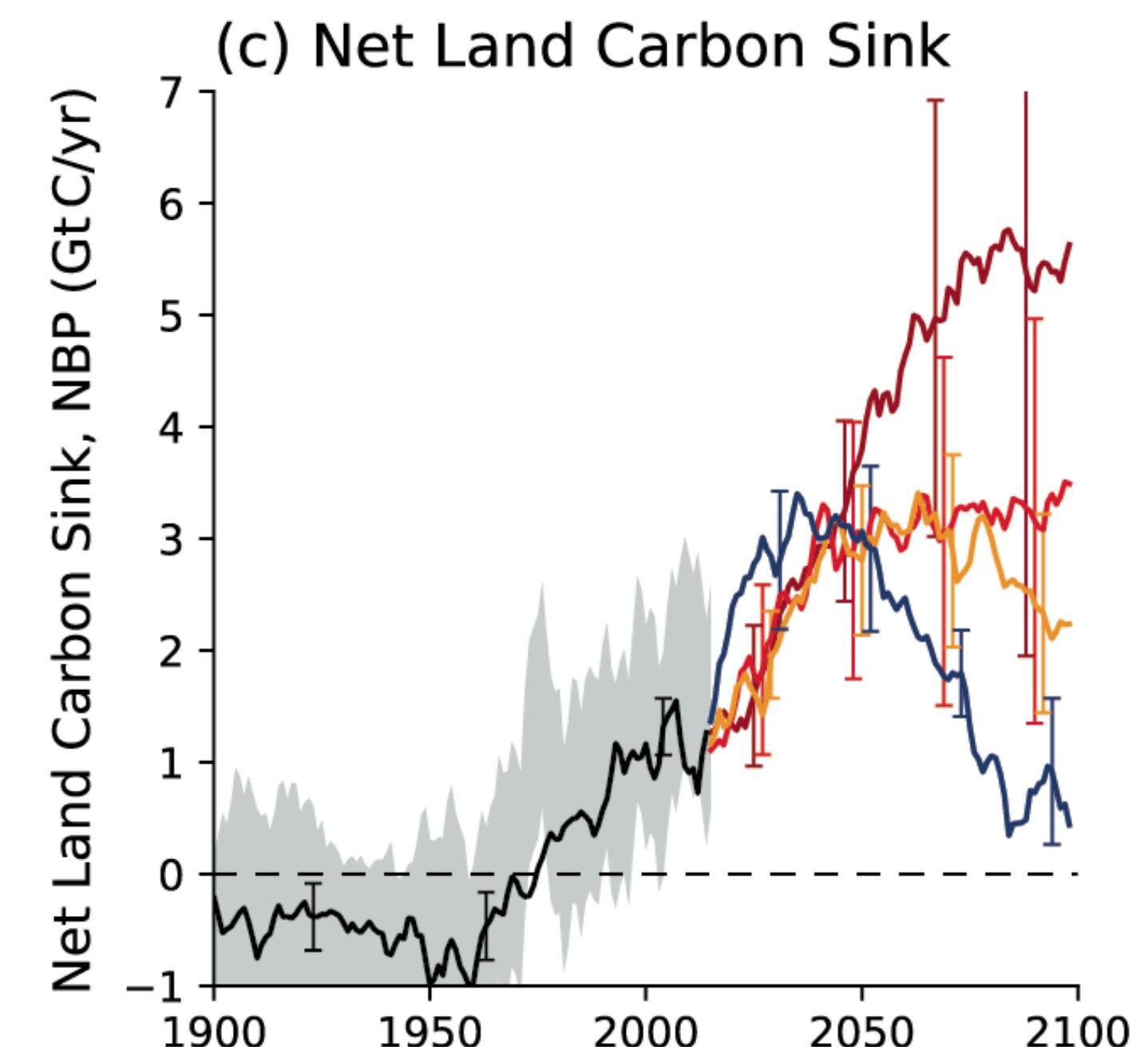
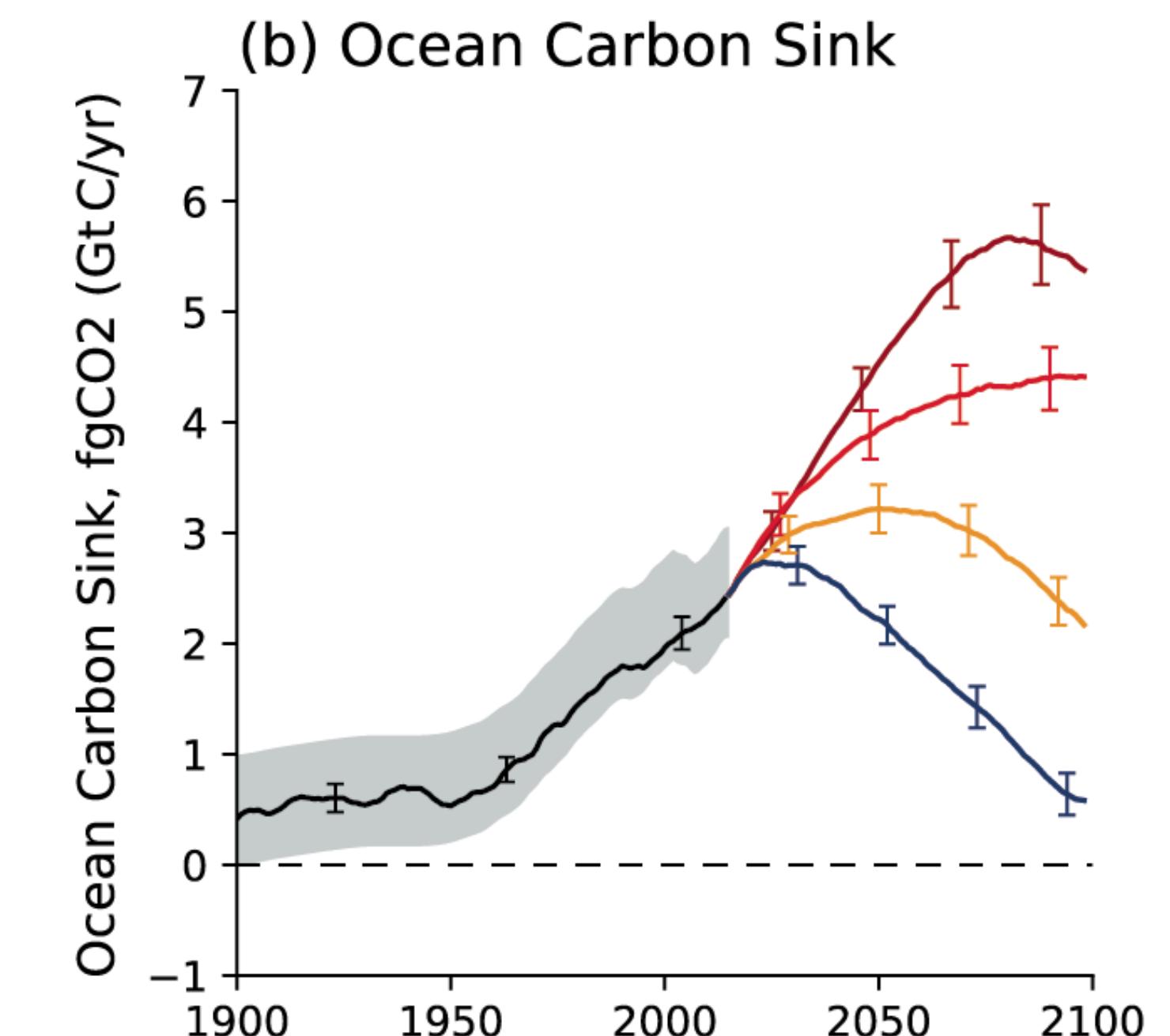


地球系统模式对
未来碳汇的预测
有很大**差异**，有
些模式预测未来
陆地会成为**碳**
源。



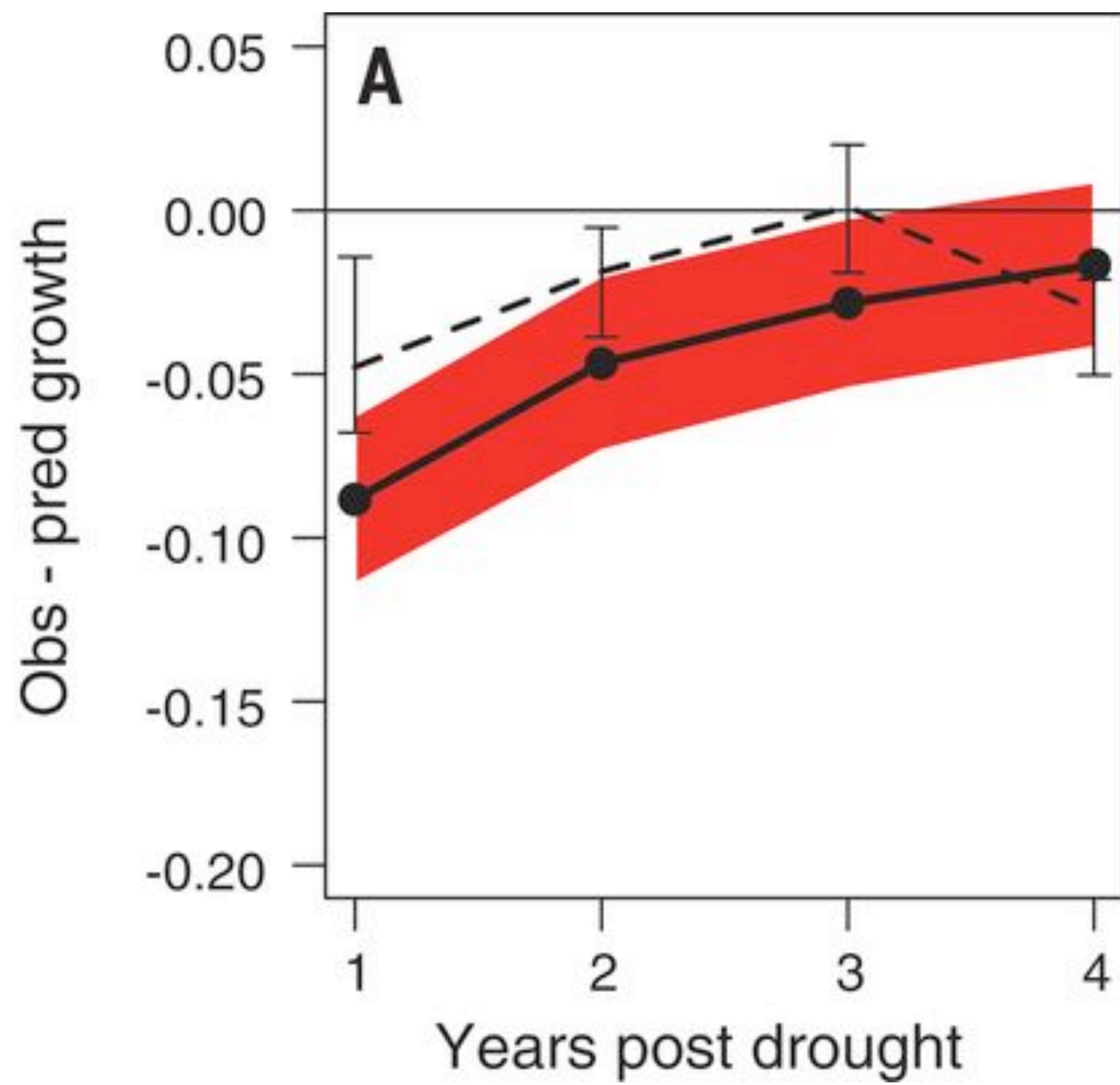
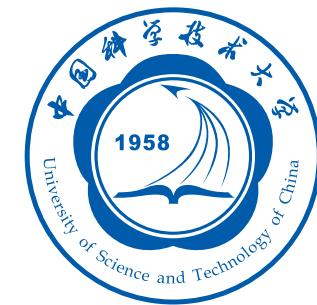


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有很大**差异**，有
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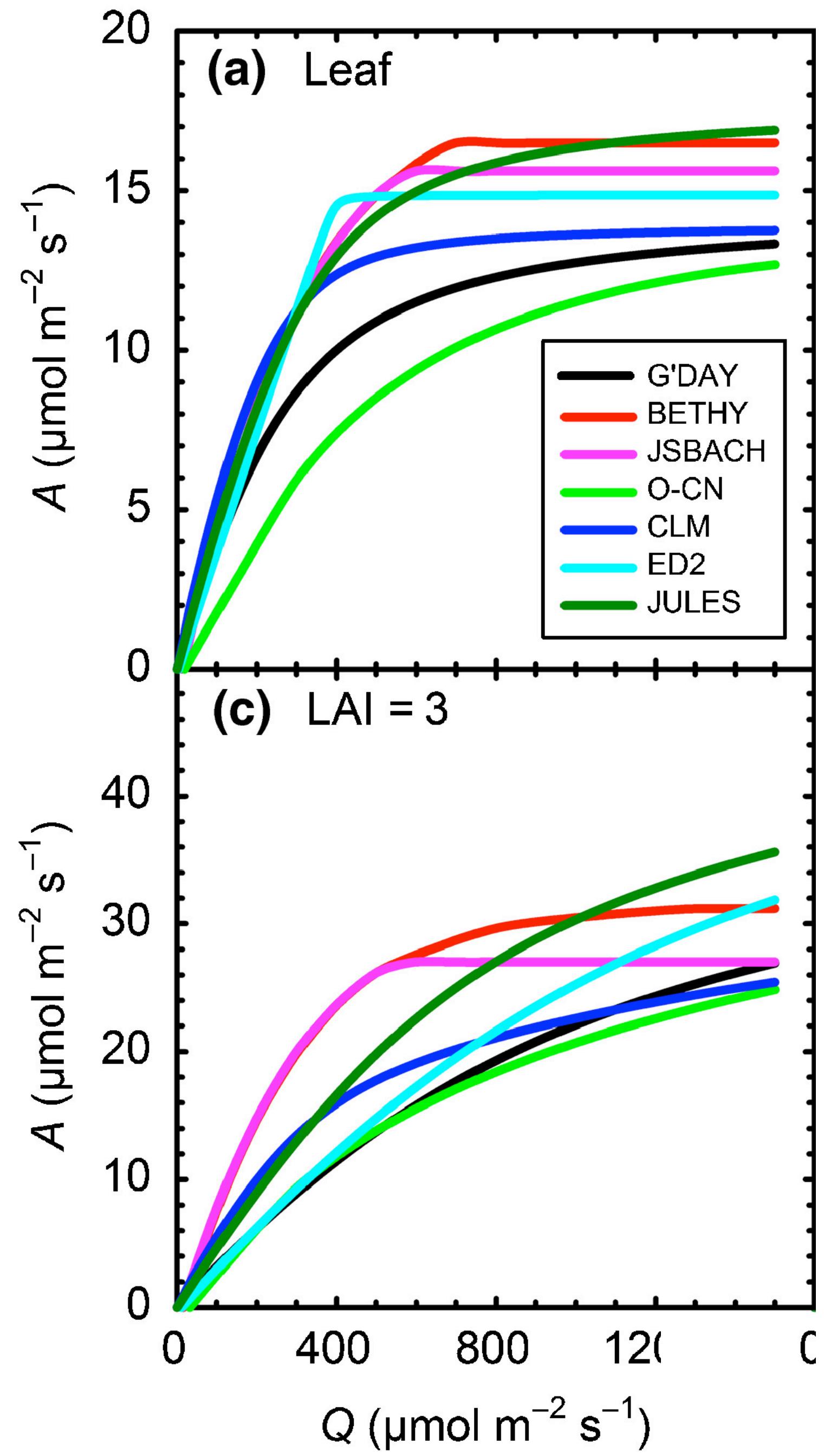


重要原因

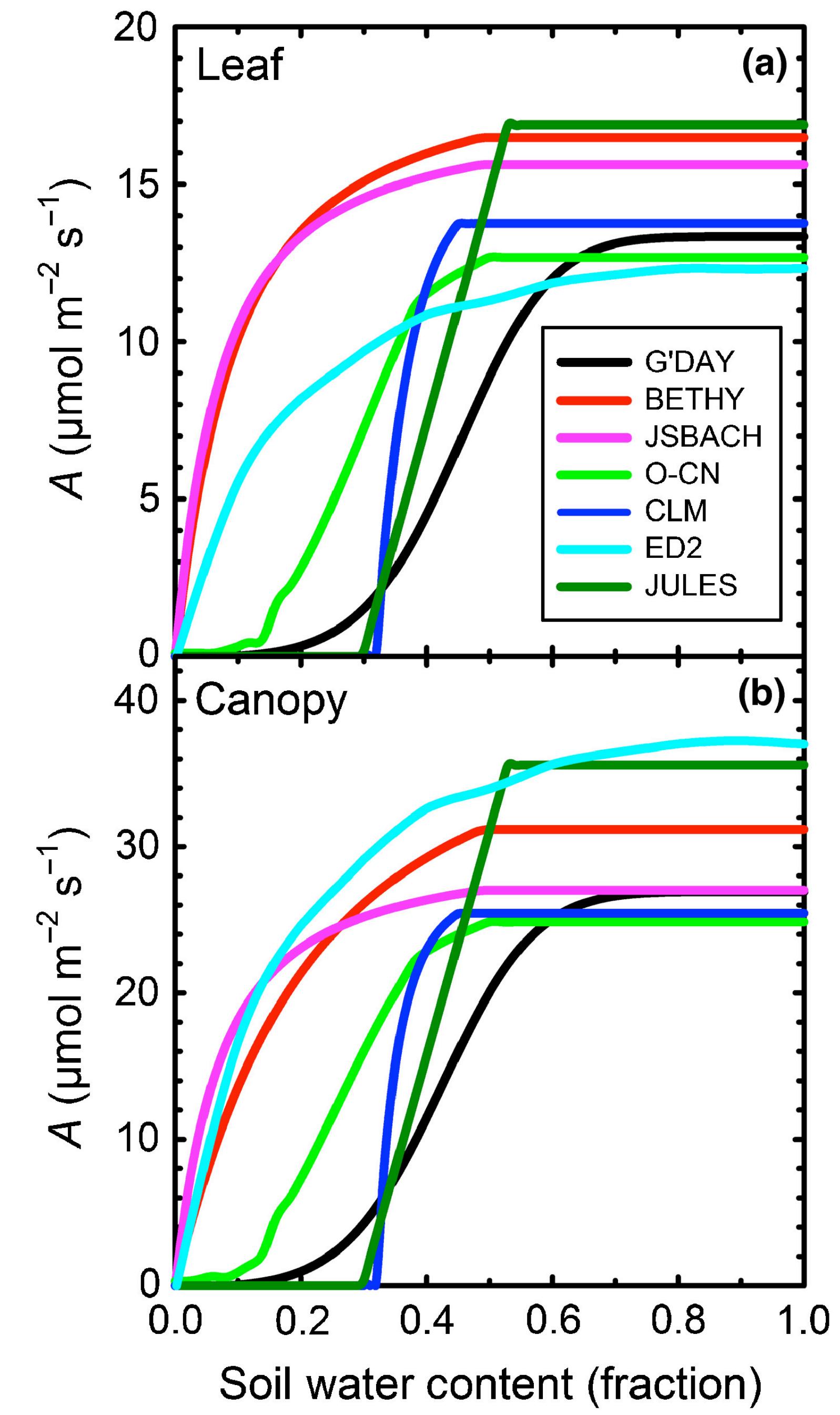
1. 现有陆面模式中生理
过程过于简单

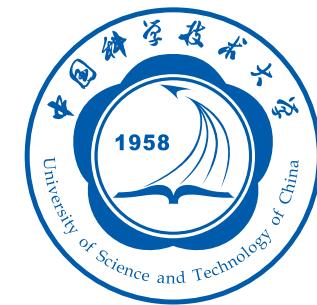


2. 模式的参数化差异很大

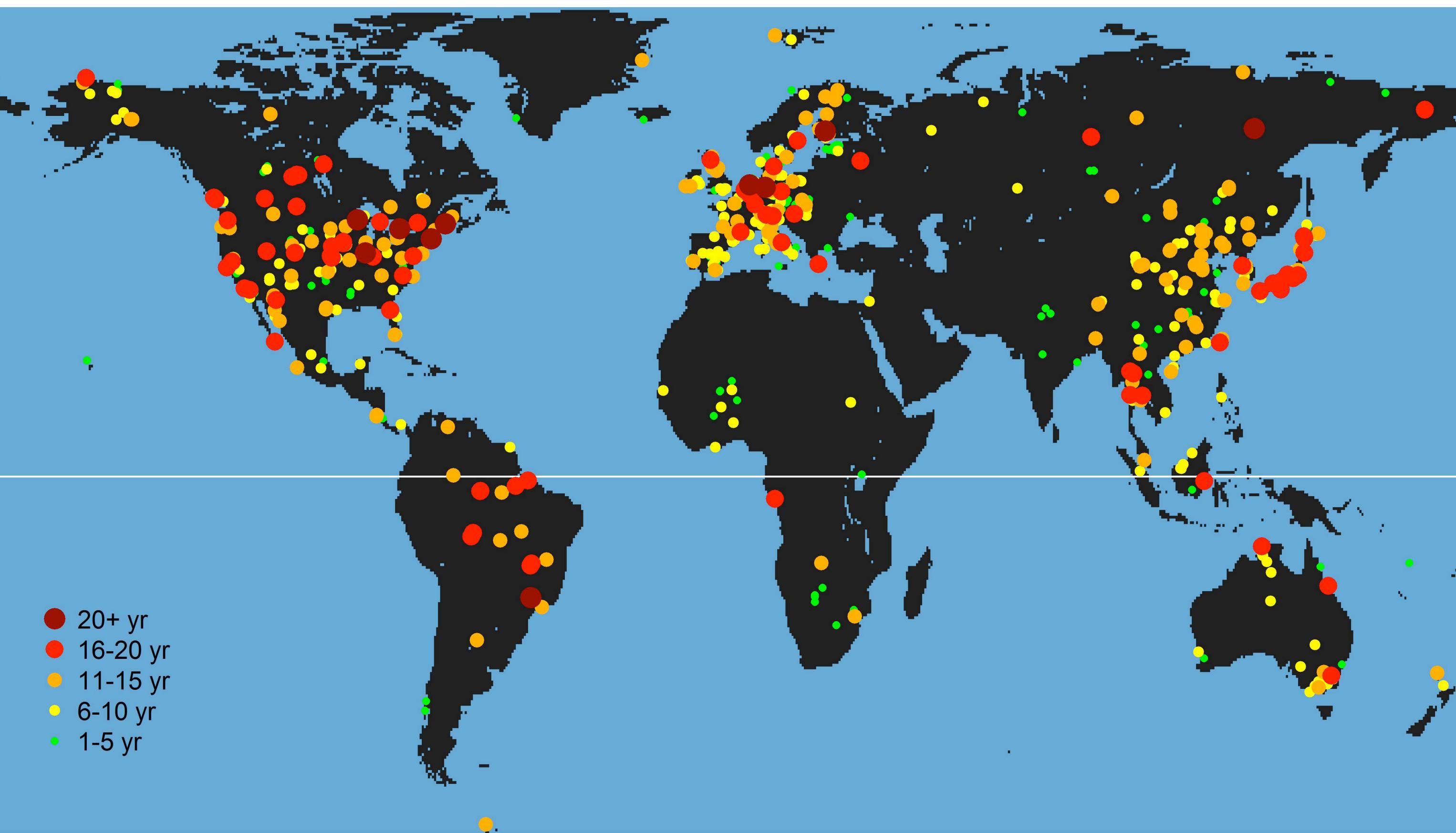


2. 模式的参数化差异很大





3. 能用于模式矫正的数据很少





3. 能用于模式矫正的数据很少



3. 能用于模式矫正的数据很少





| | Site ID | Policy <small>i</small> | Data Product <small>i</small> (Variables) <small>i</small> | 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) | | | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ | | | | |

面临的挑战



1. 模式开发

改进土壤-植物-
大气连续体模
型，加入更多的
生理机制

2. 模式设置

使用更合理的模
型设置与组合，
降低对经验模式
的依赖

3. 参数矫正

使用更多、更系
统的多来源数据
进行模型参数的
矫正

新一代 陆面模式

CLiMA Land





新一代模式

新一代模式应该
包含哪些元素？

从数据中学习

- 学习什么？
- 怎么学习？
- 向谁学习？

模式框架

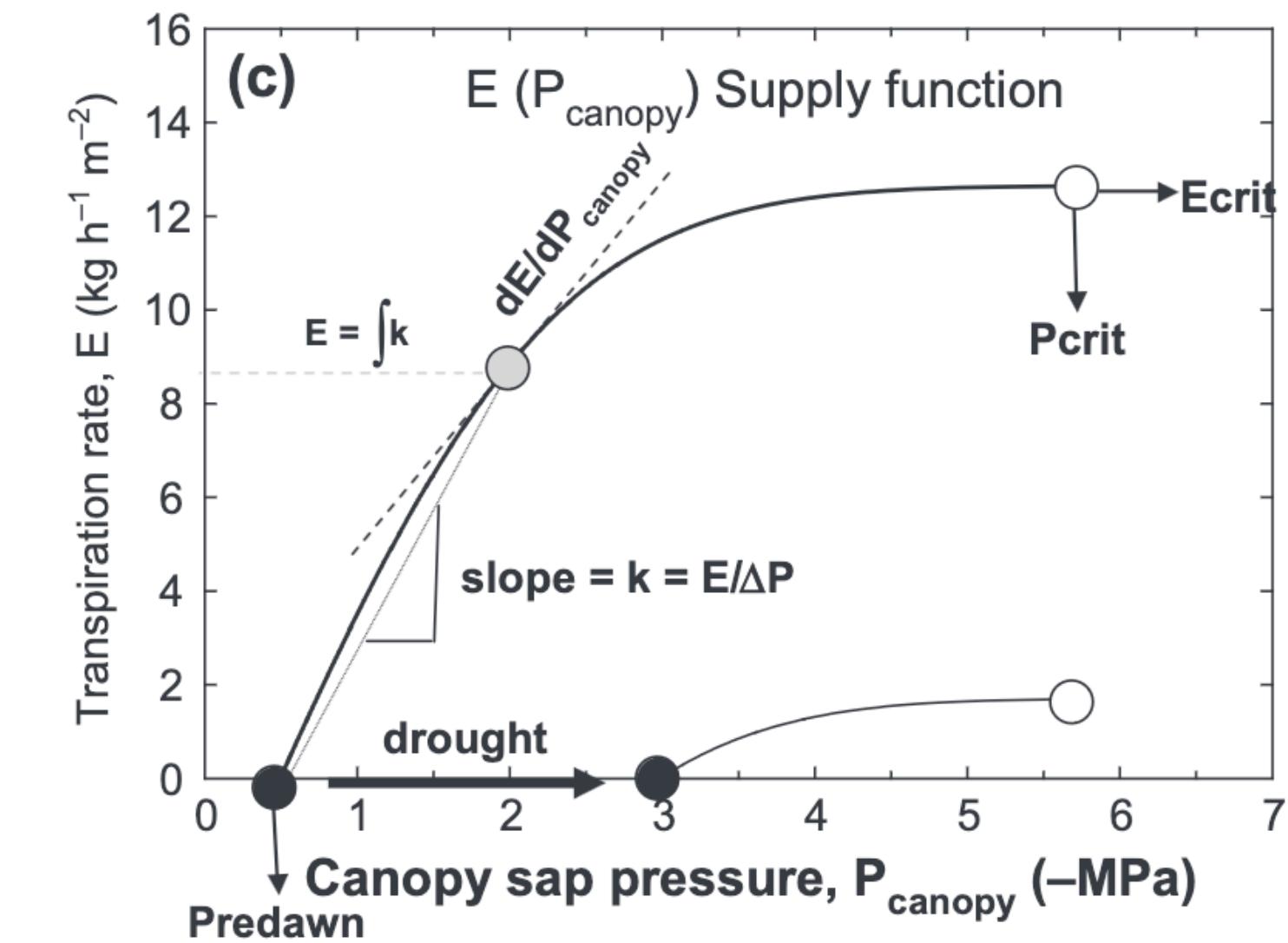
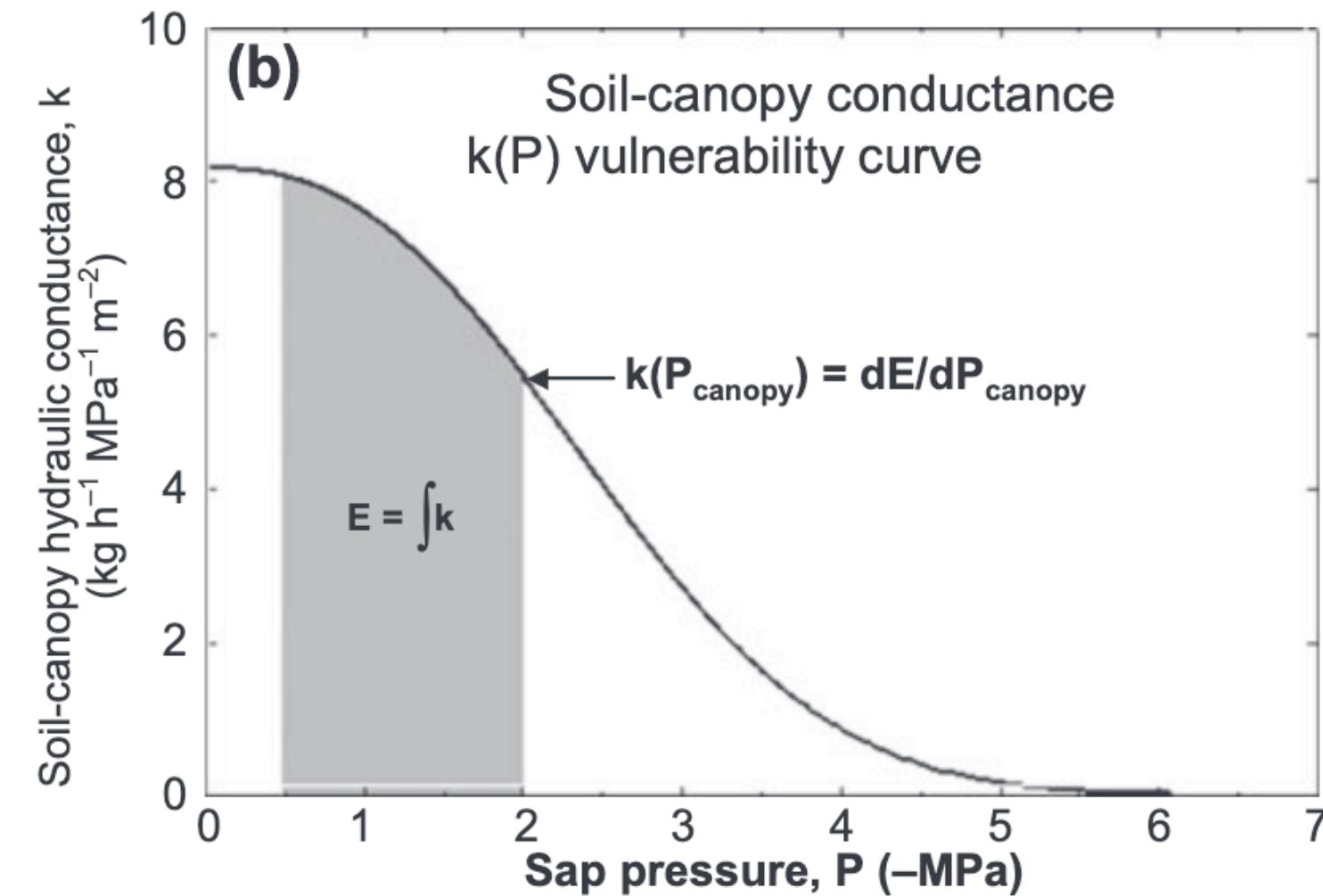
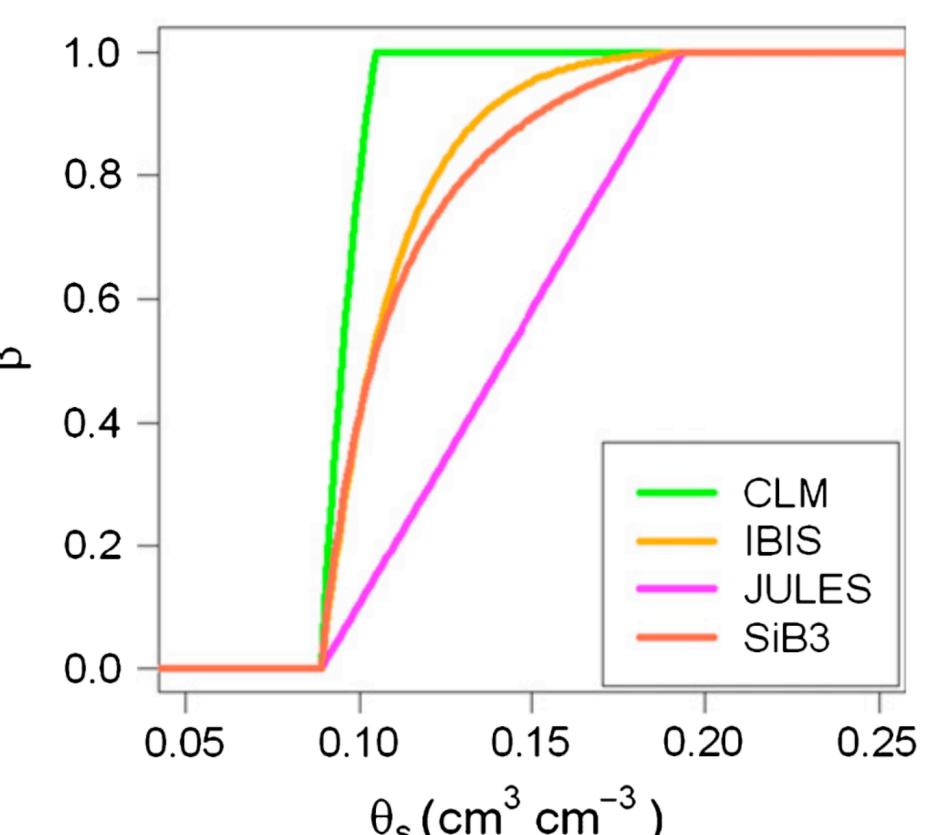
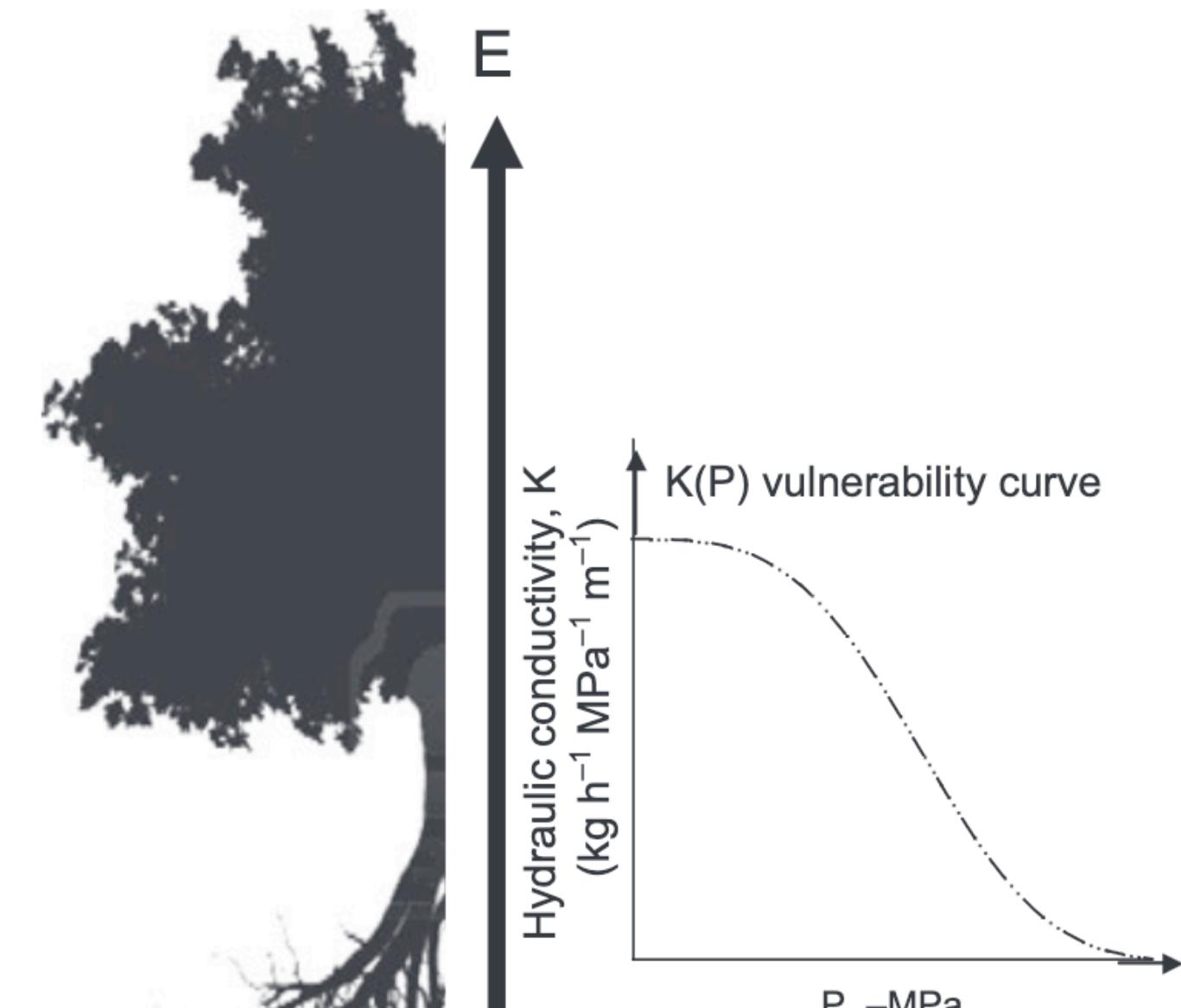
- 模块化
- 伸缩性
- 体系结构
- 对用户更友好



1. 模式开发

改进陆面模式中
土壤-植物-大气
连续体，加入更
多的生理机制

(a) Single element continuum with one conductivity $K(P)$ vulnerability curve

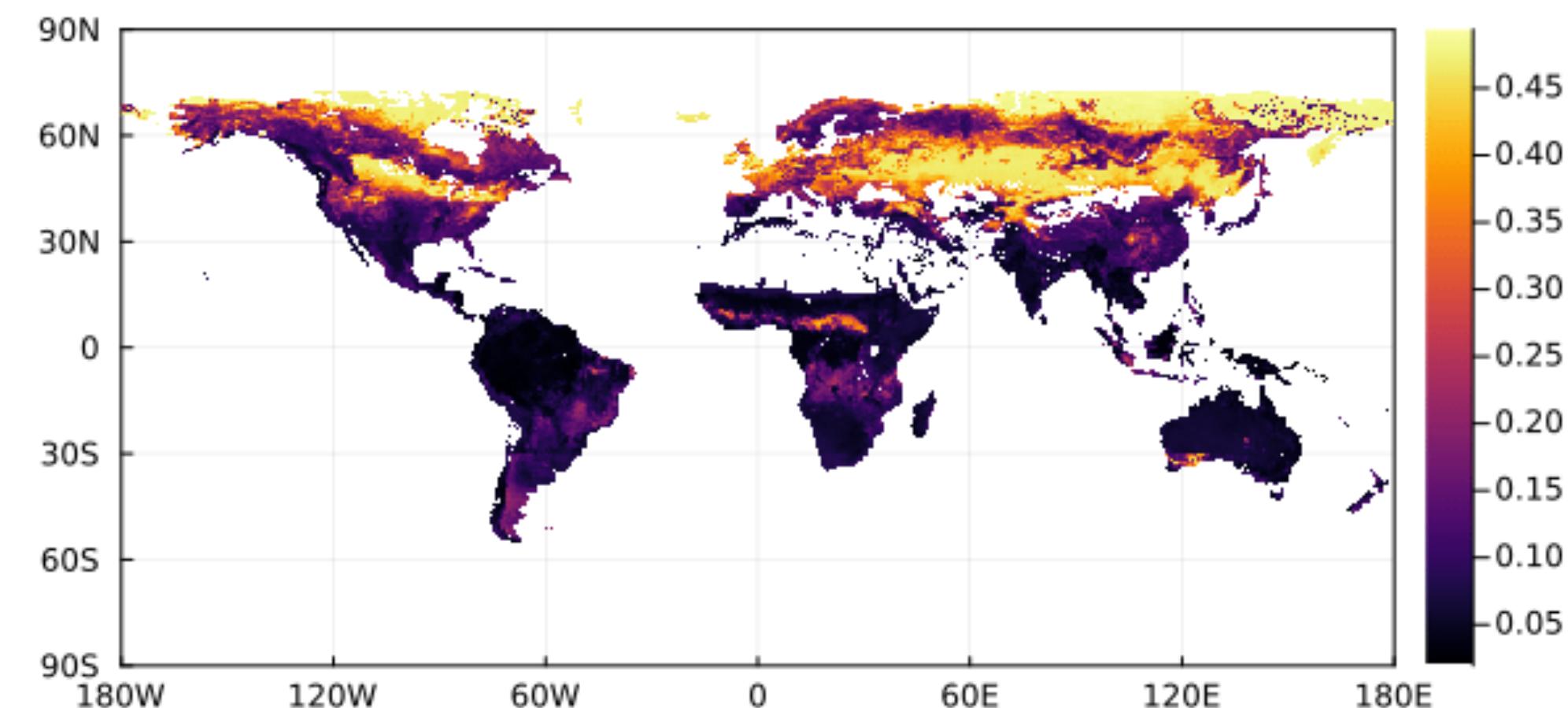




2. 模式设置

使用更合理的模式设置与组合，降低对经验模式的依赖

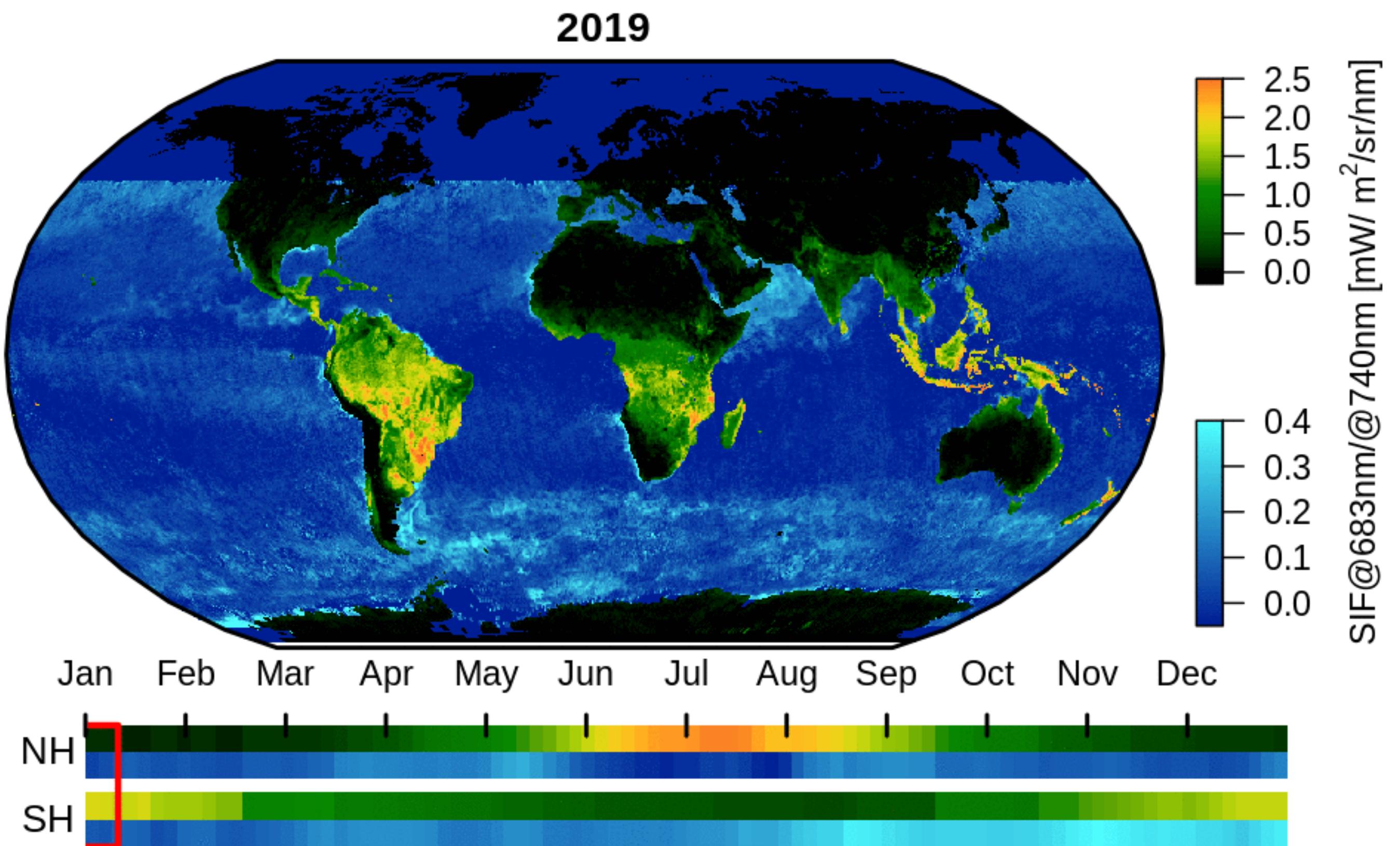
| Plant Functional Type | χ_L | α_{vis}^{leaf} | α_{nir}^{leaf} | α_{vis}^{stem} | α_{nir}^{stem} | τ_{vis}^{leaf} | τ_{nir}^{leaf} |
|-----------------------|----------|-----------------------|-----------------------|-----------------------|-----------------------|---------------------|---------------------|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





3. 参数矫正

使用更多、更系统的多来源数据
进行模式参数的
矫正



基于植物生理过程的日间气孔导度的模型



1. 模式开发

改进土壤-植物-
大气连续体模
型，加入更多的
生理机制

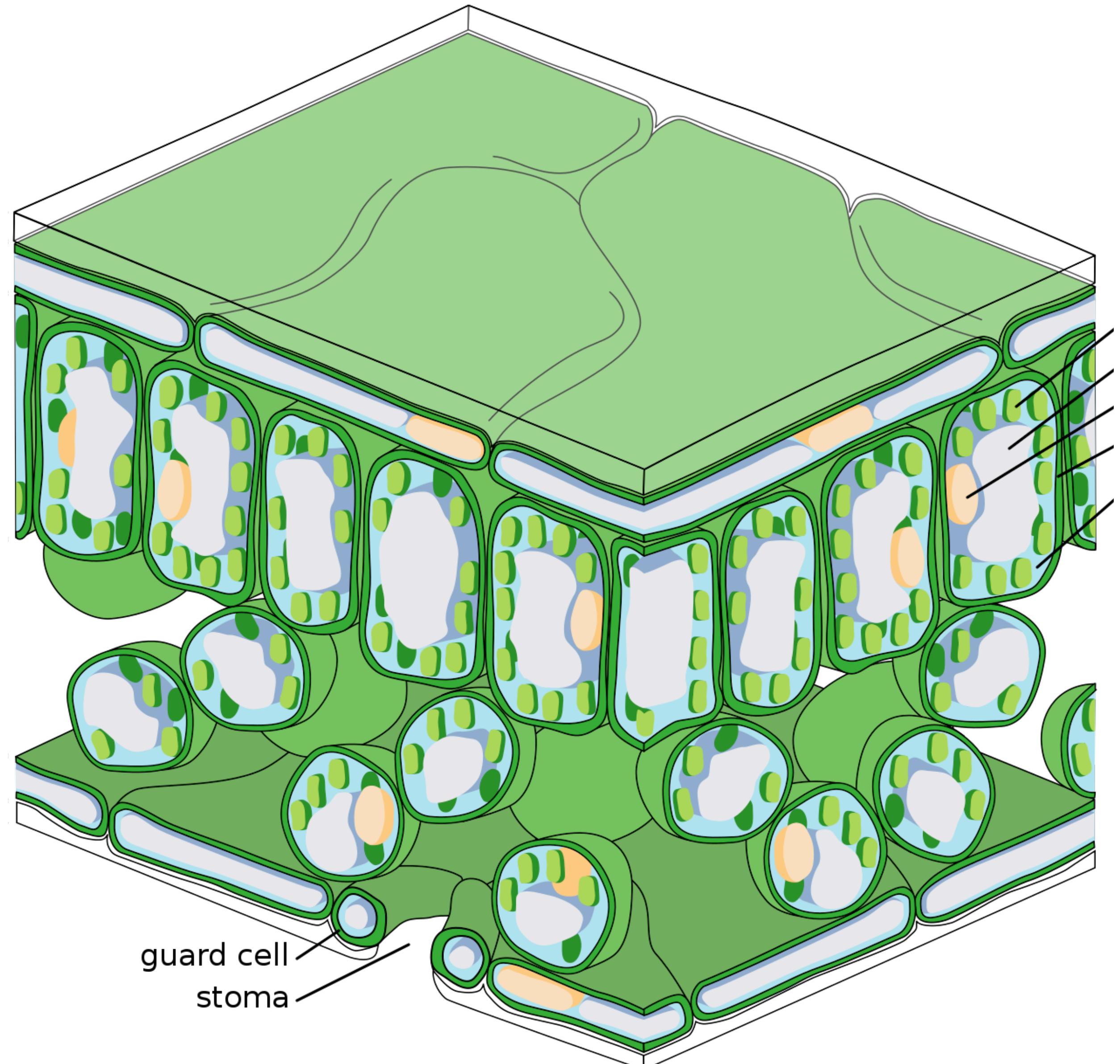
2. 模式设置

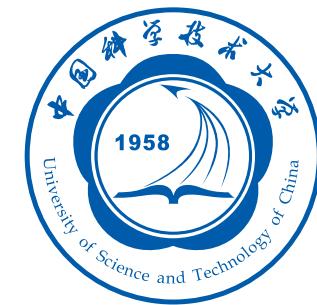
3. 参数矫正



通过气孔的蒸腾将
~40%的降水返还到
大气

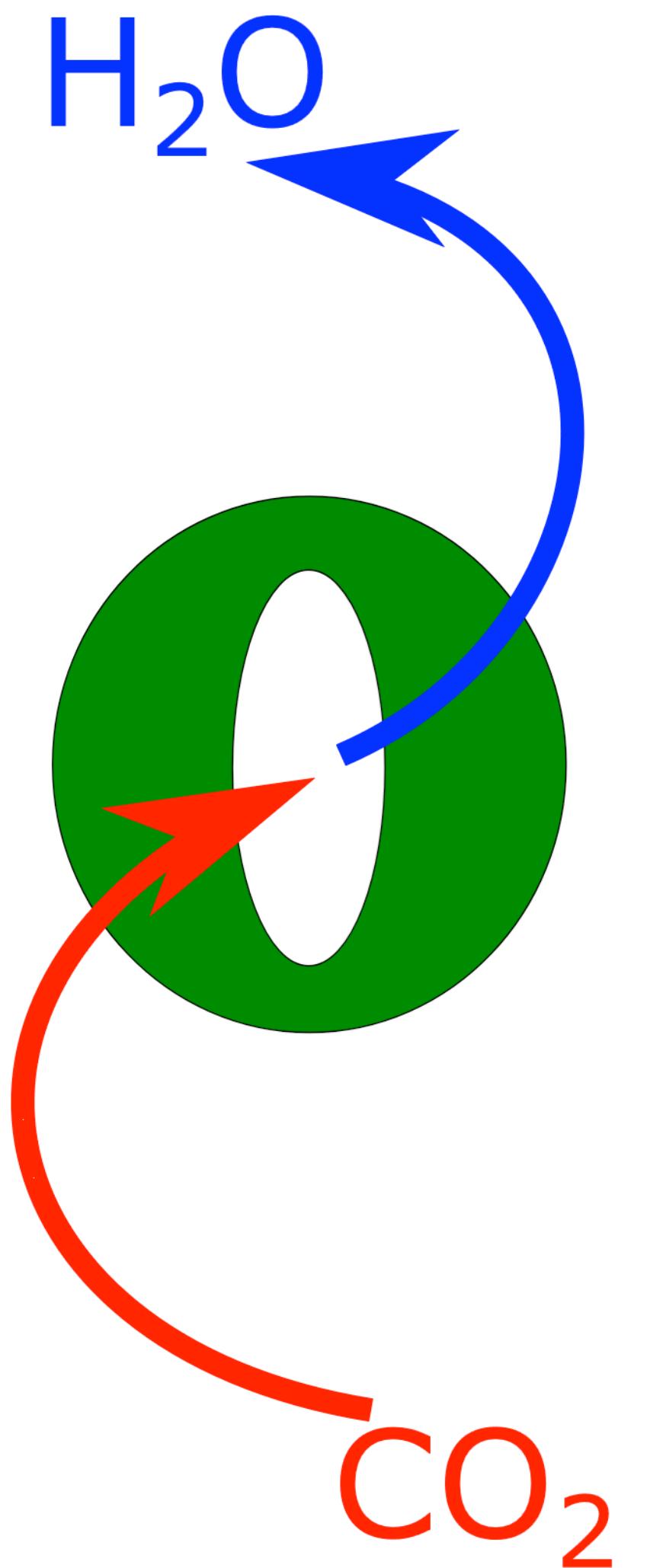
通过气孔的光合作用
固定 >99% 的 CO₂





植物生理

- 脱落酸
- 细胞膨压
- 水力导度
- 光合能力
- 叶肉导度
- ...

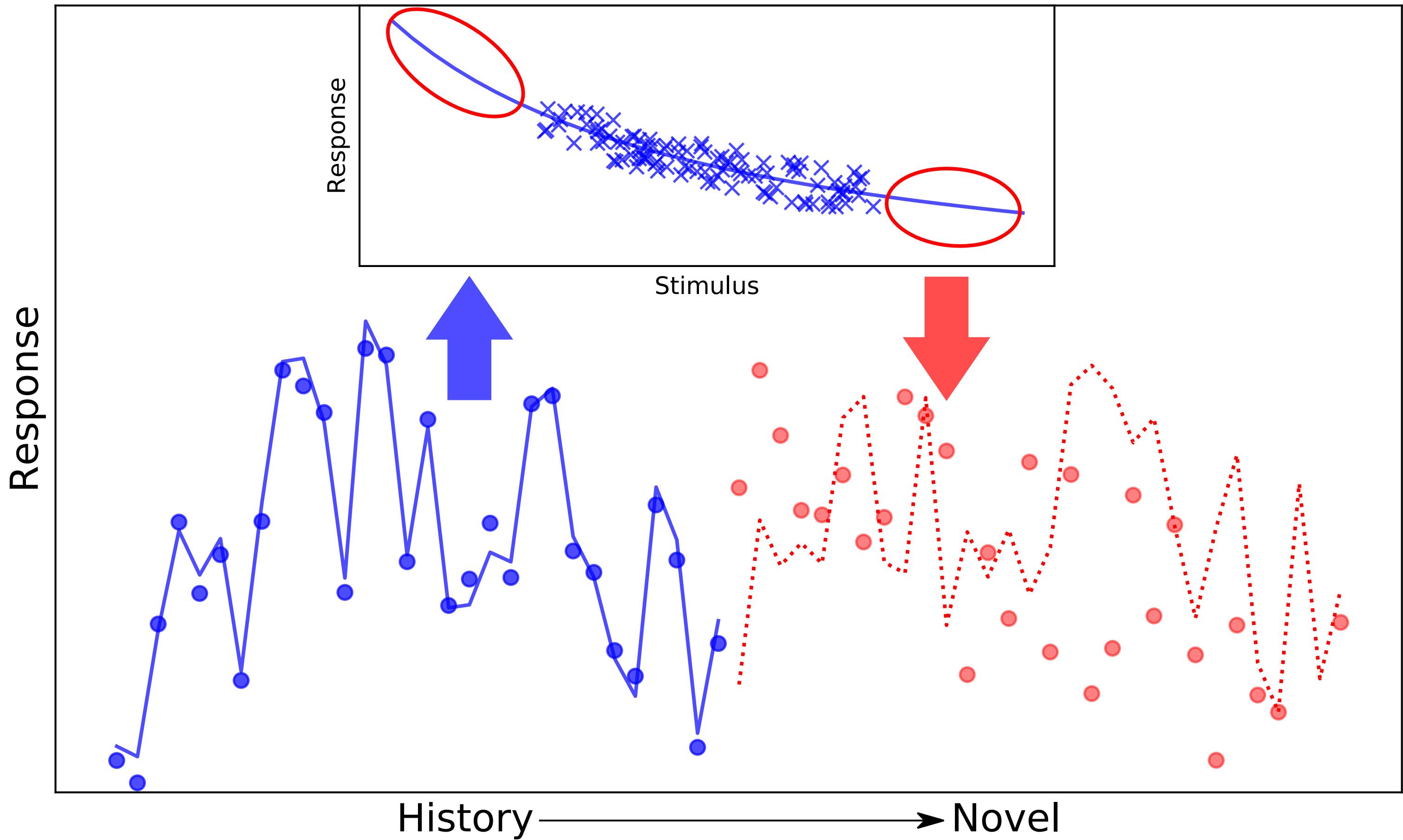


环境因素

- 大气CO₂浓度
- 空气湿度
- 空气温度
- 光照条件
- 风速
- 土壤湿度
- ...

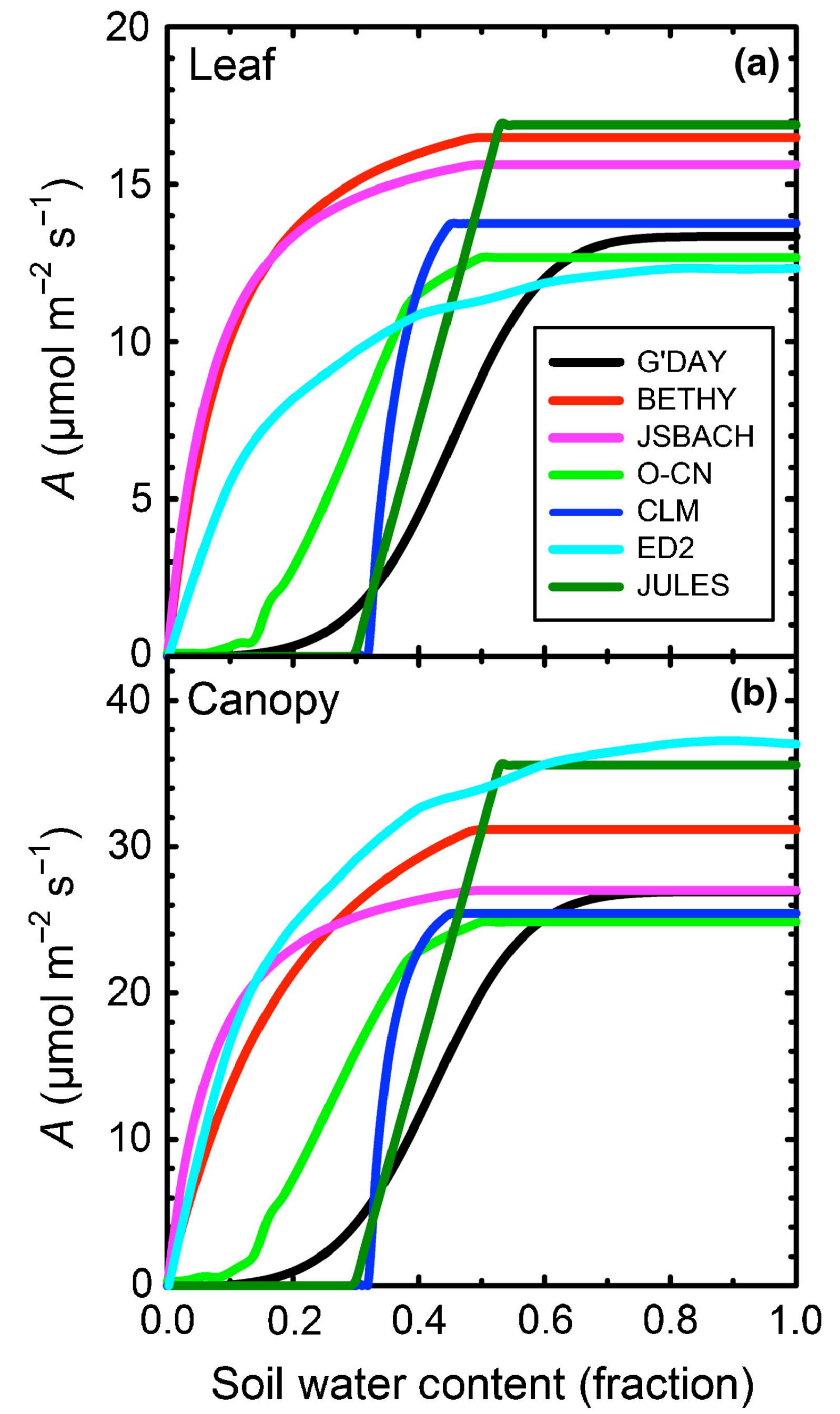


传统的经验模型运行效率高，但不能很好地预测植物对新环境的响应。



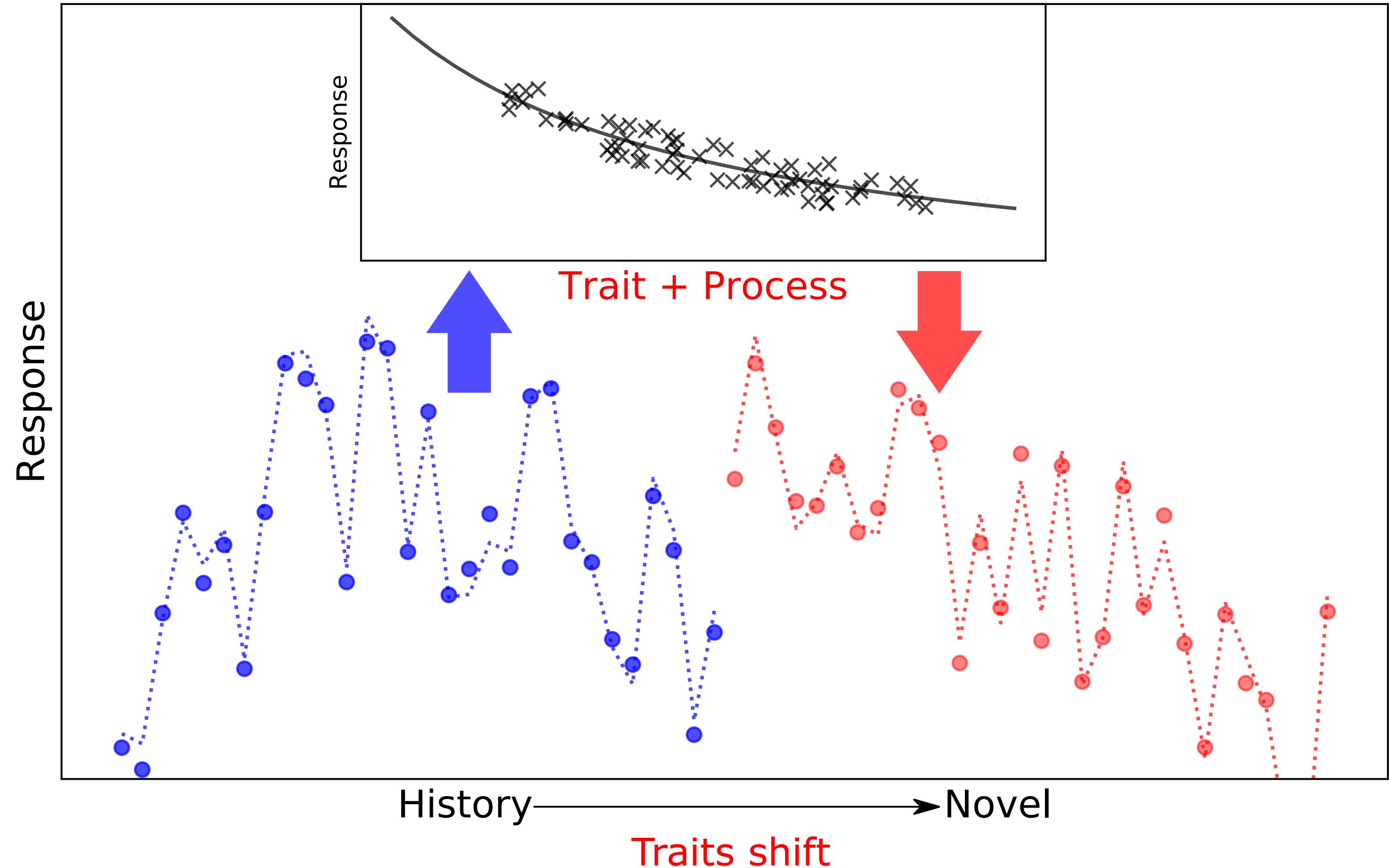


传统的经验模型运行效率高，但不能很好地预测植物对新环境的响应。





机理模型运行速度更慢，
但能够更好地表征植物在
新环境下的响应。生理与
性状的使用更使得模型能
够模拟植物对环境的适
应。



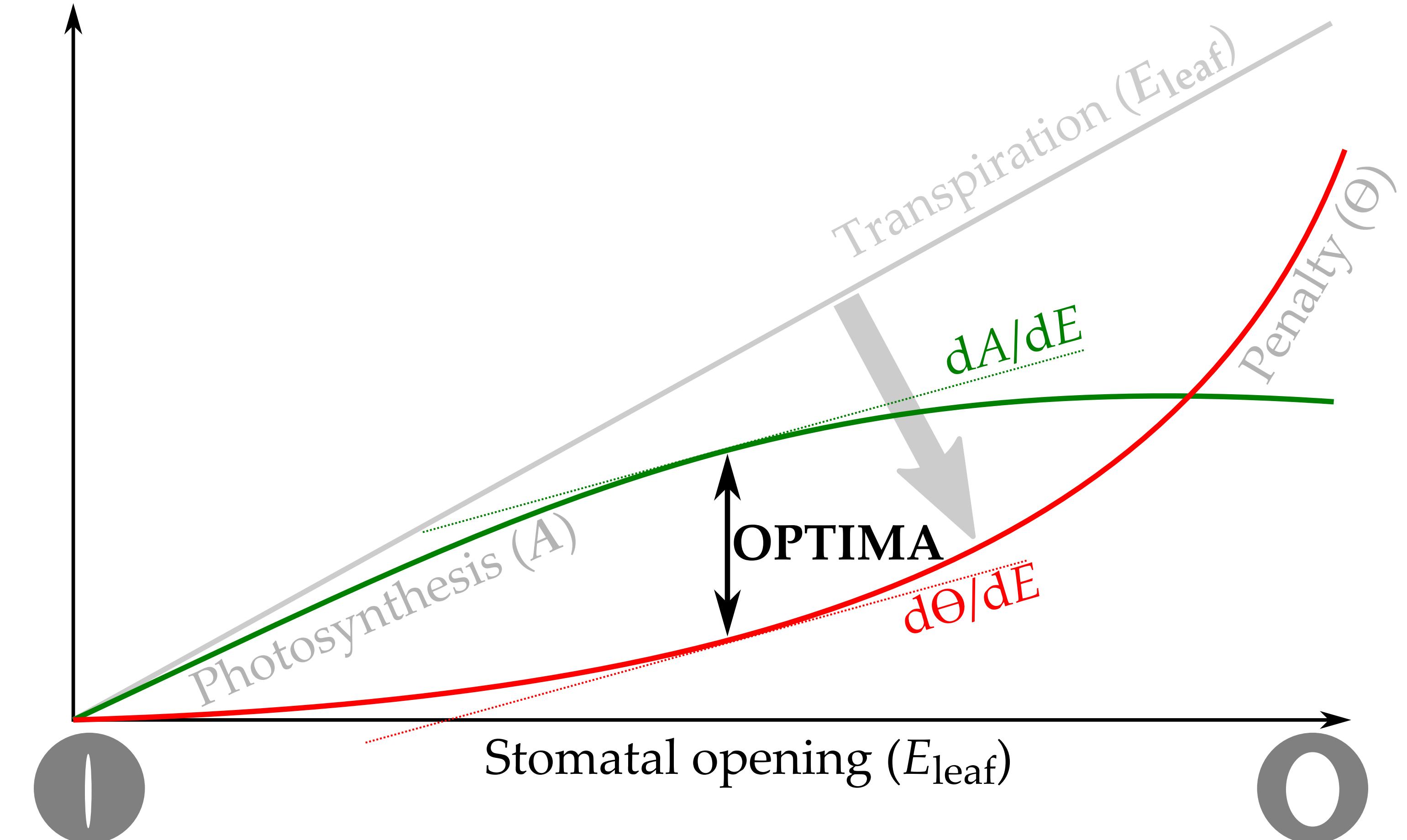


最优化理论

生物会进化出为了适应环境的行为模式。

我们需要去找：

- 收益
- 损耗

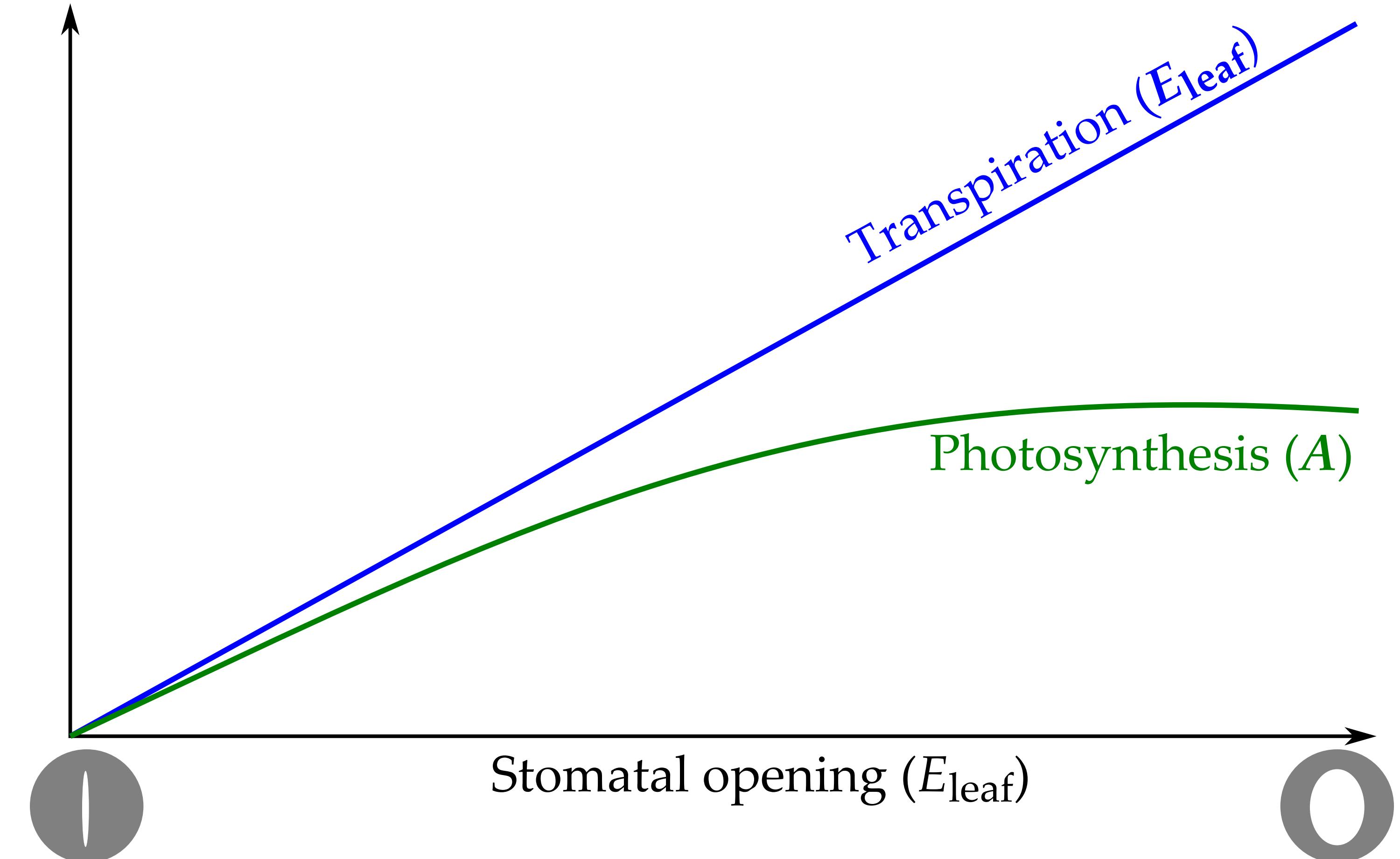




最优化理论

最大化收益与损
耗之间的差异

收益: $A(E_{leaf})$

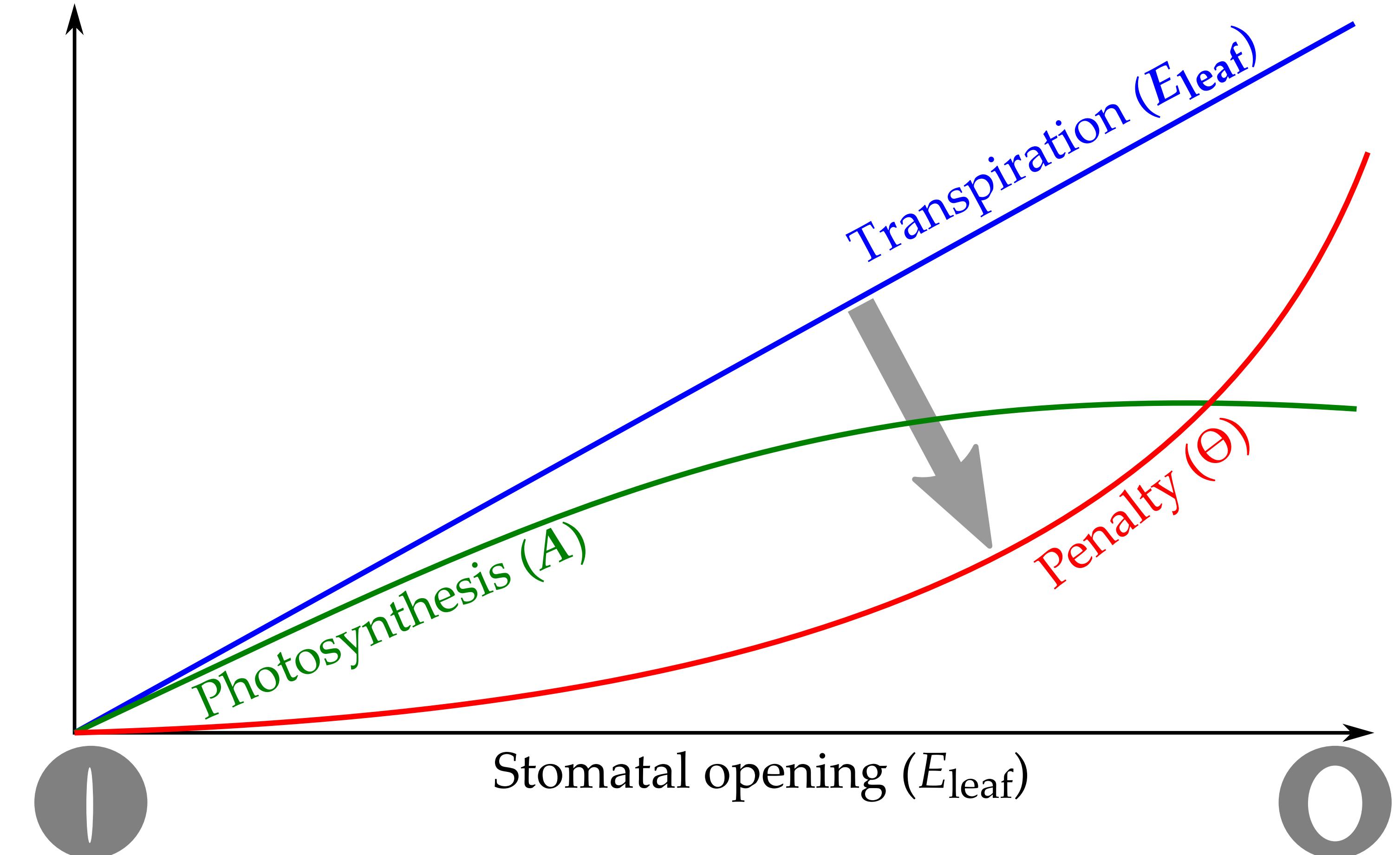




最优化理论

最大化收益与损
耗之间的差异

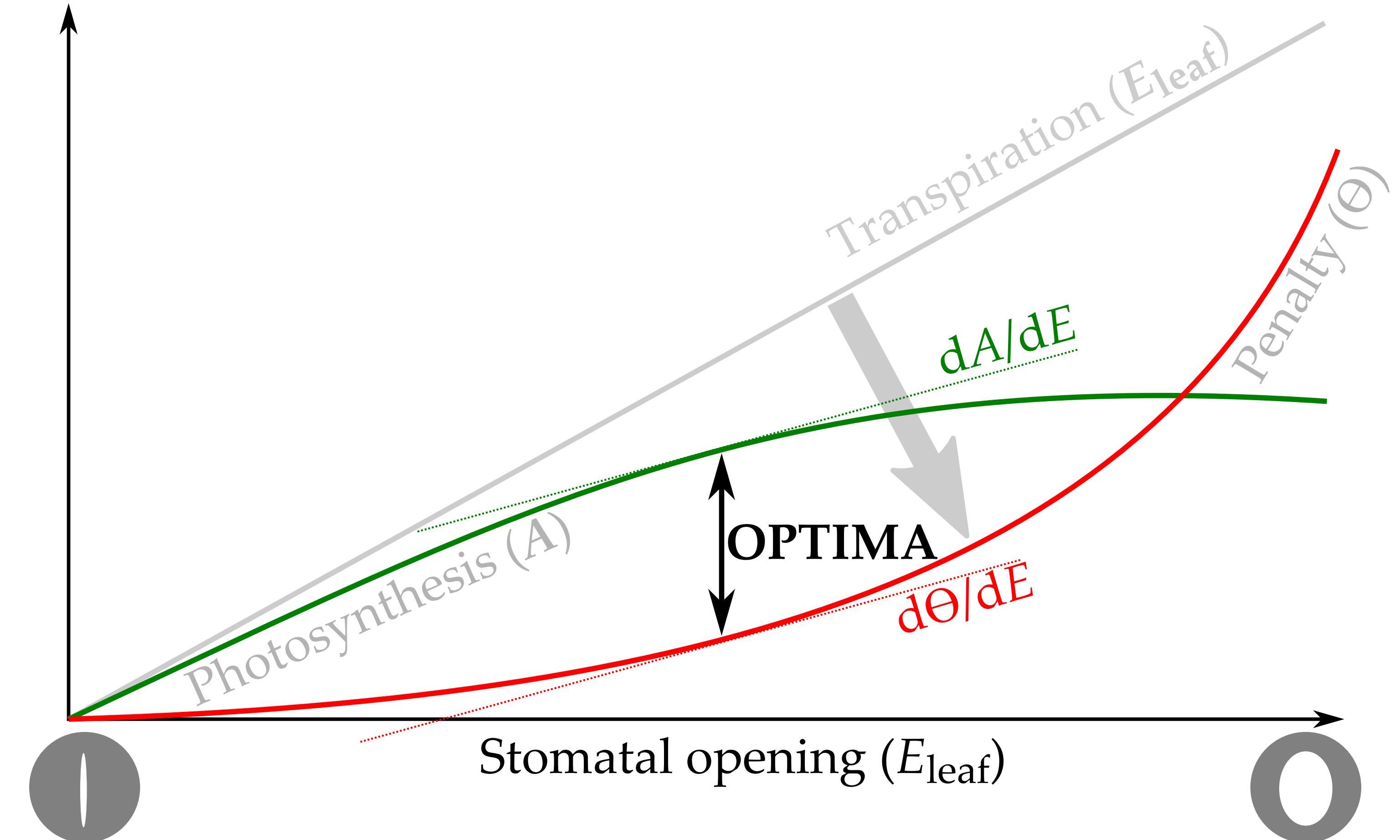
损耗: $\Theta(E_{leaf})$

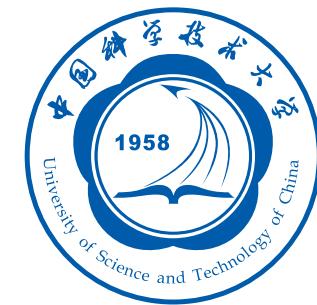




最优化理论
满足以下条件

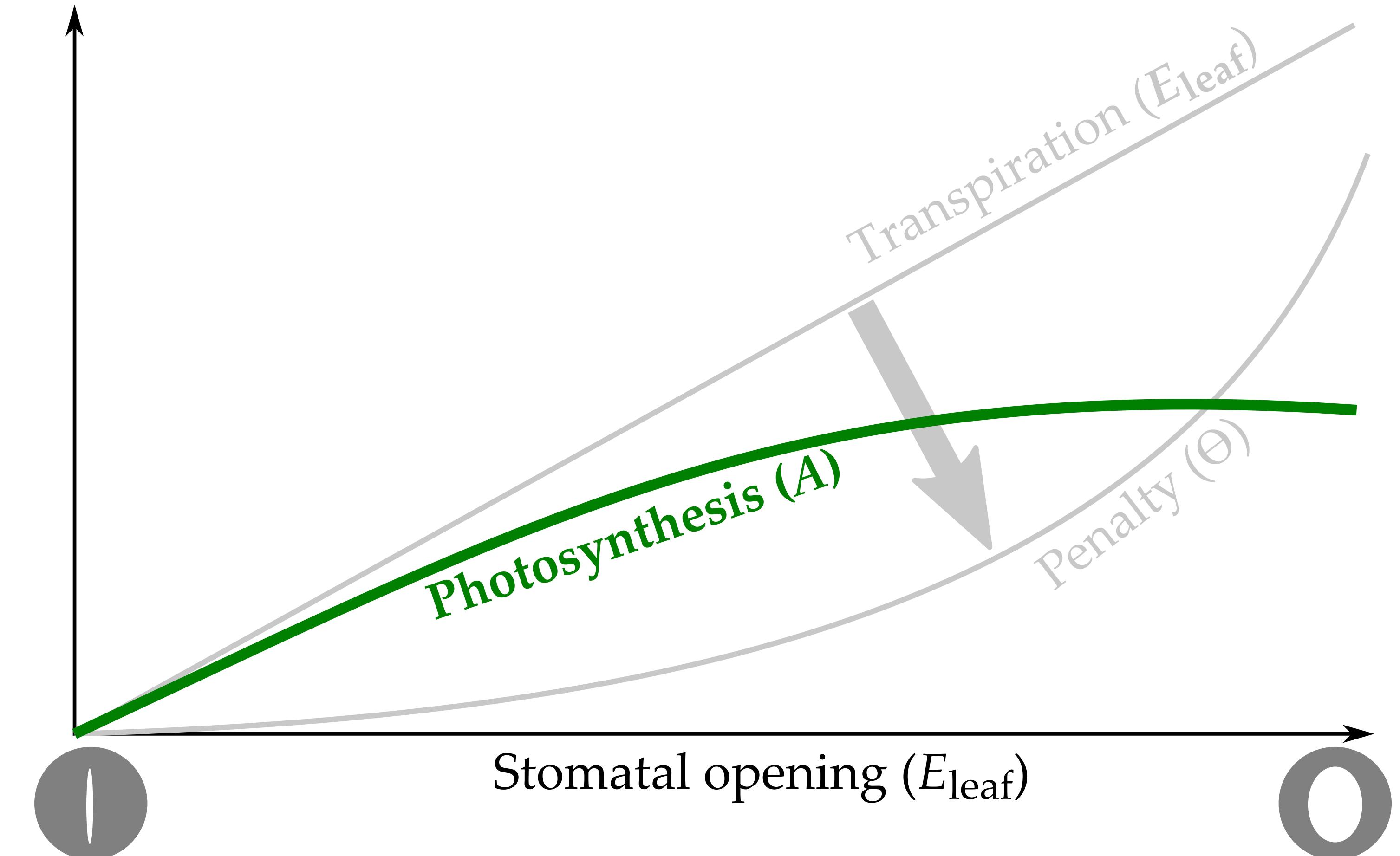
$$\frac{dA}{dE_{leaf}} = \frac{d\Theta}{dE_{leaf}}$$

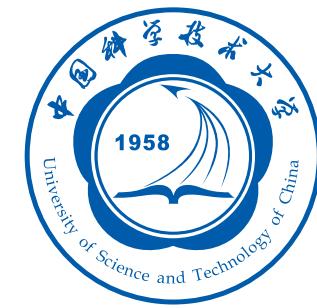




收益方程

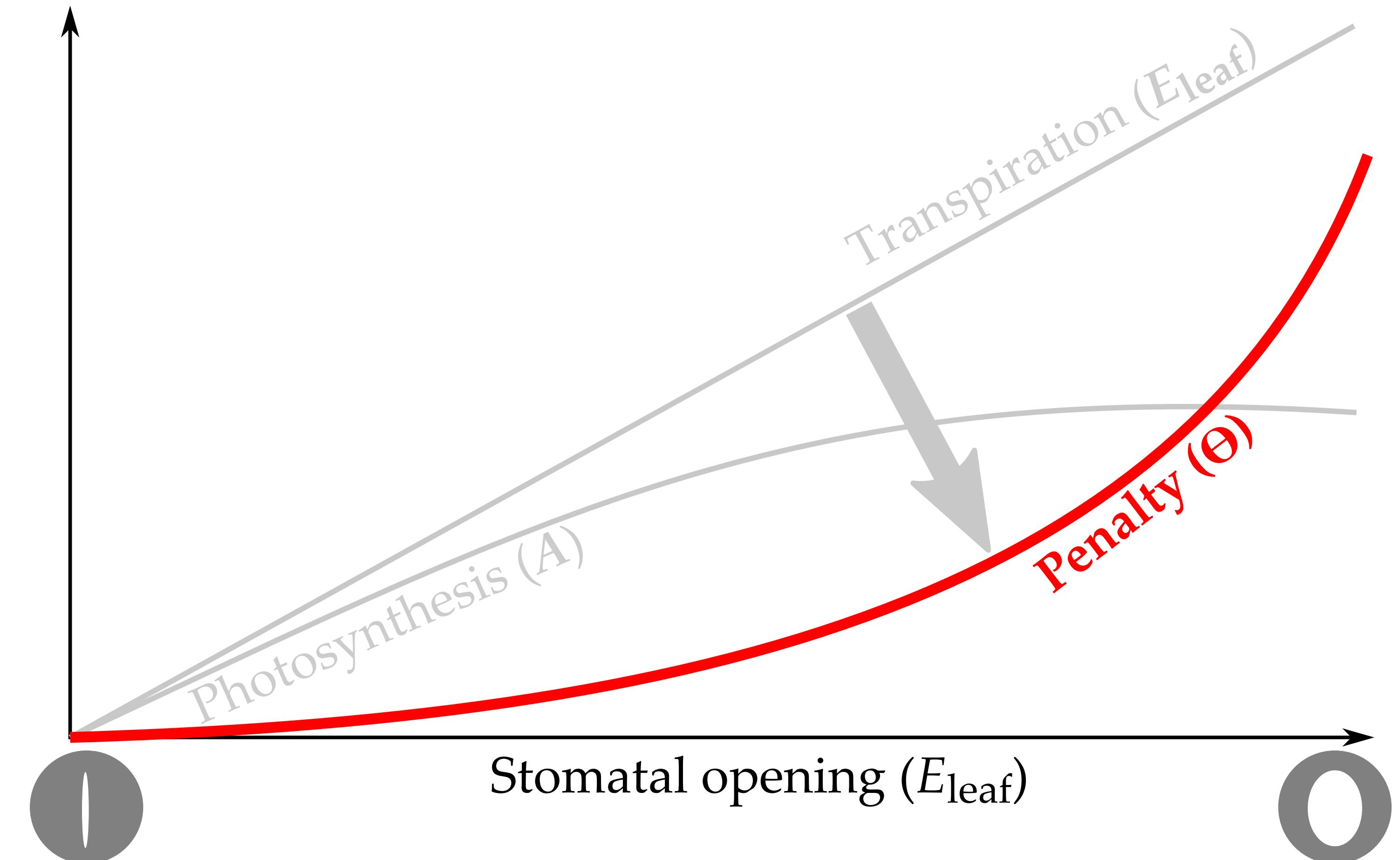
瞬时的光合作用

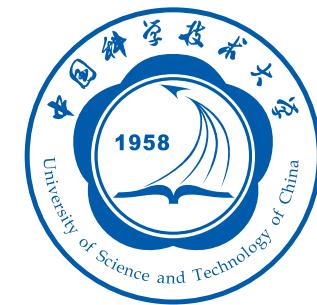




损耗方程

？？？



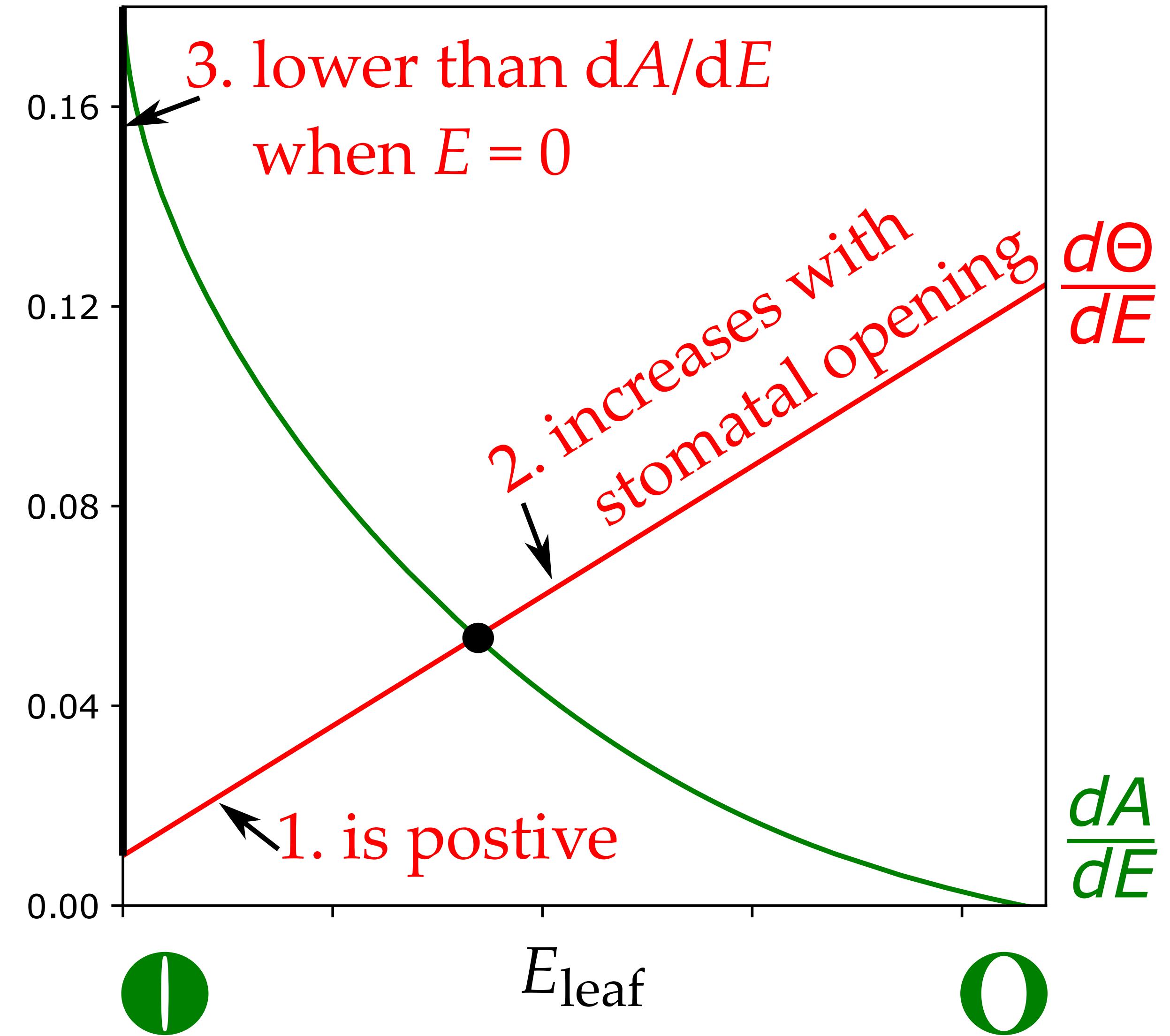


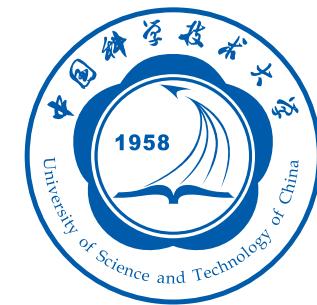
Criteria

1. Positive

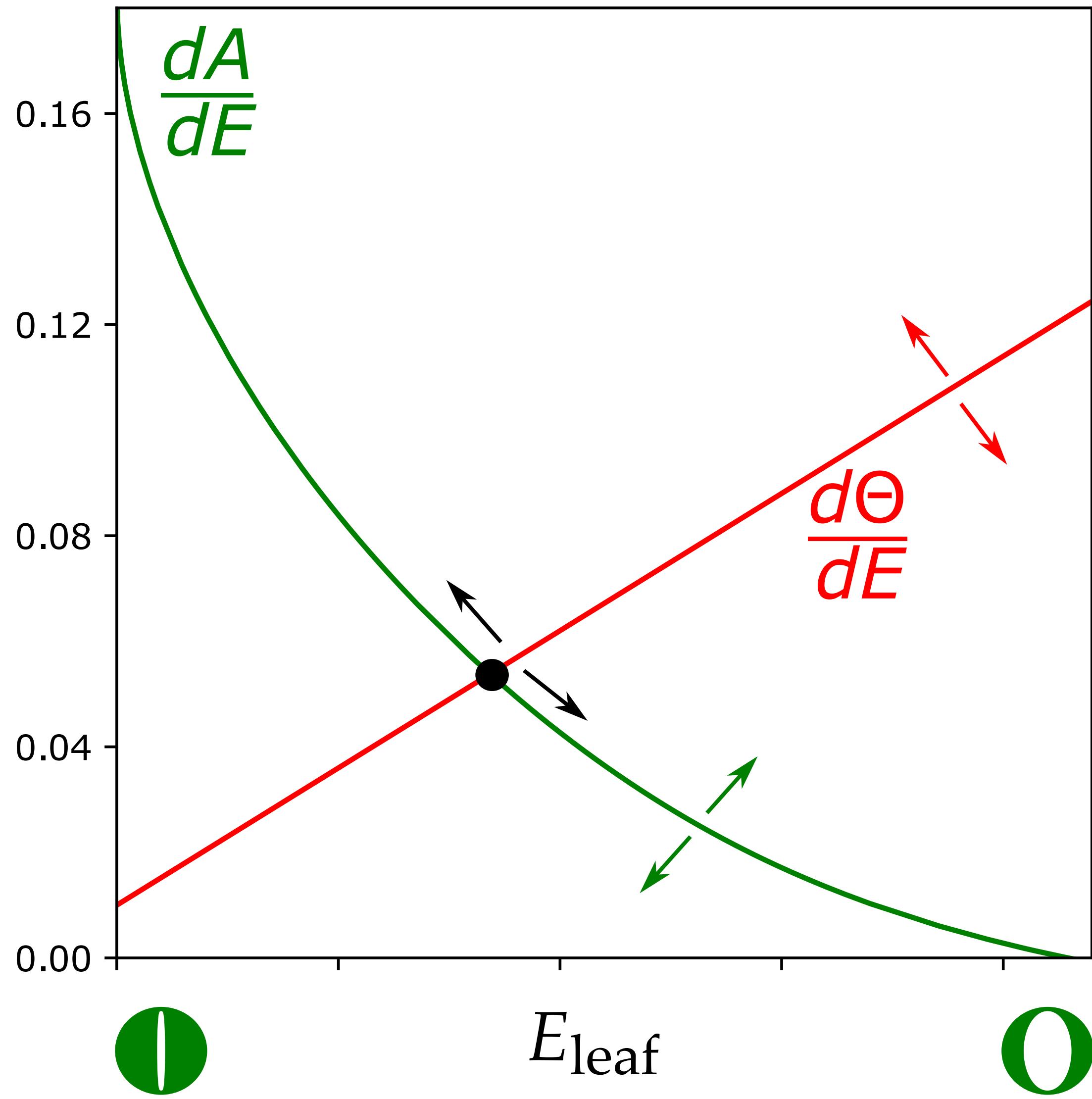
2. Increase with E

3. Lower than gain
when $E = 0$





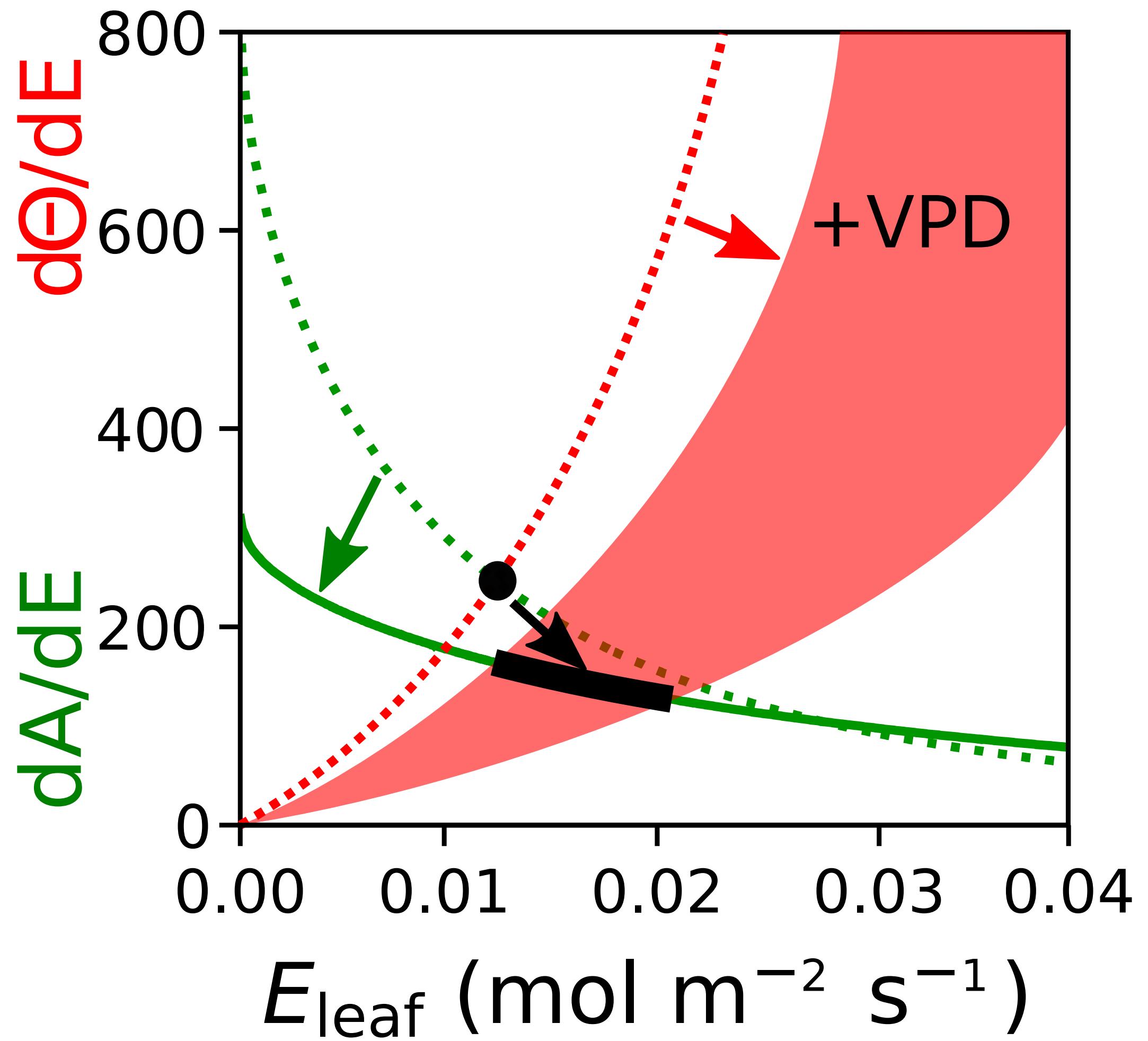
Criteria

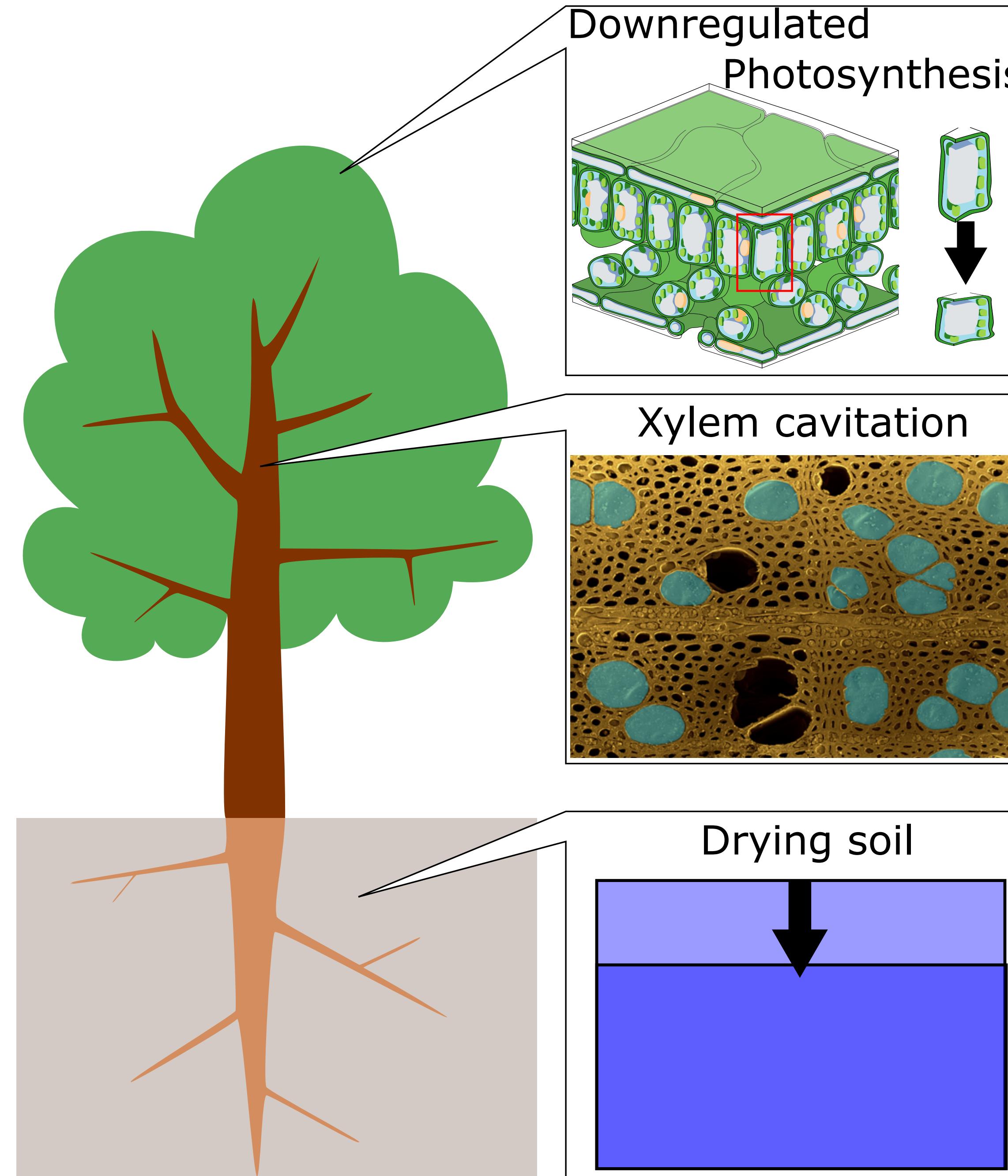




Criteria

4. Decrease with VPD
5. Increase with CO₂
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)

... ...



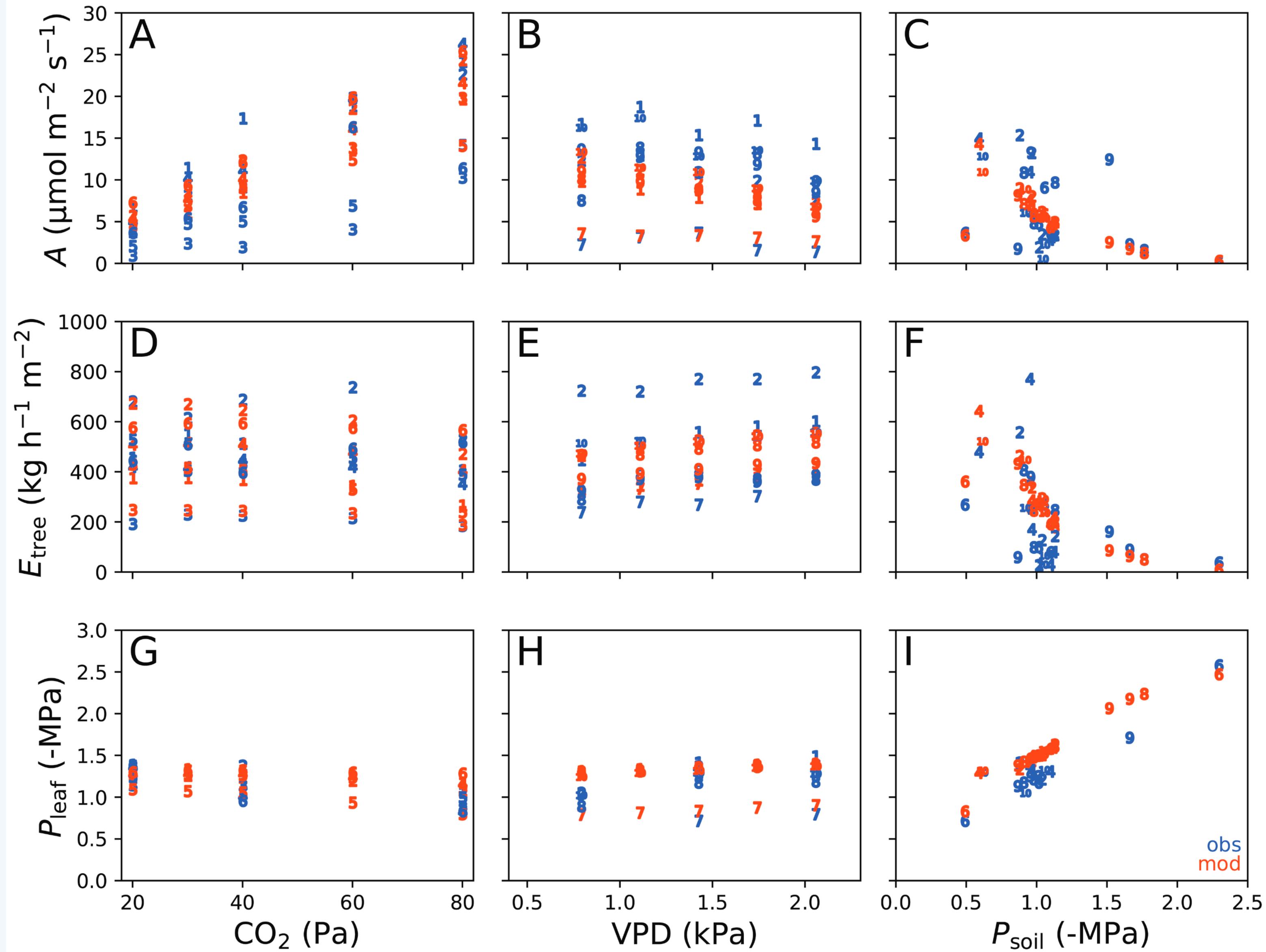
| Model | Reference | Water Penalty (Θ or Θ') | Marginal Penalty ($d\Theta/dE$ or $d\Theta'/dE$) | Response Criteria | |
|----------------|--|---|--|-------------------|----------------|
| | | | | I–III | IV–VII DCPK |
| Cowan-Farquhar | (Cowan and Farquhar, 1977) | $\Theta = \frac{E_{leaf}}{\lambda}$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



测试数据1

生长室实验

- 大气CO₂
- 空气湿度
- 土壤湿度

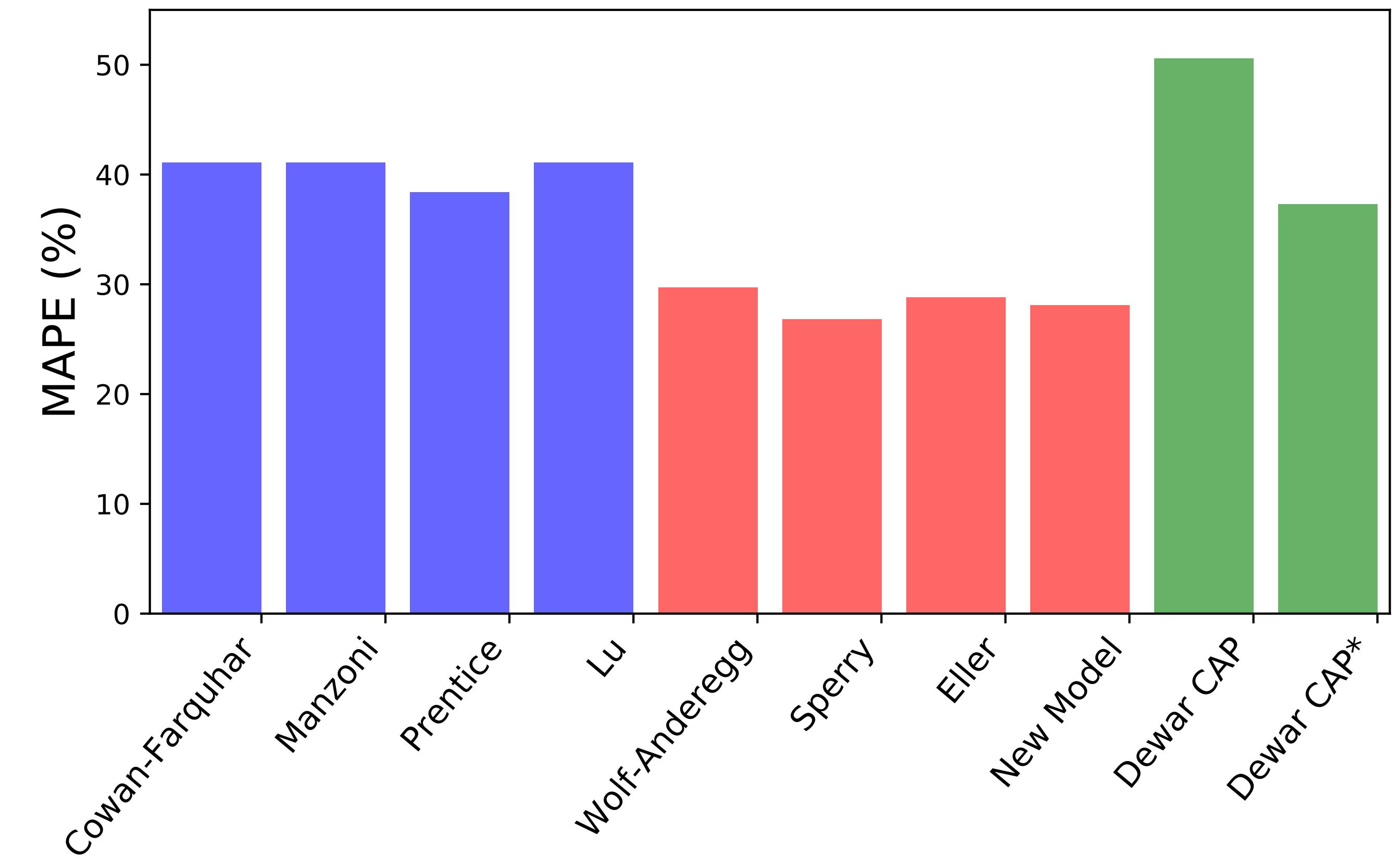




测试数据1

生长室实验

- 大气CO₂
- 空气湿度
- 土壤湿度

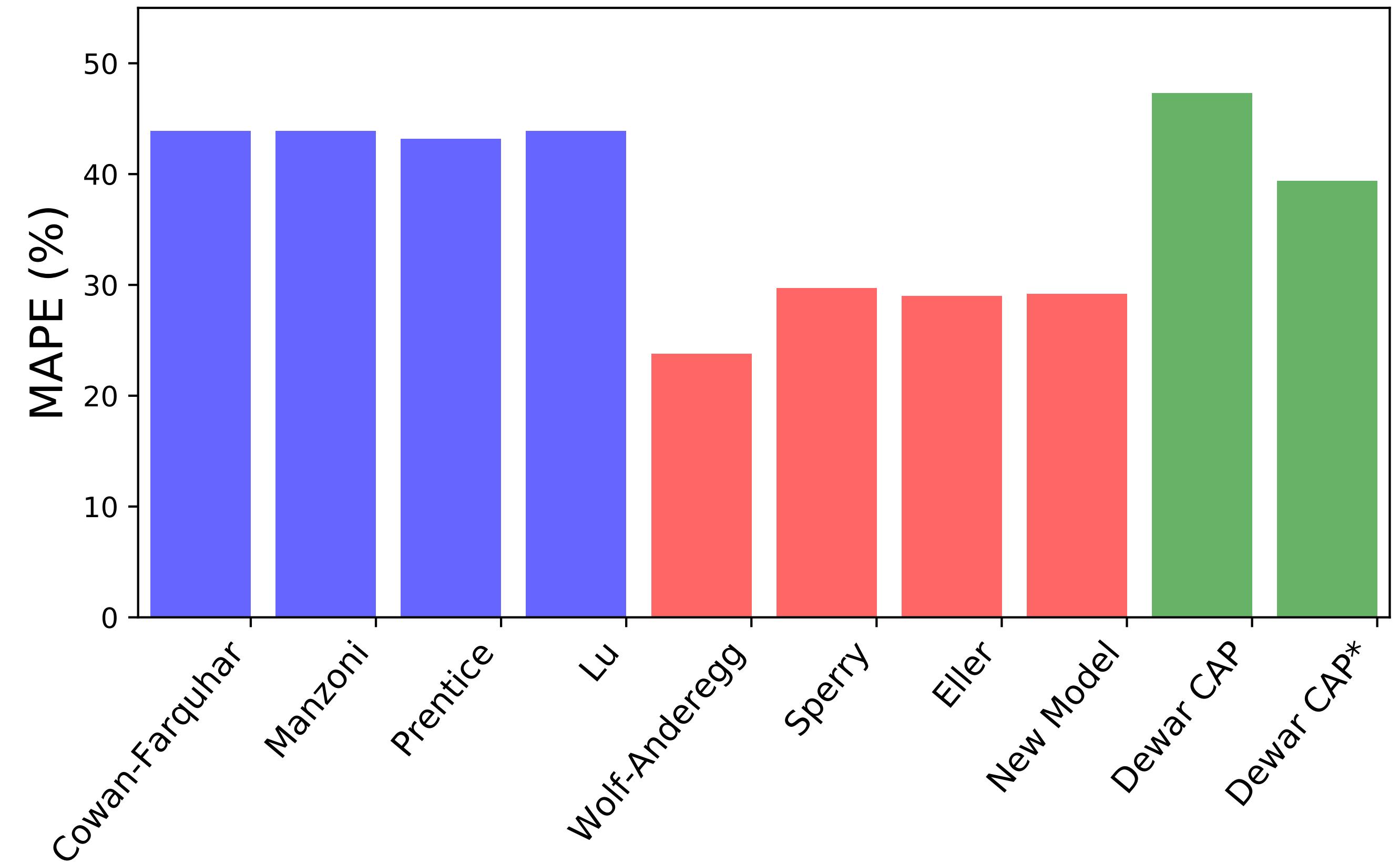




测试数据2

人工站点

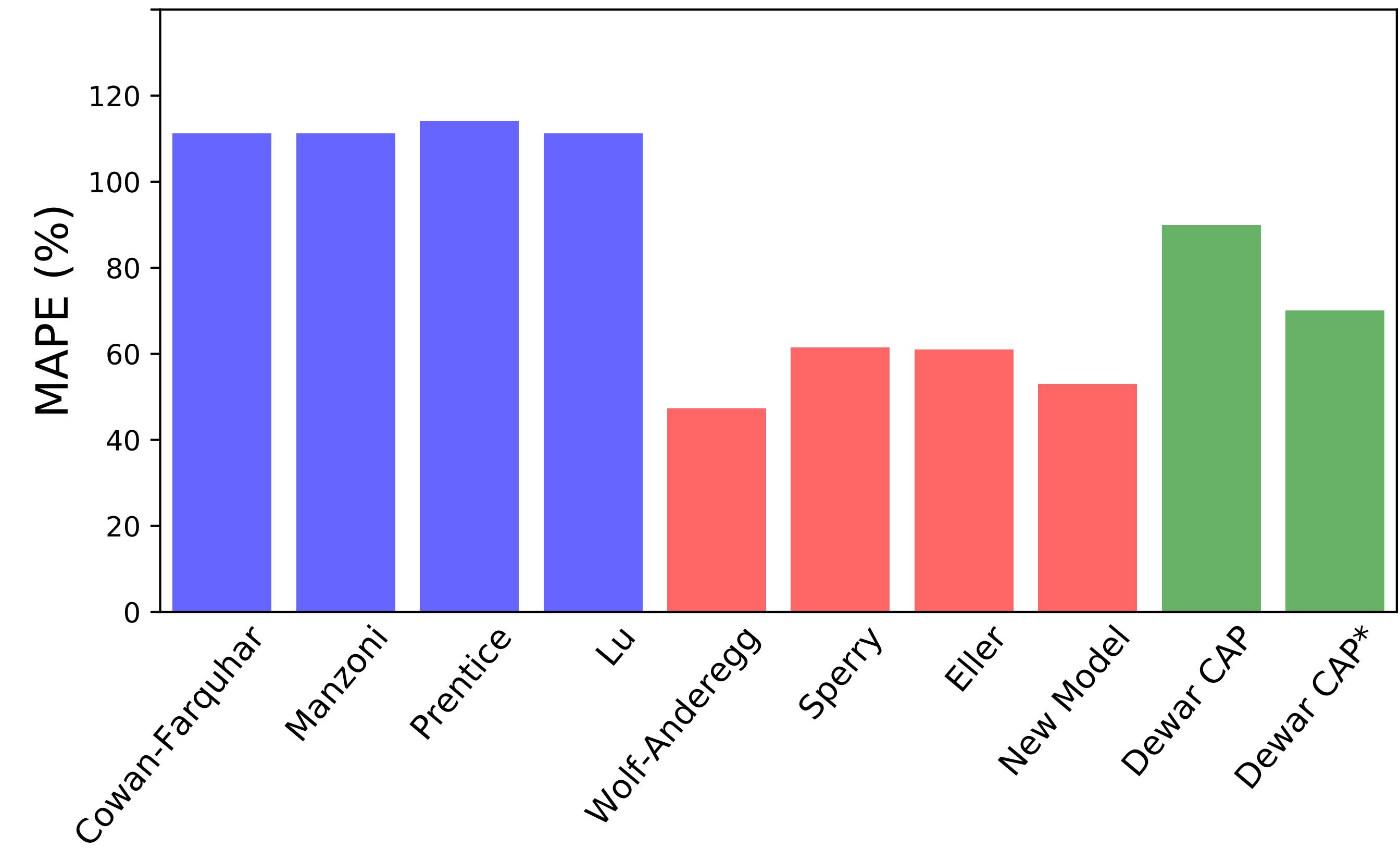
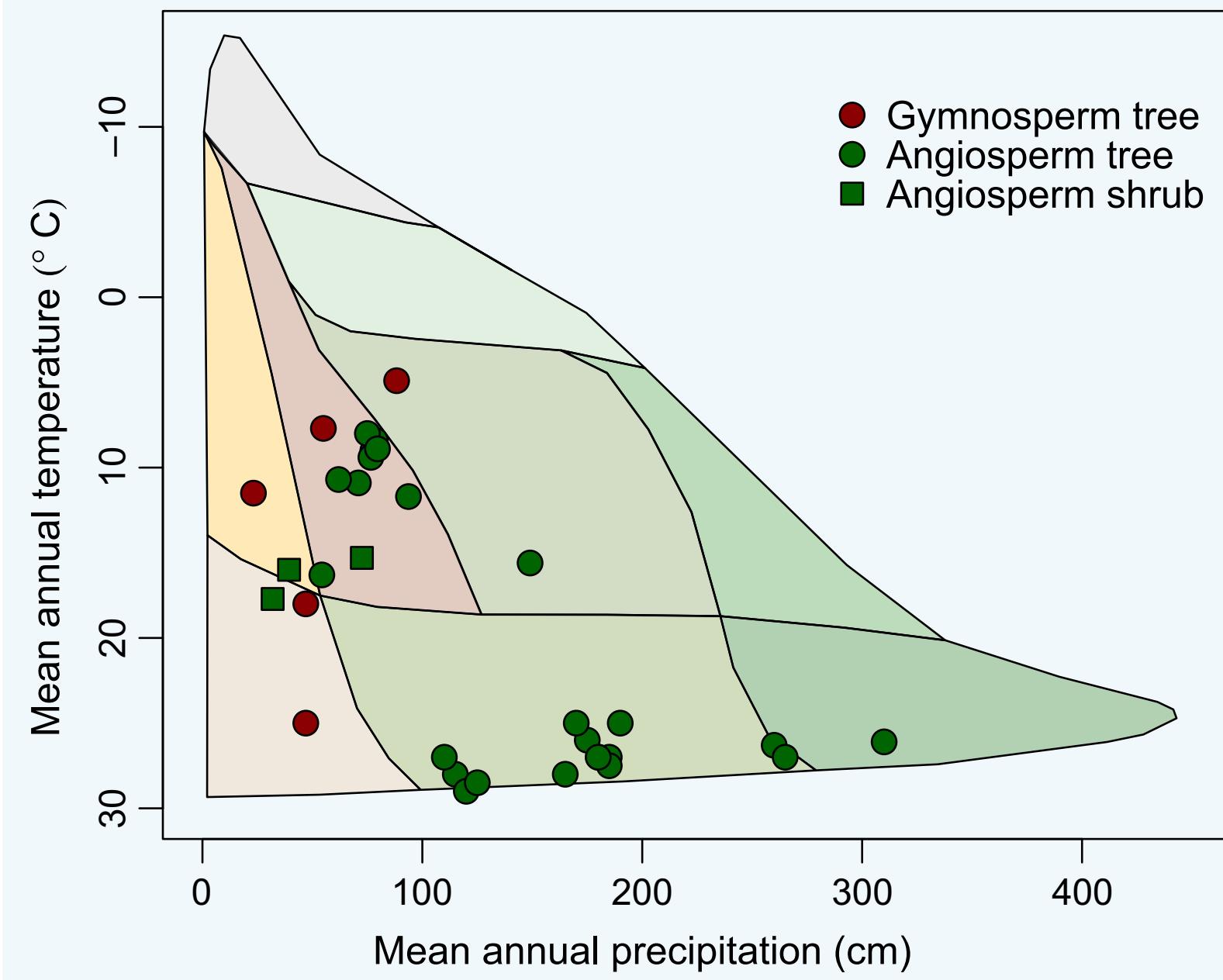
- 土壤湿度
- 空气湿度*



测试数据3

野外站点

- 土壤湿度*
- 空气湿度*





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

基于植物生理过程的夜间气孔导度的模型



1. 模式开发

改进土壤-植物-
大气连续体模
型，加入更多的
生理机制

2. 模式设置

3. 参数矫正

植物会在夜间开放气孔吗？

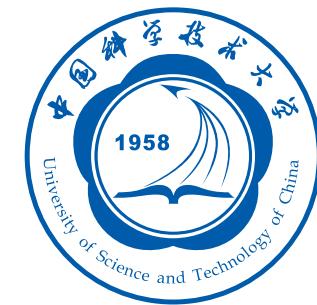
Yes?

- 气孔泄漏
- 营养运输
- 氧气吸收
- 竞争
- 蒸腾散热
- 昼夜循环
- ...

No?

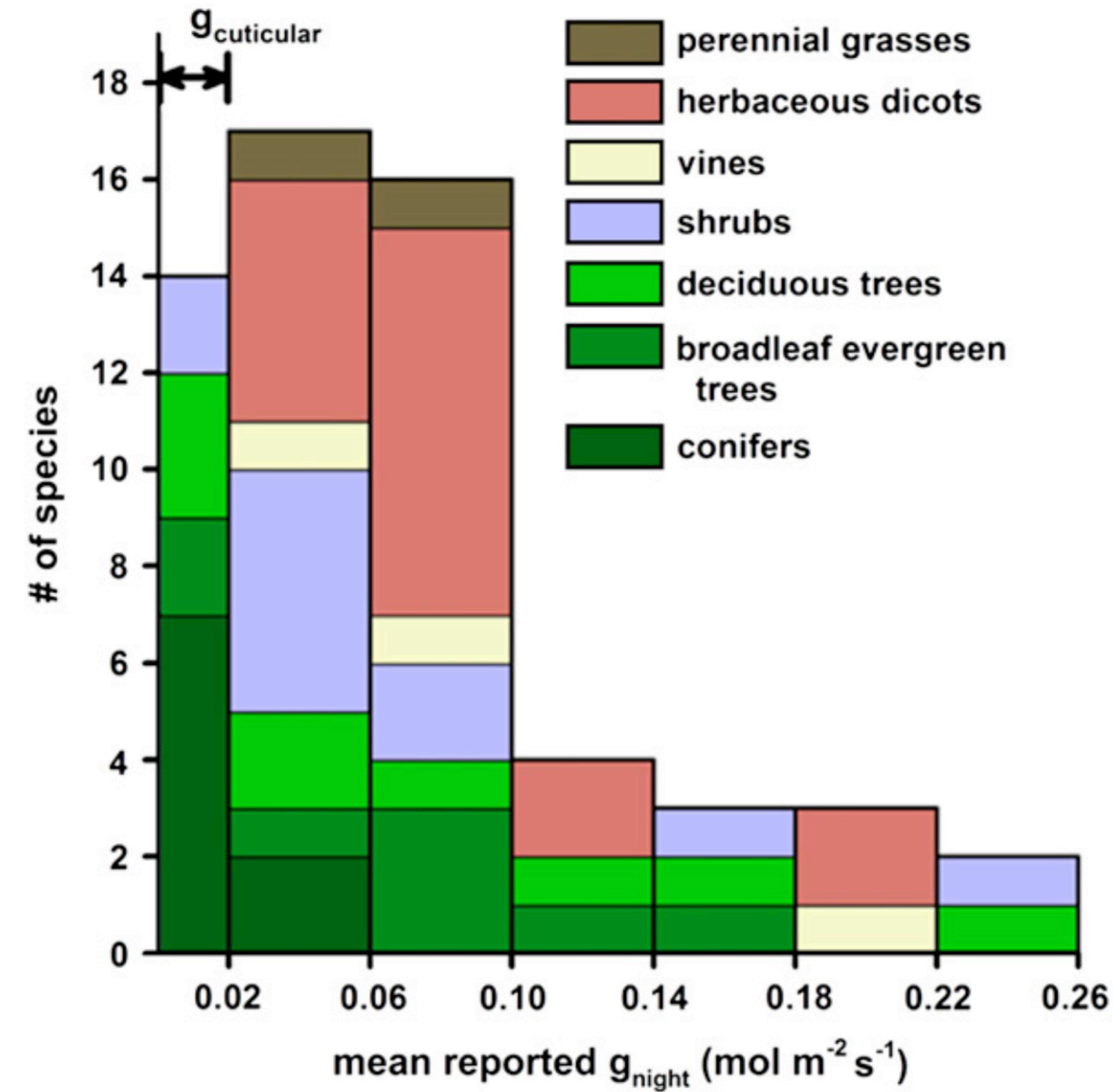
- 水可以在日间使用，促进光合作用
- 维持细胞膨压用来生长
- ...





夜间蒸腾

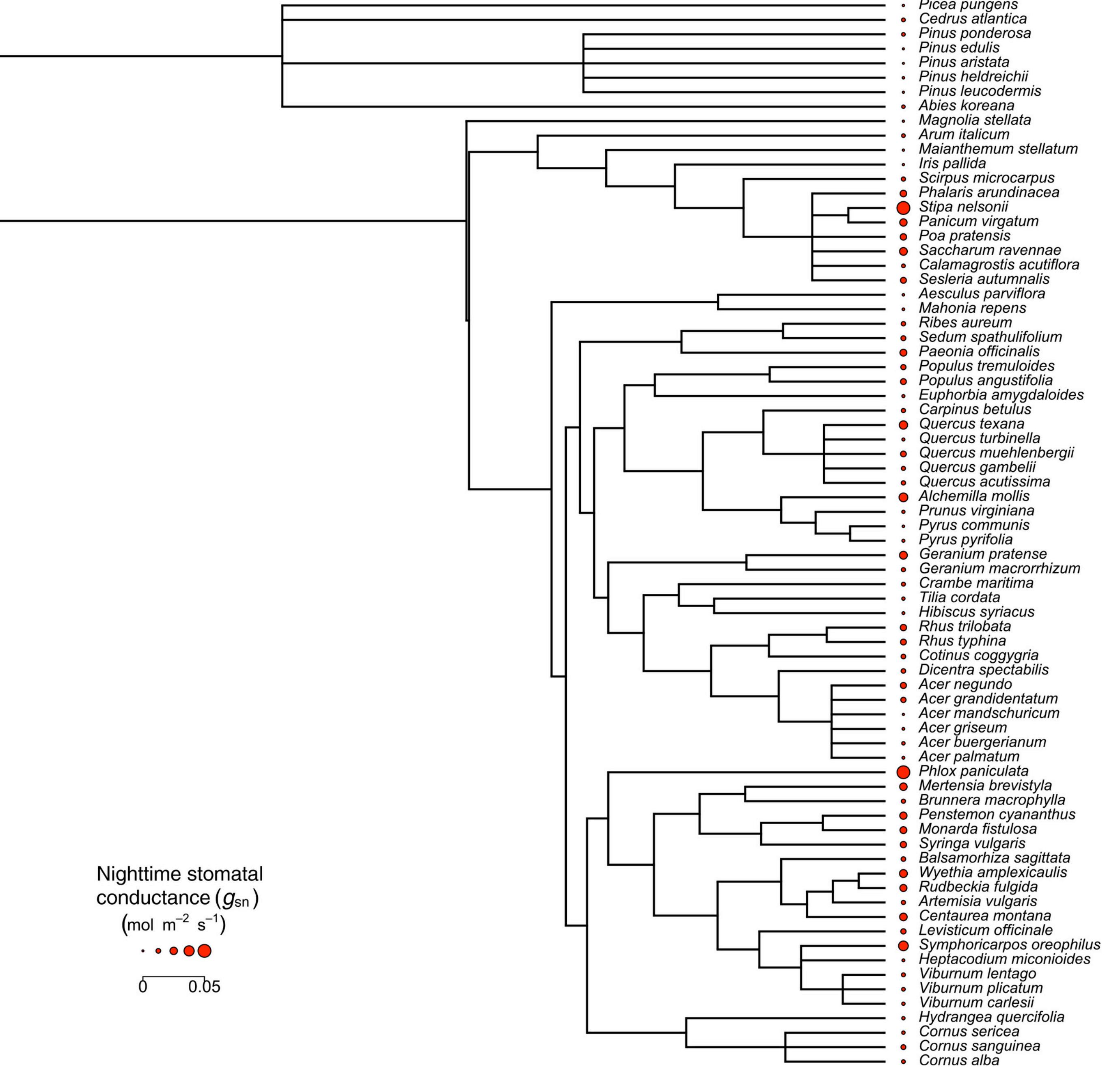
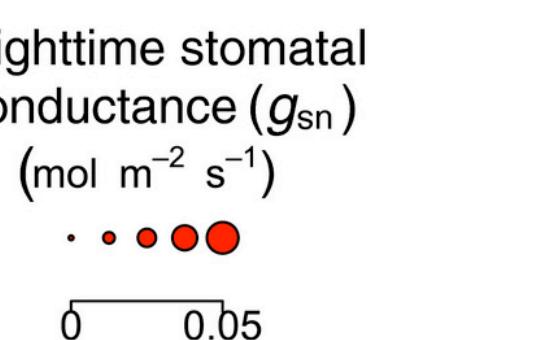
平均占比日间蒸
腾的10%到15%





夜间蒸腾

广泛存在于不同物种和植被类型之间



夜间蒸腾对生理与环境的响应：

主要原因?

- 气孔泄漏
- 营养运输
- 氧气吸收
- 竞争
- 蒸腾散热
- 昼夜循环
- ...



- 空气湿度
- 大气CO₂浓度
- 土壤湿度
- 叶片温度
- 叶片呼吸



最优化理论

最大化收益与损
耗之间的差异

收益

- 夜间可能的收益

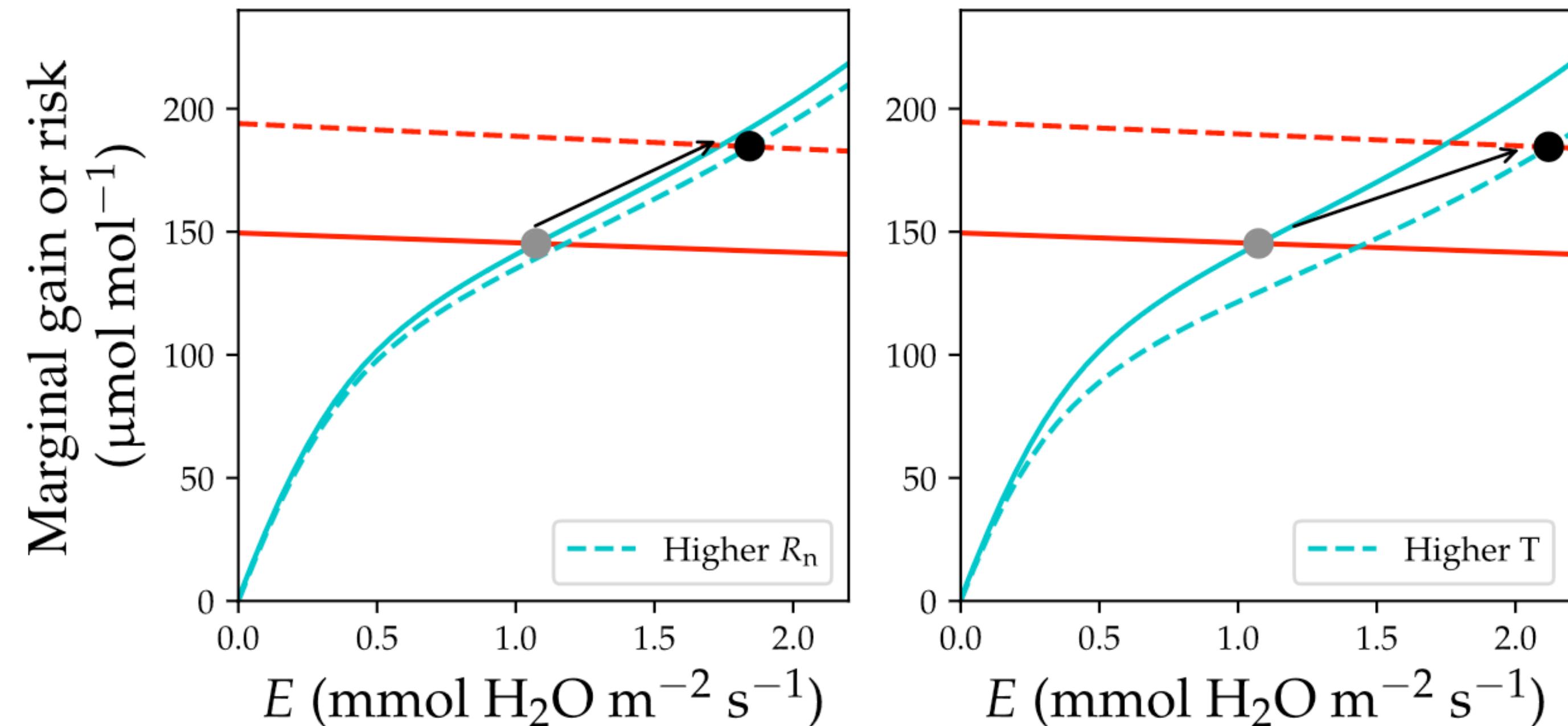
损耗

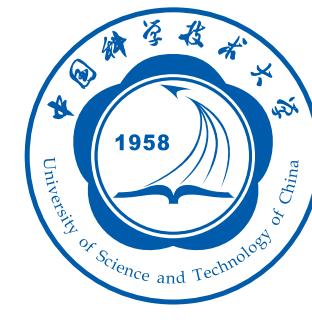
- 日间的光合作用

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

最优化理论

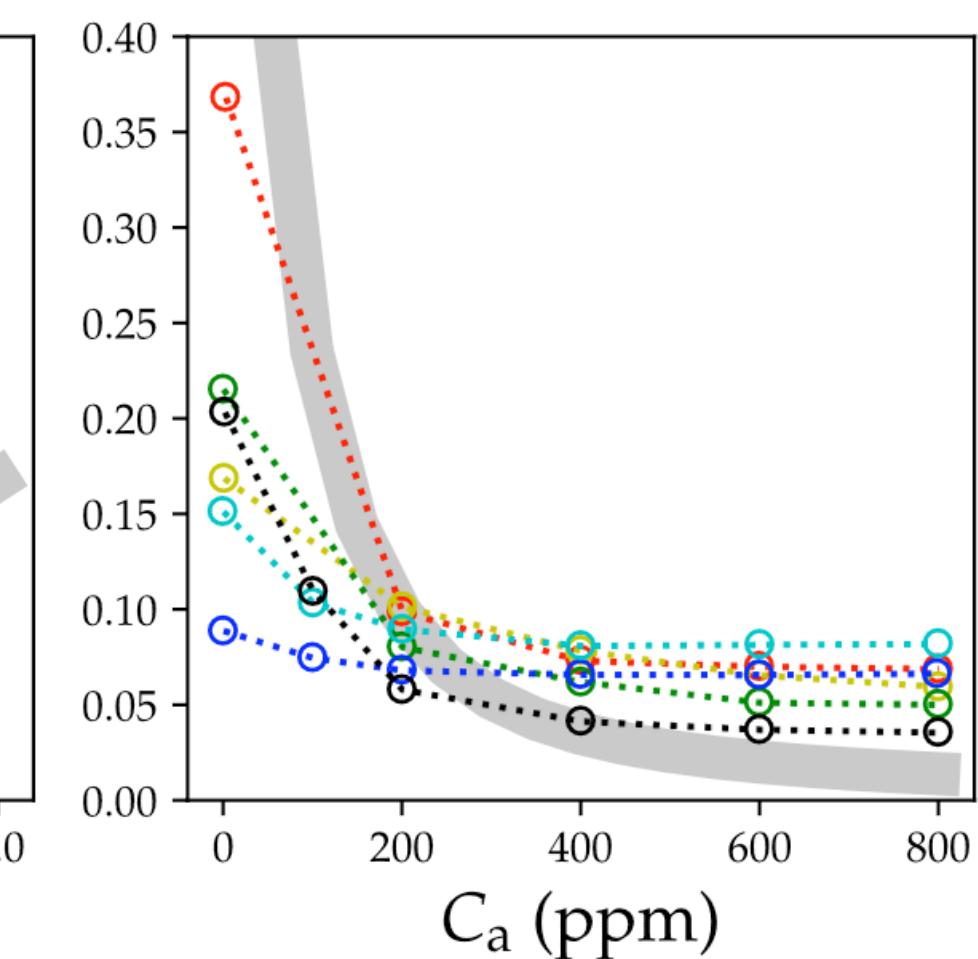
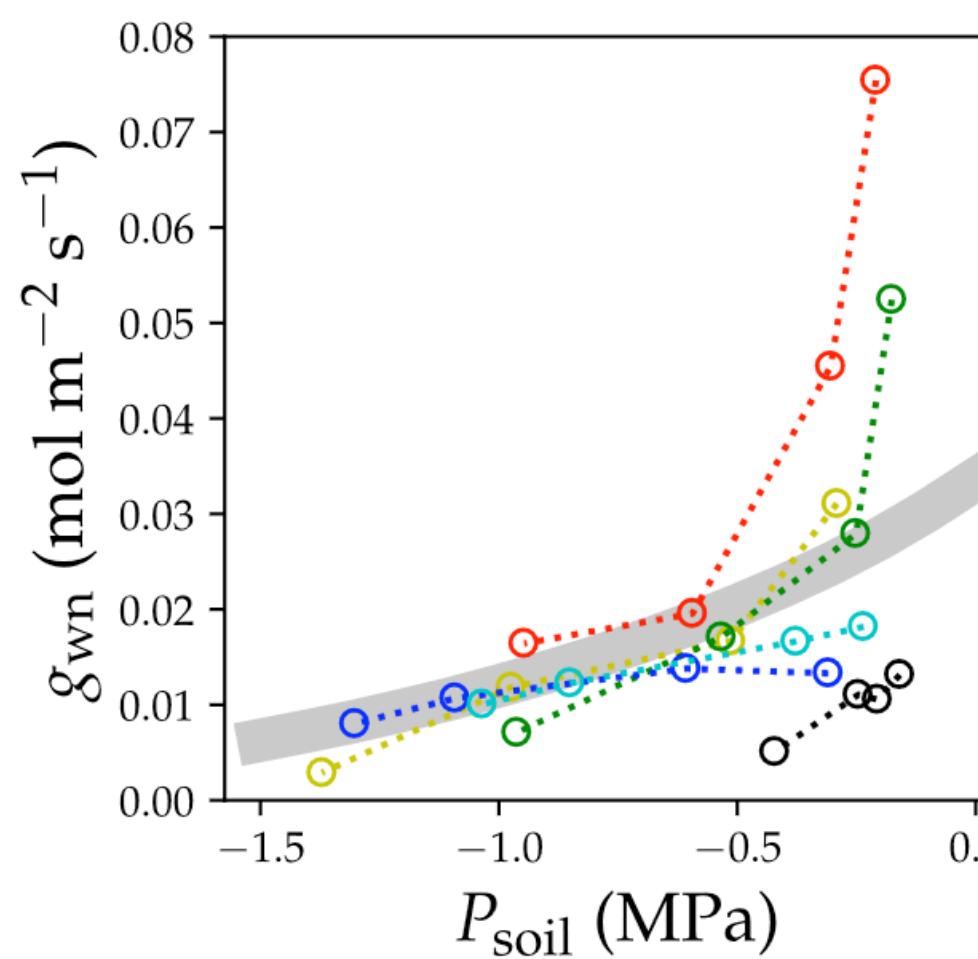
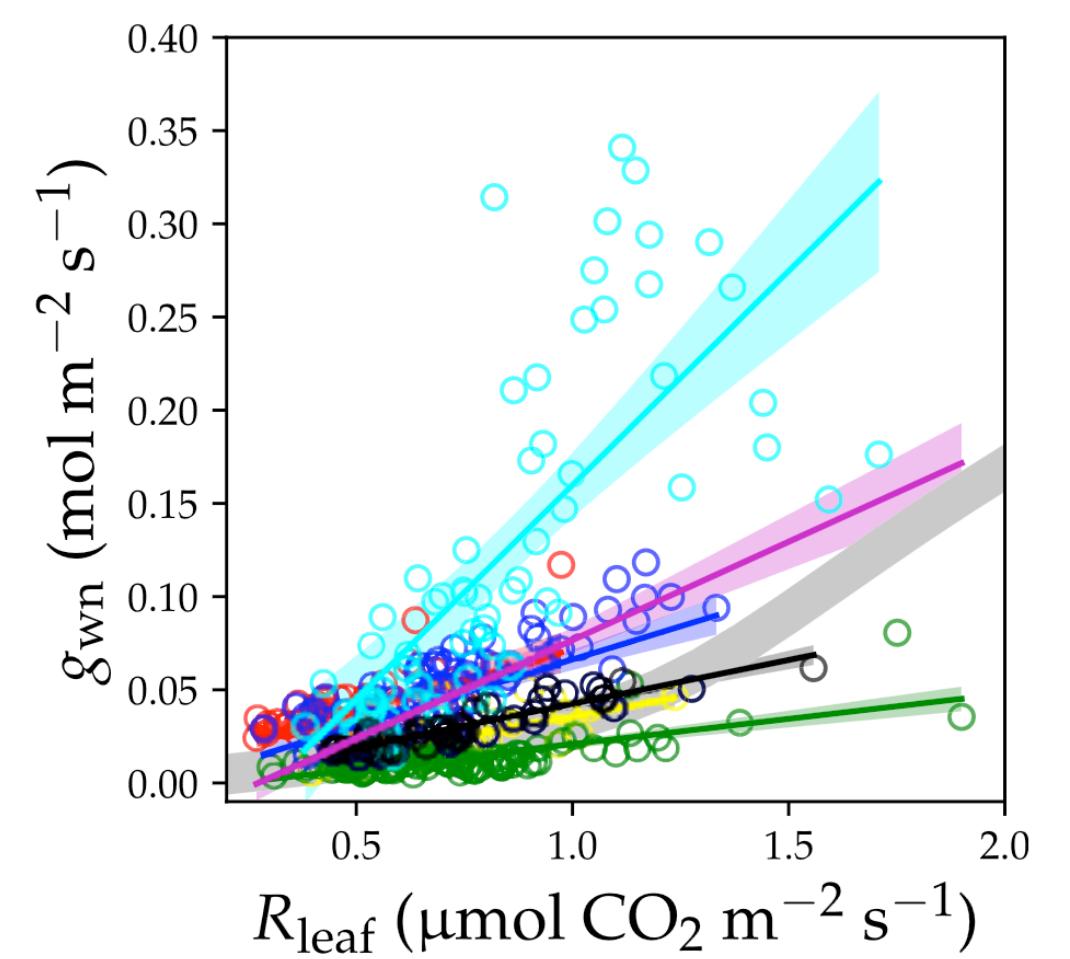
最大化收益与损
耗之间的差异

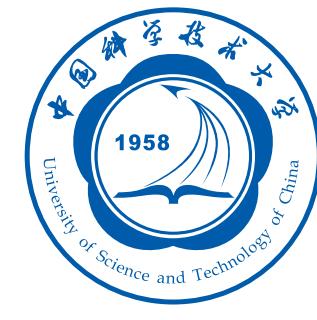




最优化理论

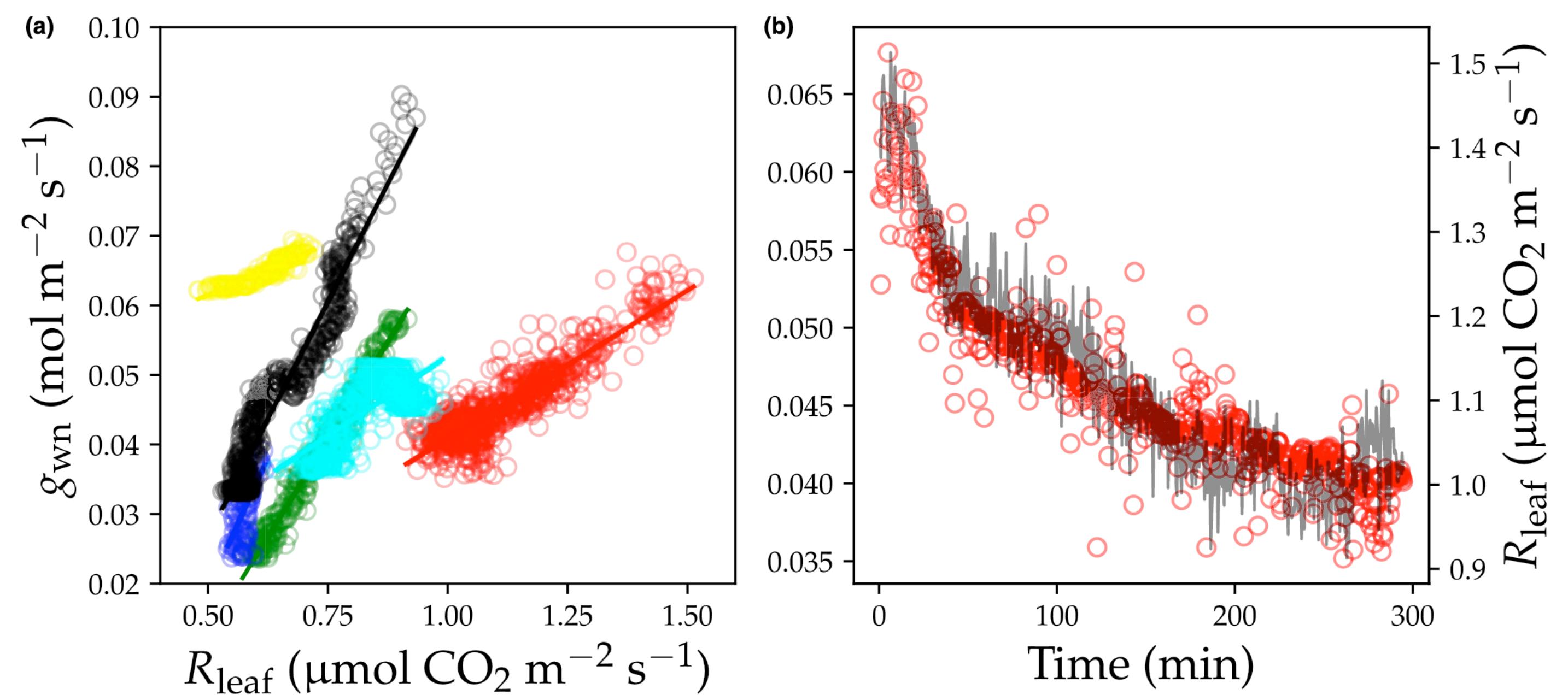
最大化收益与损
耗之间的差异





最优化理论

最大化收益与损
耗之间的差异



新一代高度模块化的陆面模式—CliMA Land

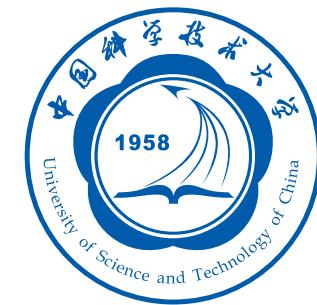


1. 模式开发

2. 模式设置

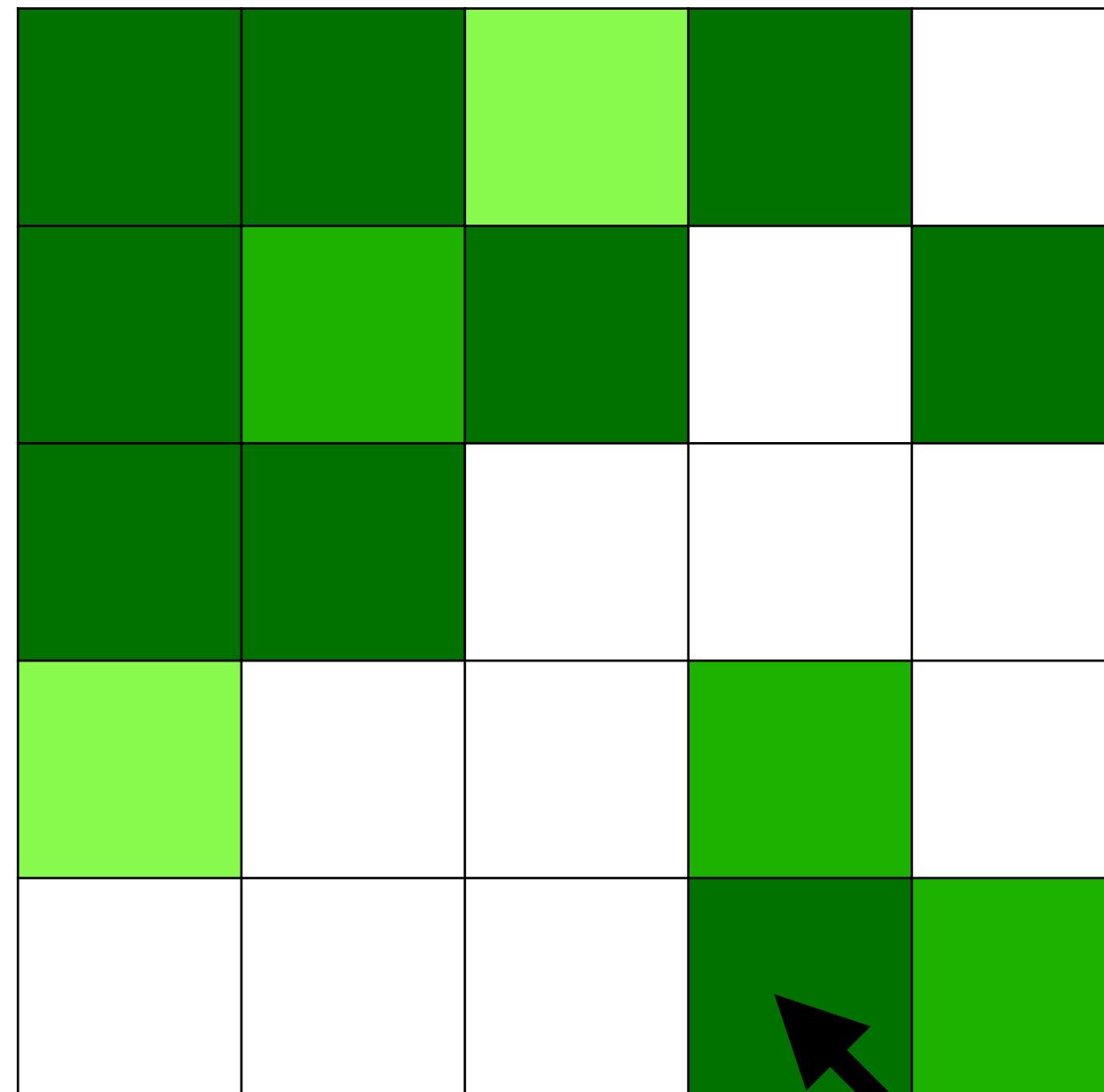
使用更合理的模式设置与组合，降低对经验模式的依赖

3. 参数矫正



利弊权衡

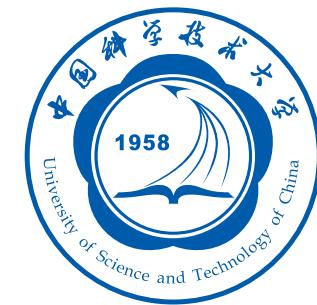
- 复杂度
- 精确度
- 可读性
- 开发速度
- 运行速度
- 学习框架



最小元素

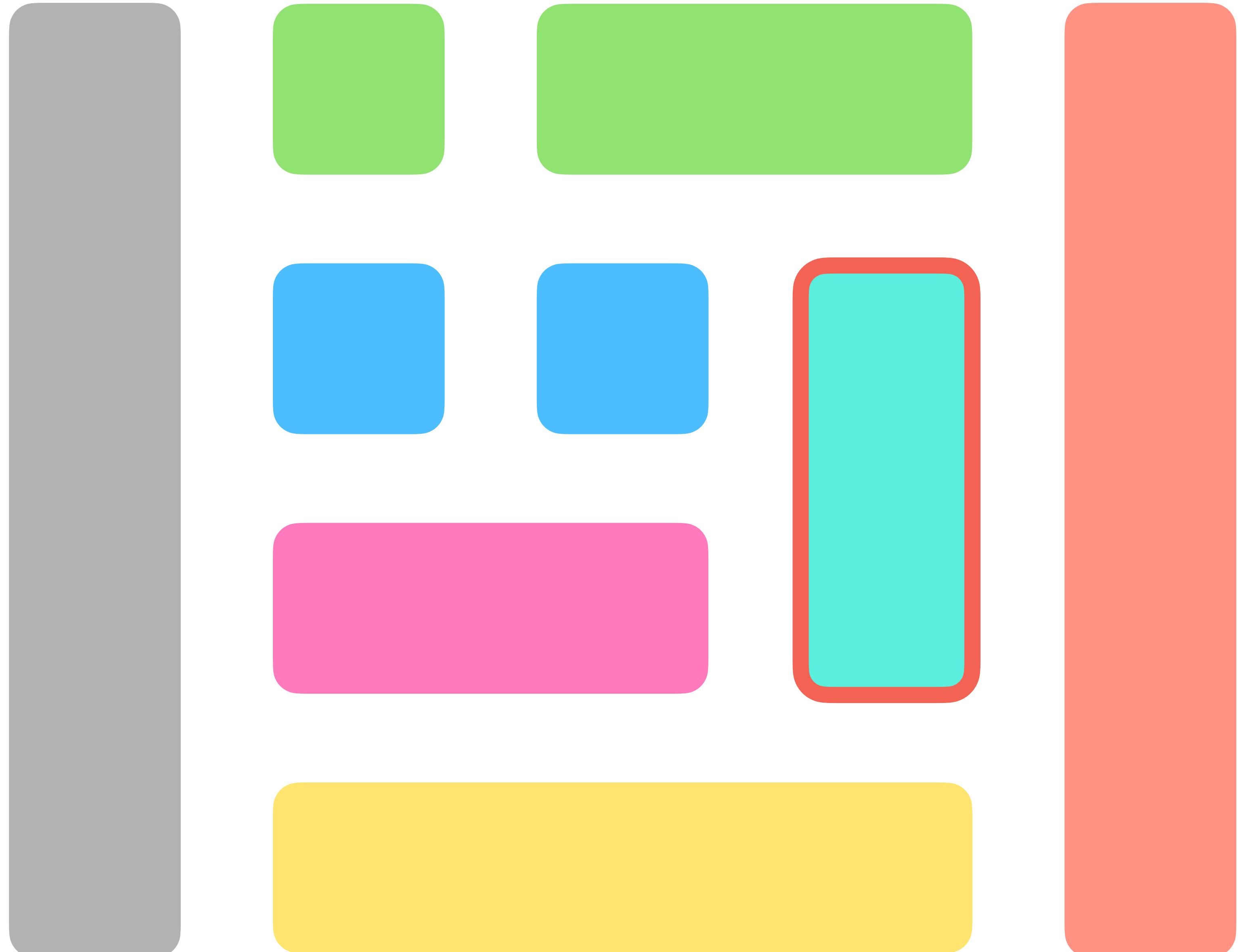
土壤-植被-大气连续体





1. 模块化

每个模块均可以
作为一个独立的
应用存在



1. 模块化

每个模块均可以
作为一个独立的
应用存在

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

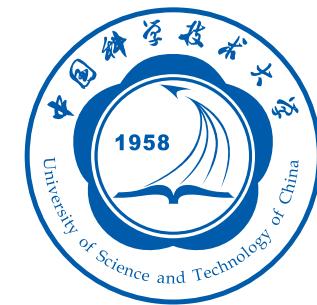


2. 用户体验

方便快捷的使用
方式

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





3. 自由度

许多不同的模型
供用户选择、自
由组合

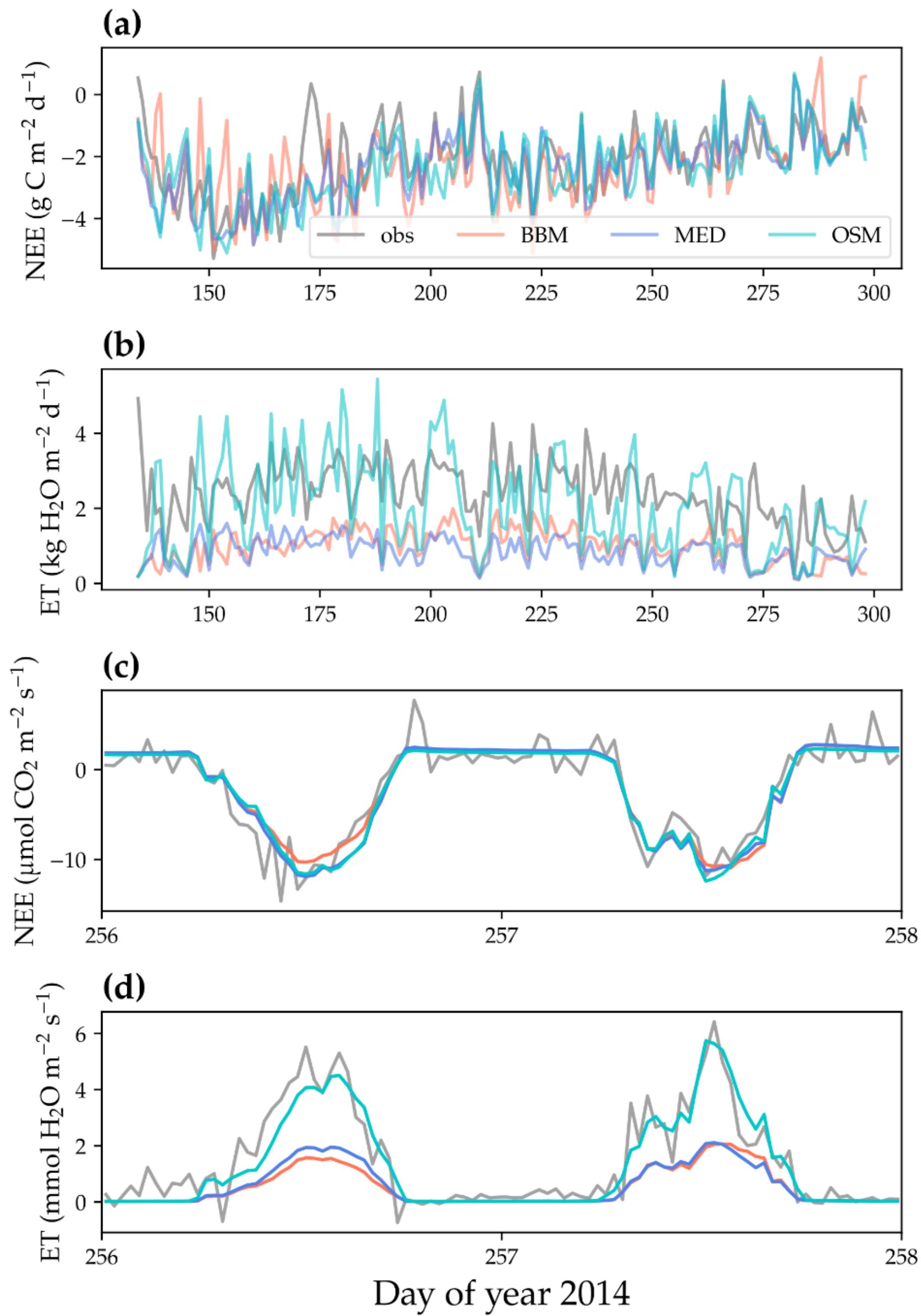




3. 自由度

示例1：

不同气孔模型的
比较

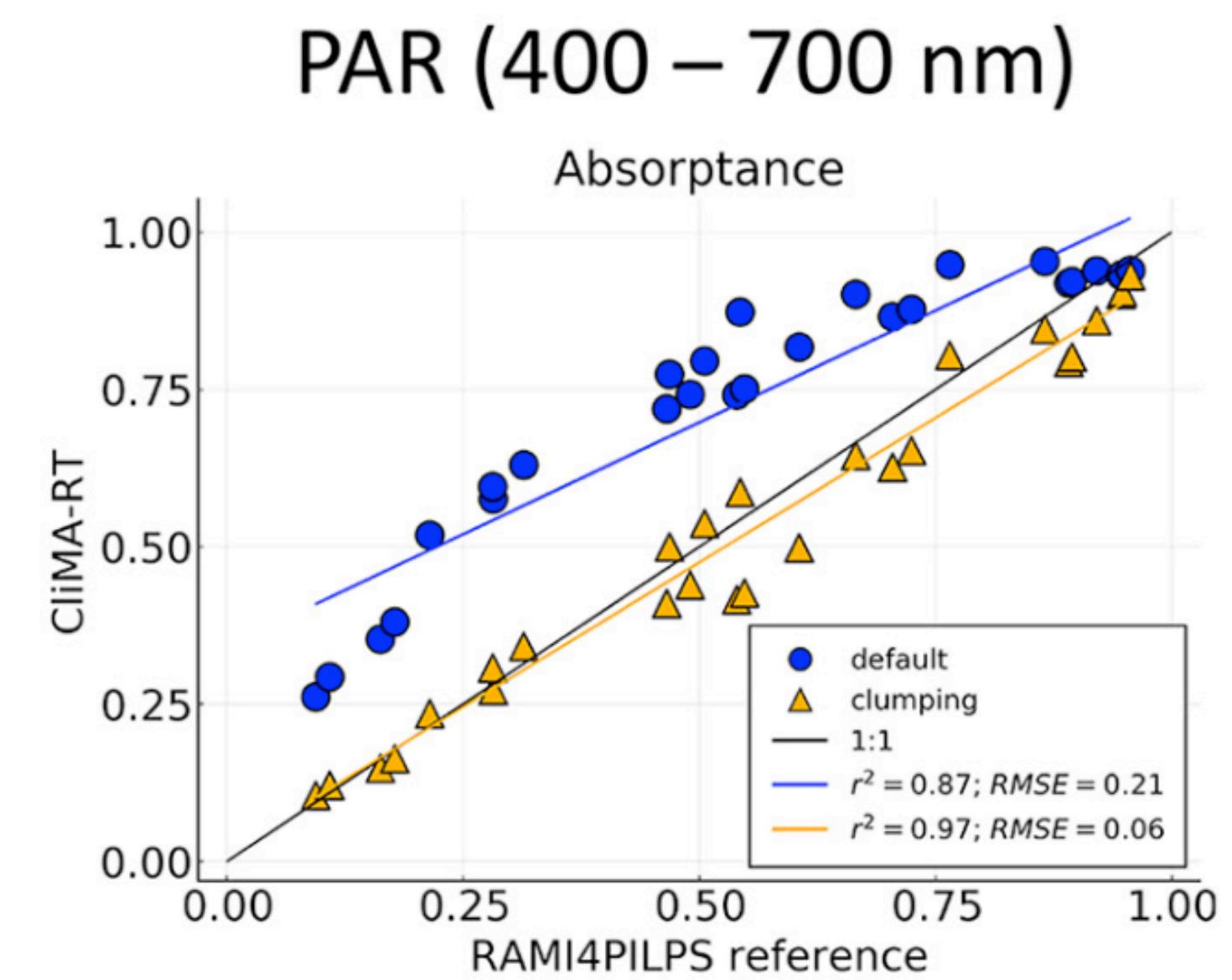
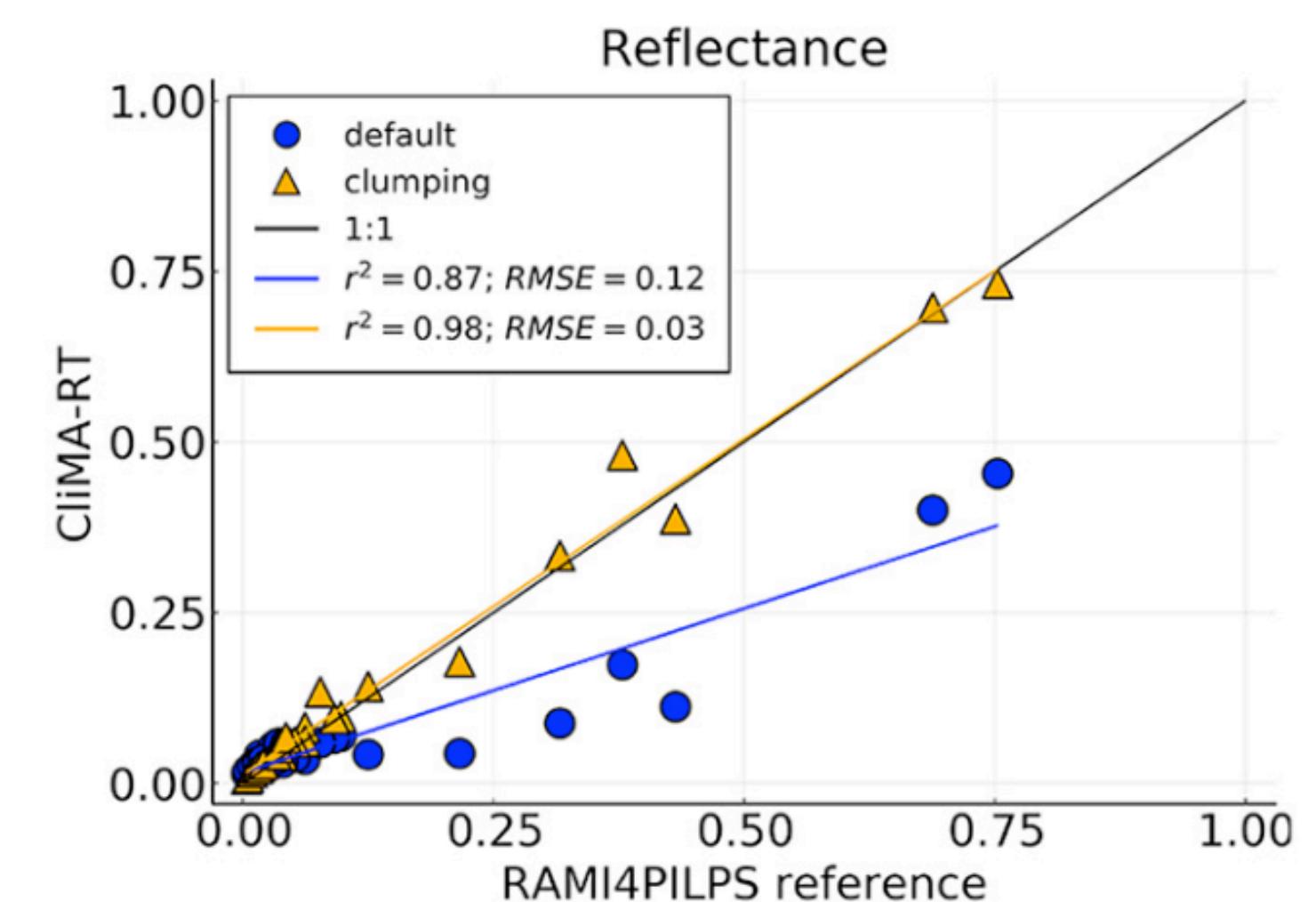




3. 自由度

示例2：

打开/关闭植被的
聚集指数功能

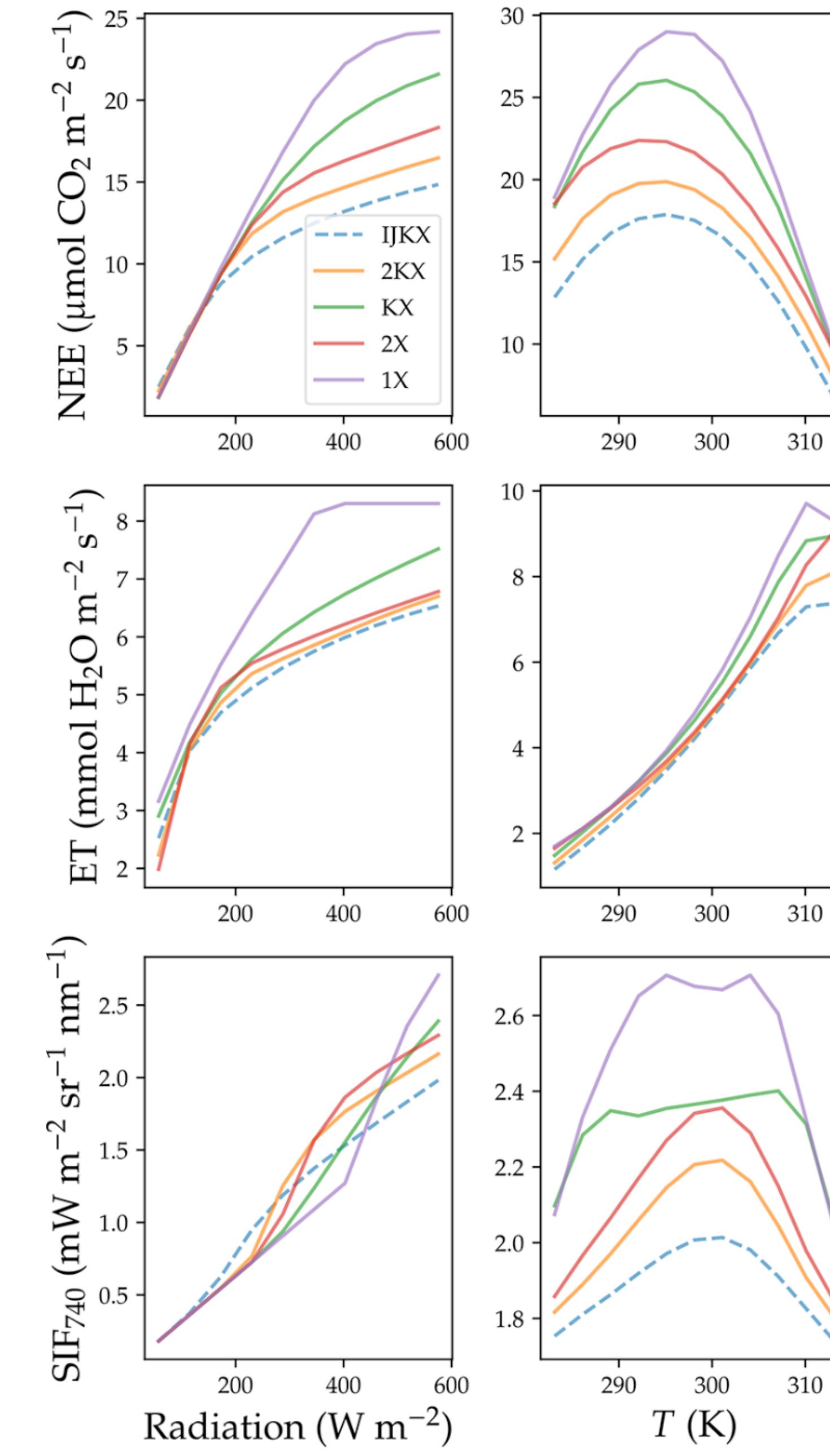
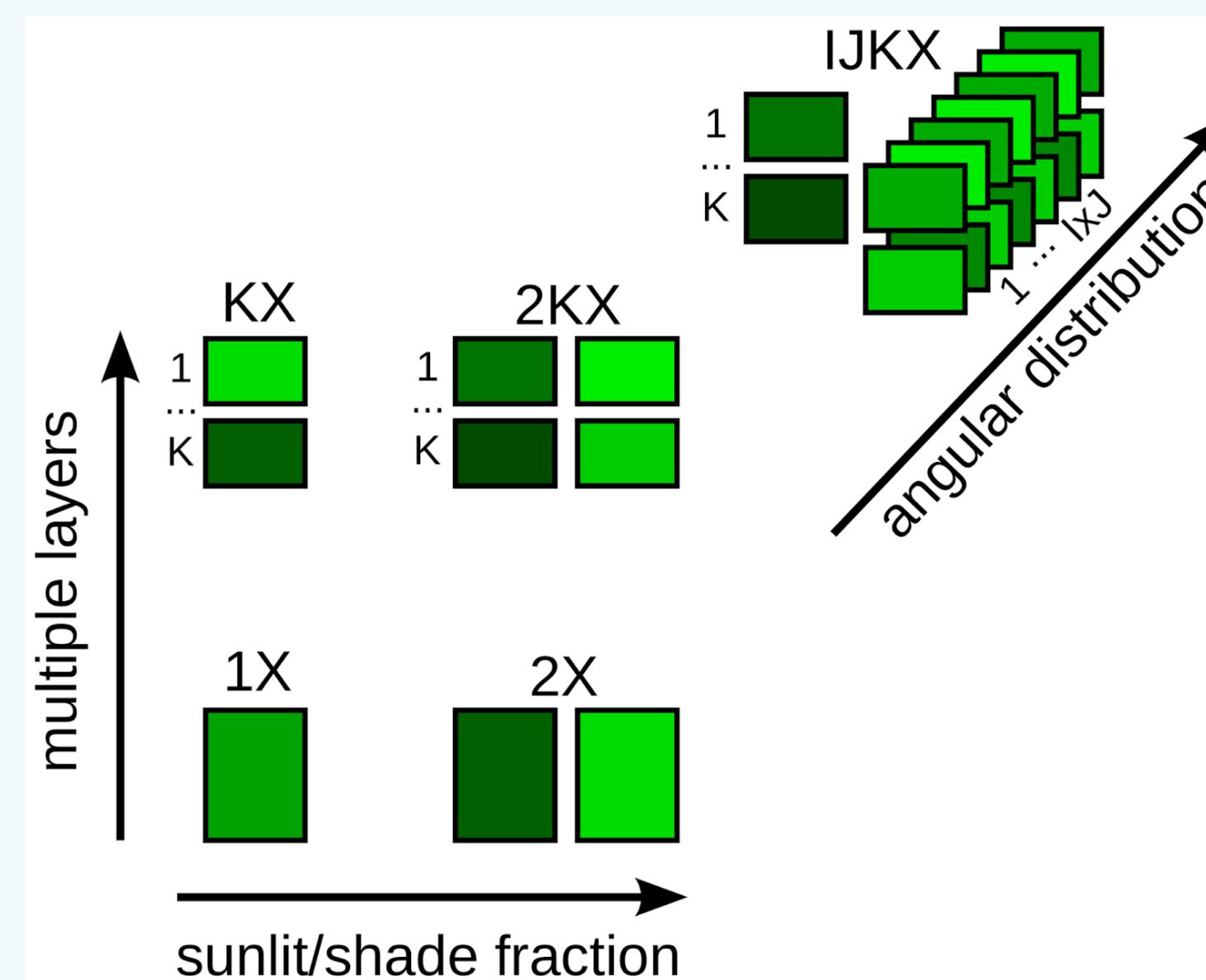




3. 自由度

示例3：

冠层结构的复杂程度可自由调节

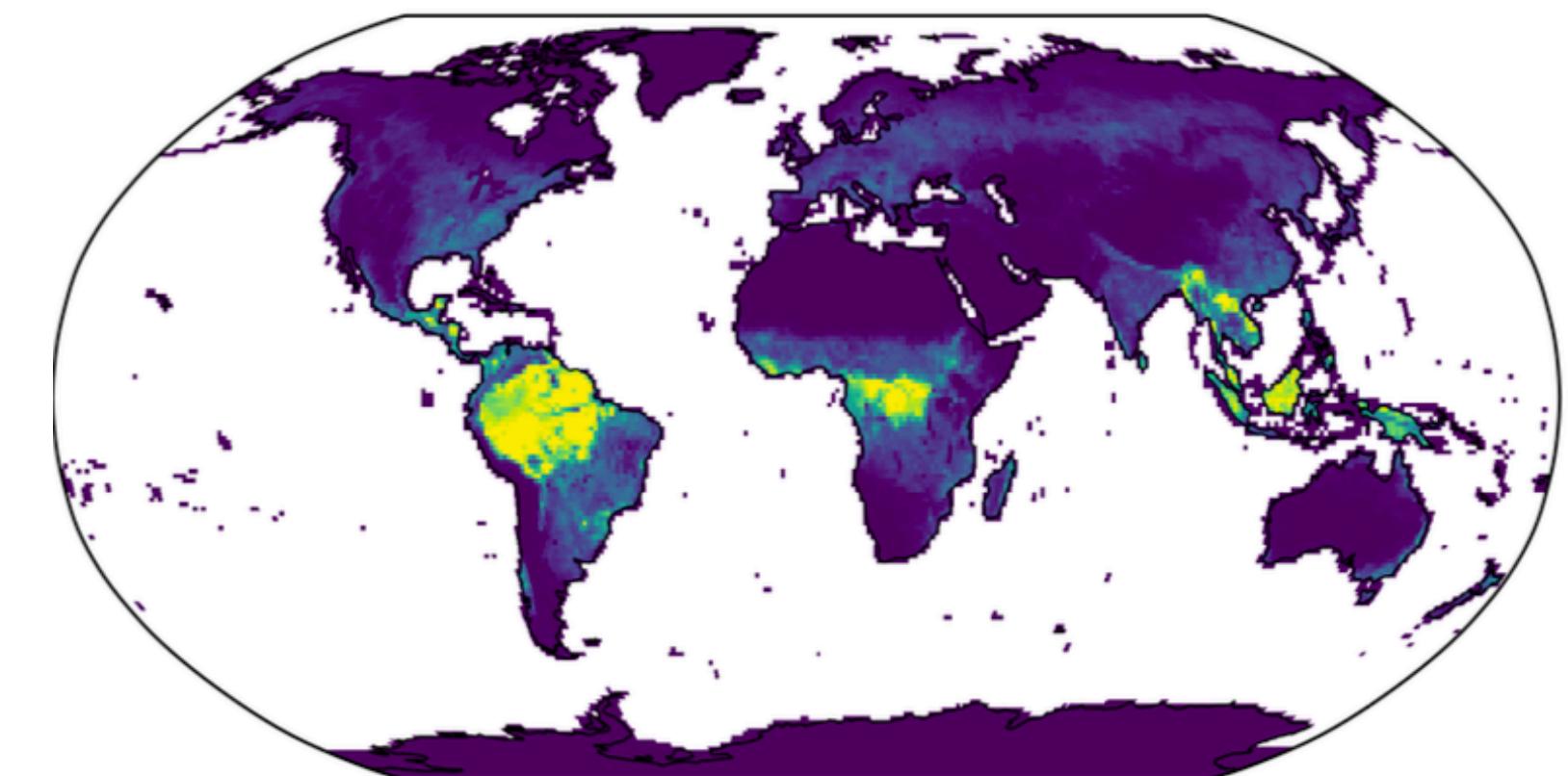
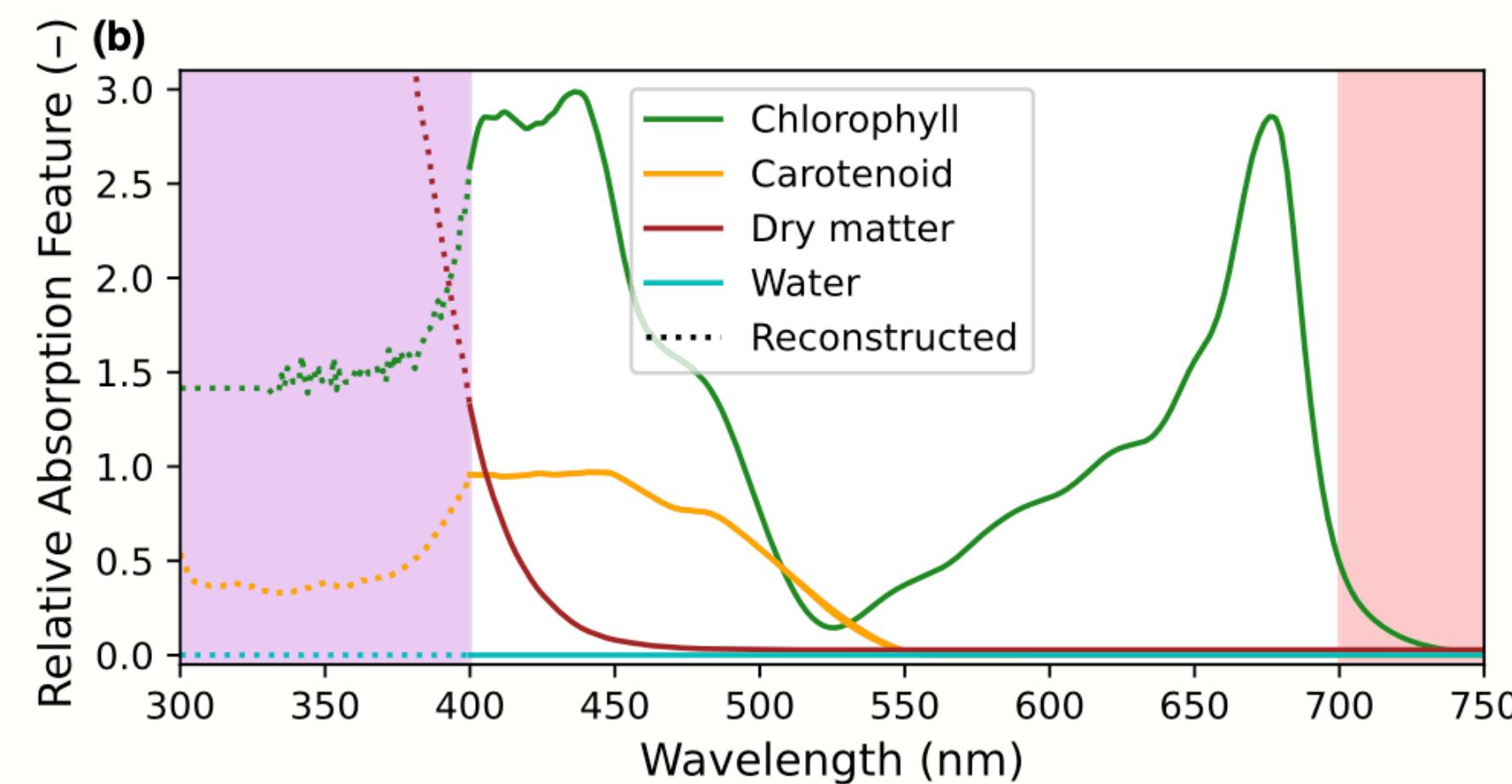
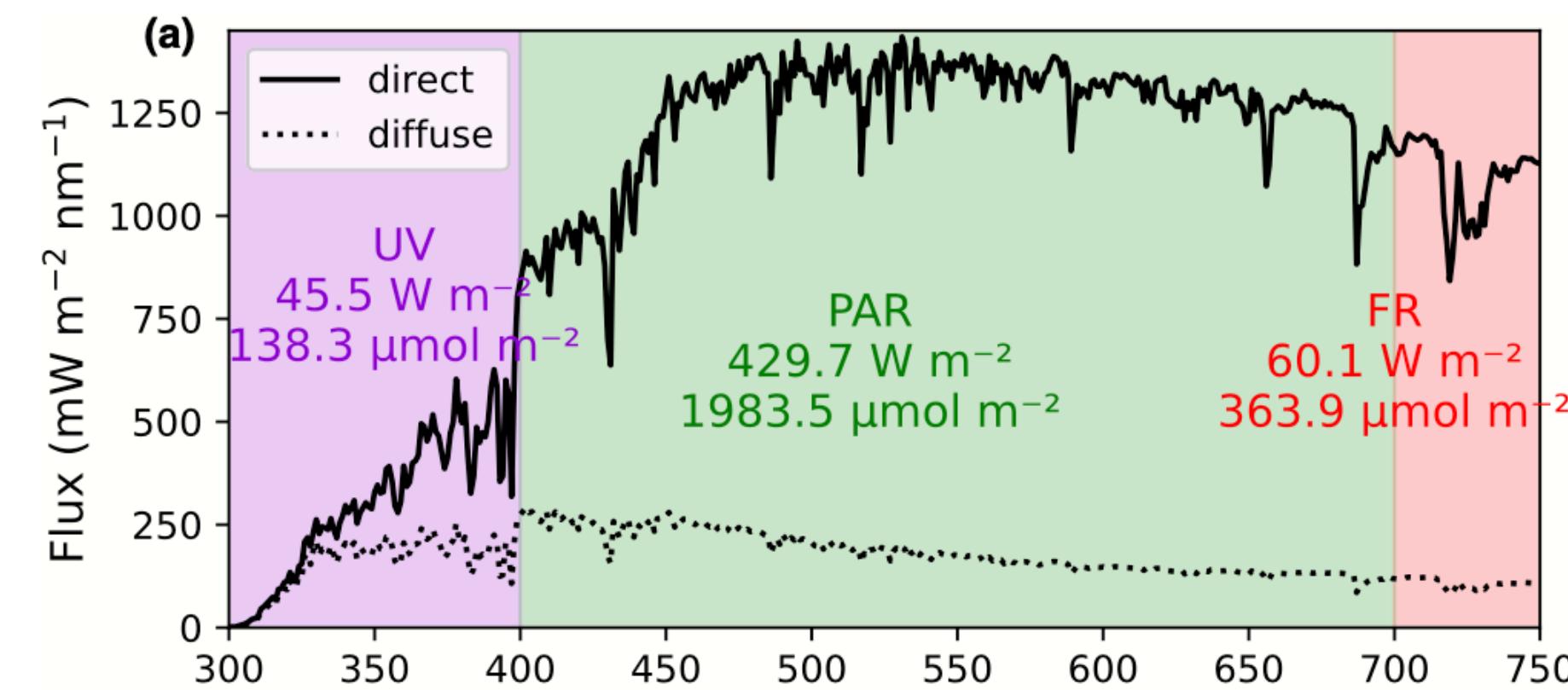




3. 自由度

示例4：

光谱扩展



GriddingMachine：新的全球尺度数据库软件



1. 模型构建

2. 模型设置

3. 参数矫正

使用更多、更系统
的多来源数据
进行模型参数的
矫正

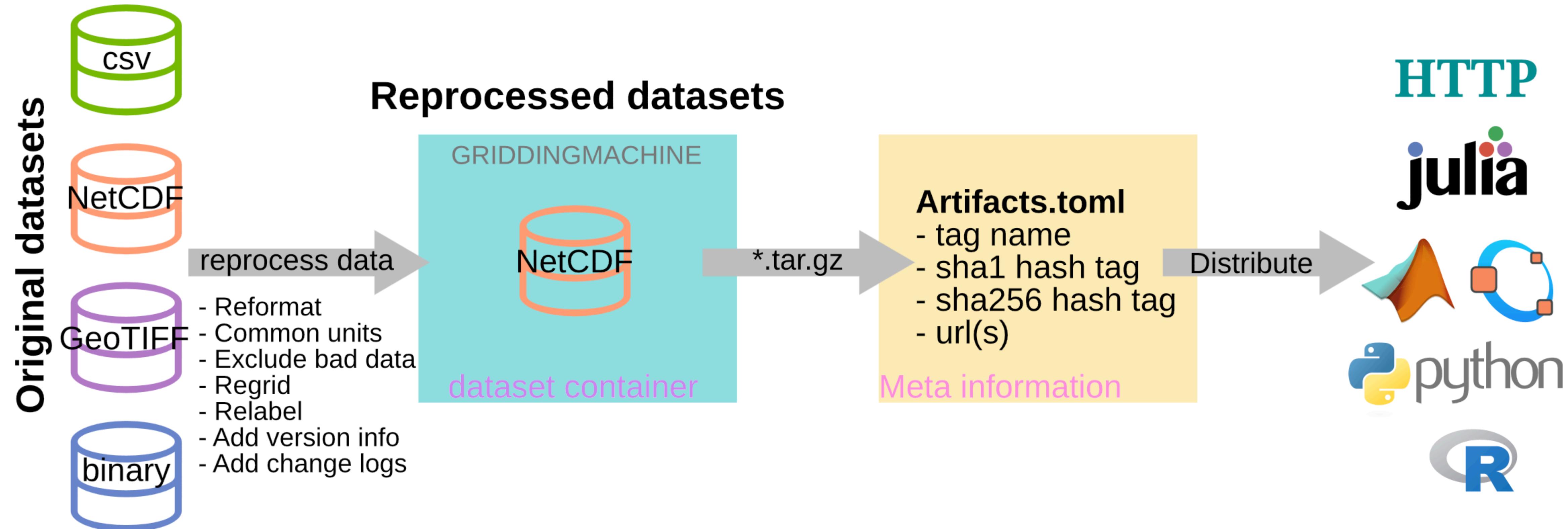


副产品

ClIMA Land需要
全球数据作为输入

挑战

- 数据存放网站
- 数据格式
- 不能直接使用
- 地图方向
- 地图覆盖面积
- 地图映射
- 数据单位
-
- 用户忘记把数据存哪了





GriddingMachine

Testing modules

- **Blender**
- **Fetcher**
- **Partitioner**

GriddingMachine.jl

Collector.jl

Tool to manage our collection of datasets locally

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

Indexer.jl

Tool to read the datasets locally

Requestor.jl

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

request_LUT

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



用户只需要知道
数据的标签

API

```
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 |

API

快速获取多边形 的数据

- **Partitioner**

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



CLiMA Land的全球模拟结果：植被过程与遥感



1. 模式开发

2. 模式设置

3. 参数矫正

使用更多、更系统
的多来源数据
进行模型参数的
矫正

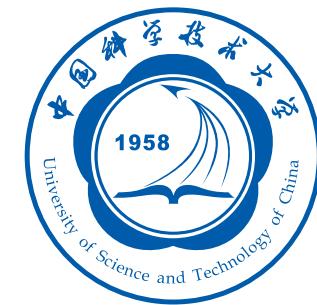


CliMA Land全球模拟

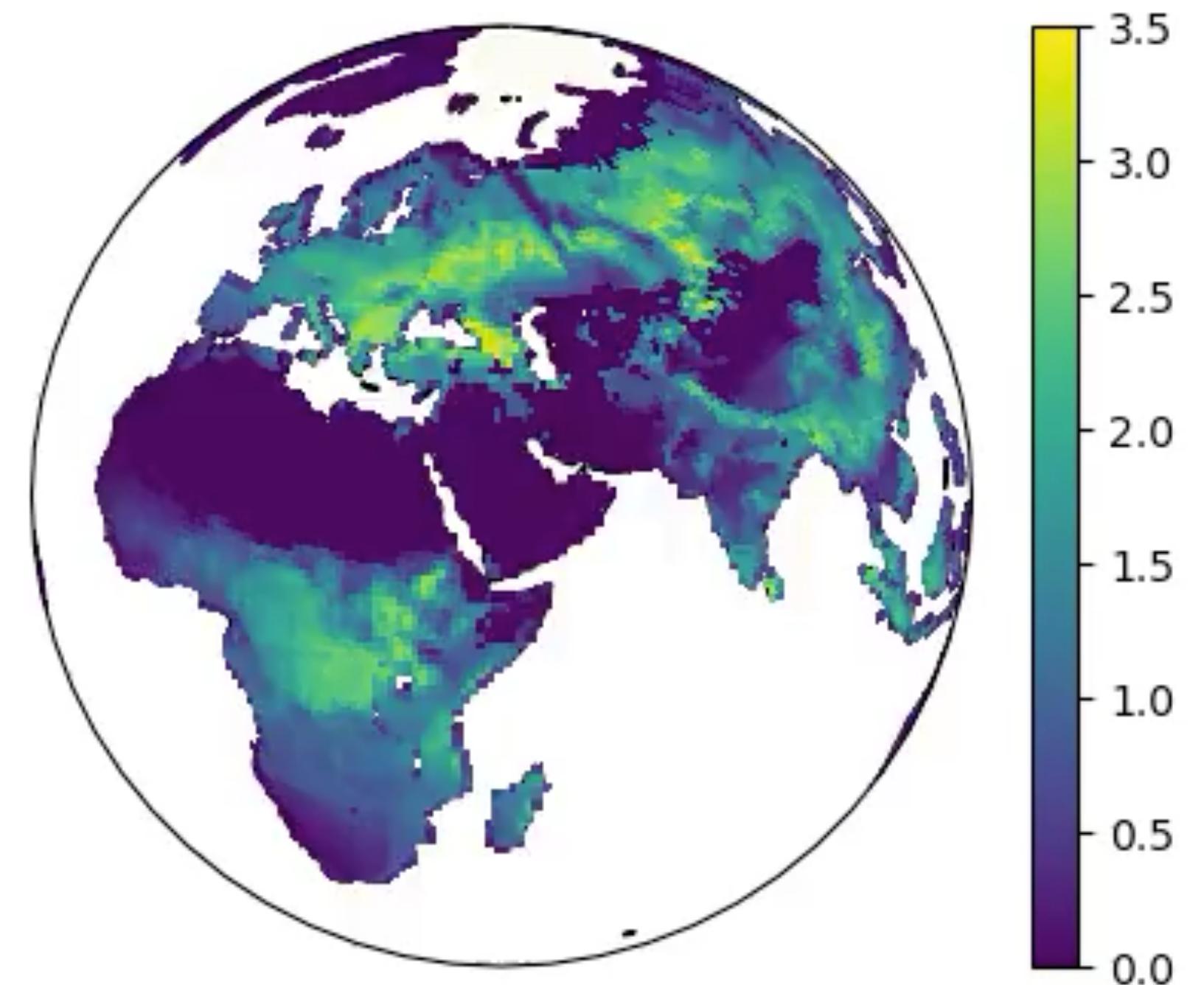
模式设置

- 高光谱的辐射模型（400–2500 nm）
- 经验气孔模型
- ERA5气候数据
- GriddingMachine输入
-
- 小时尺度的模拟

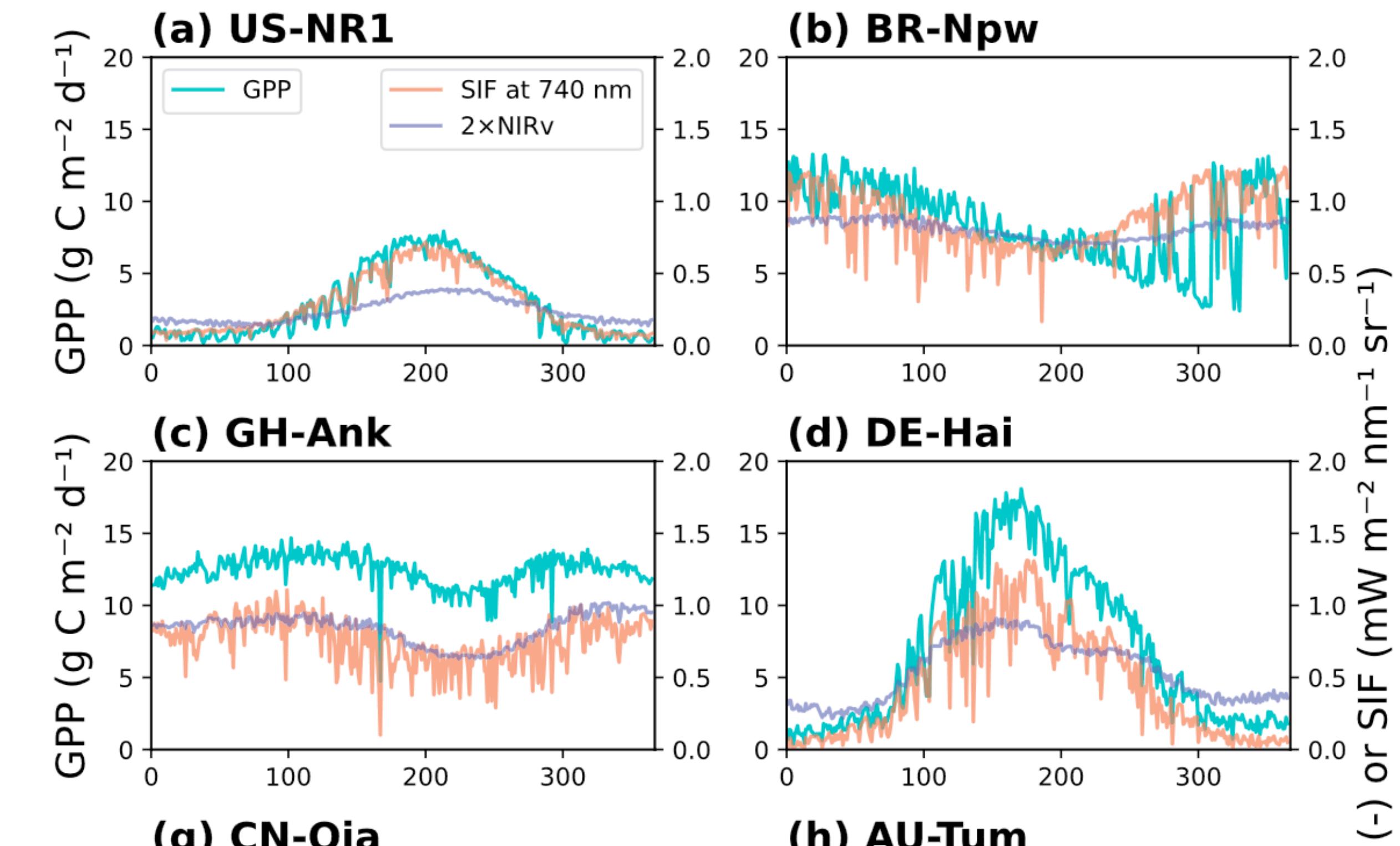
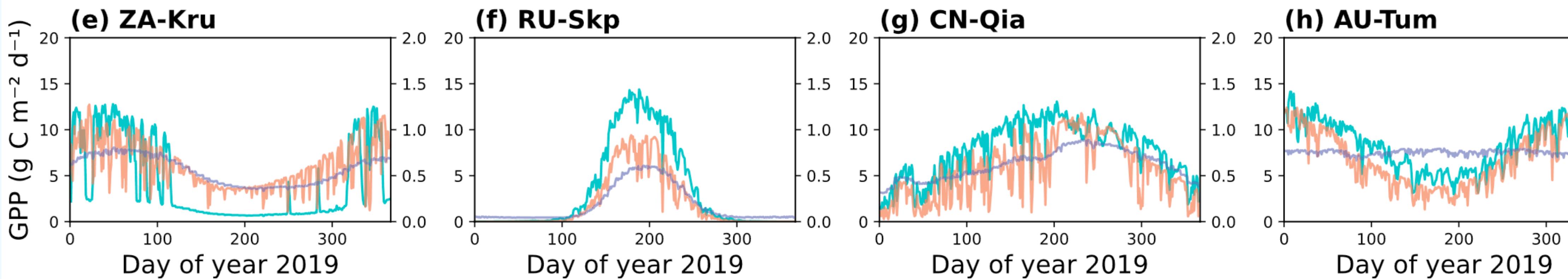
~2小时/年/160核

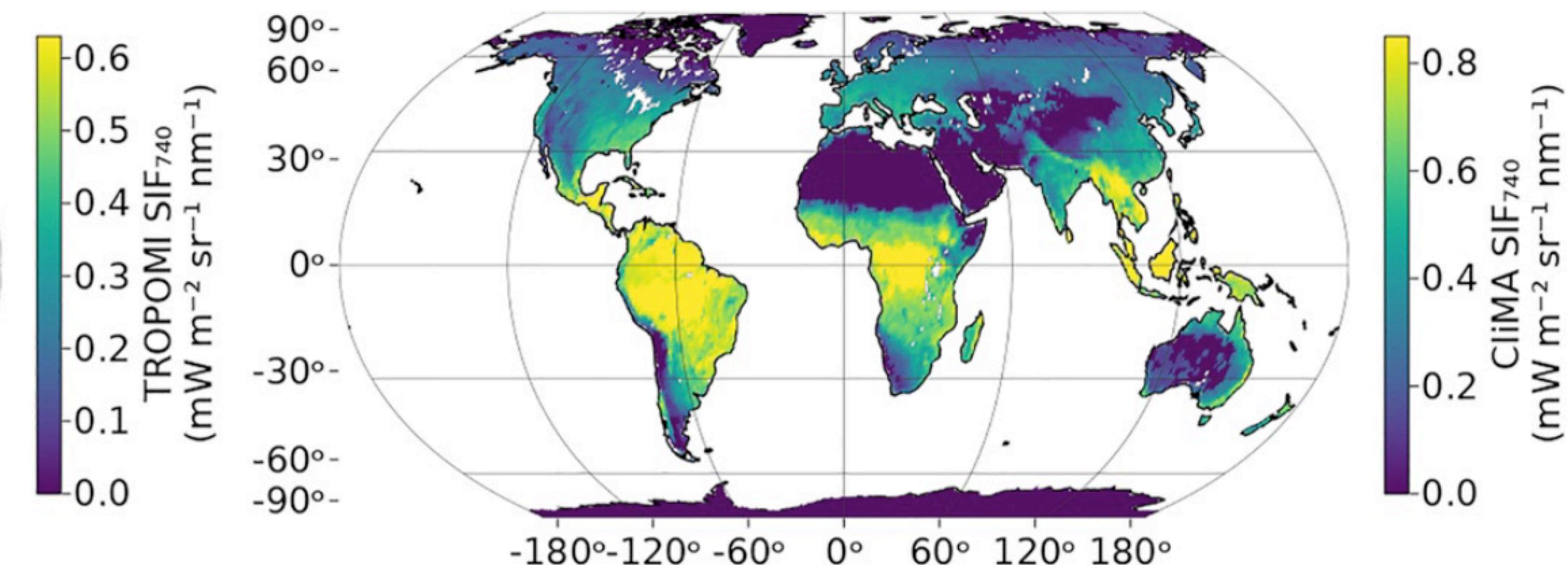
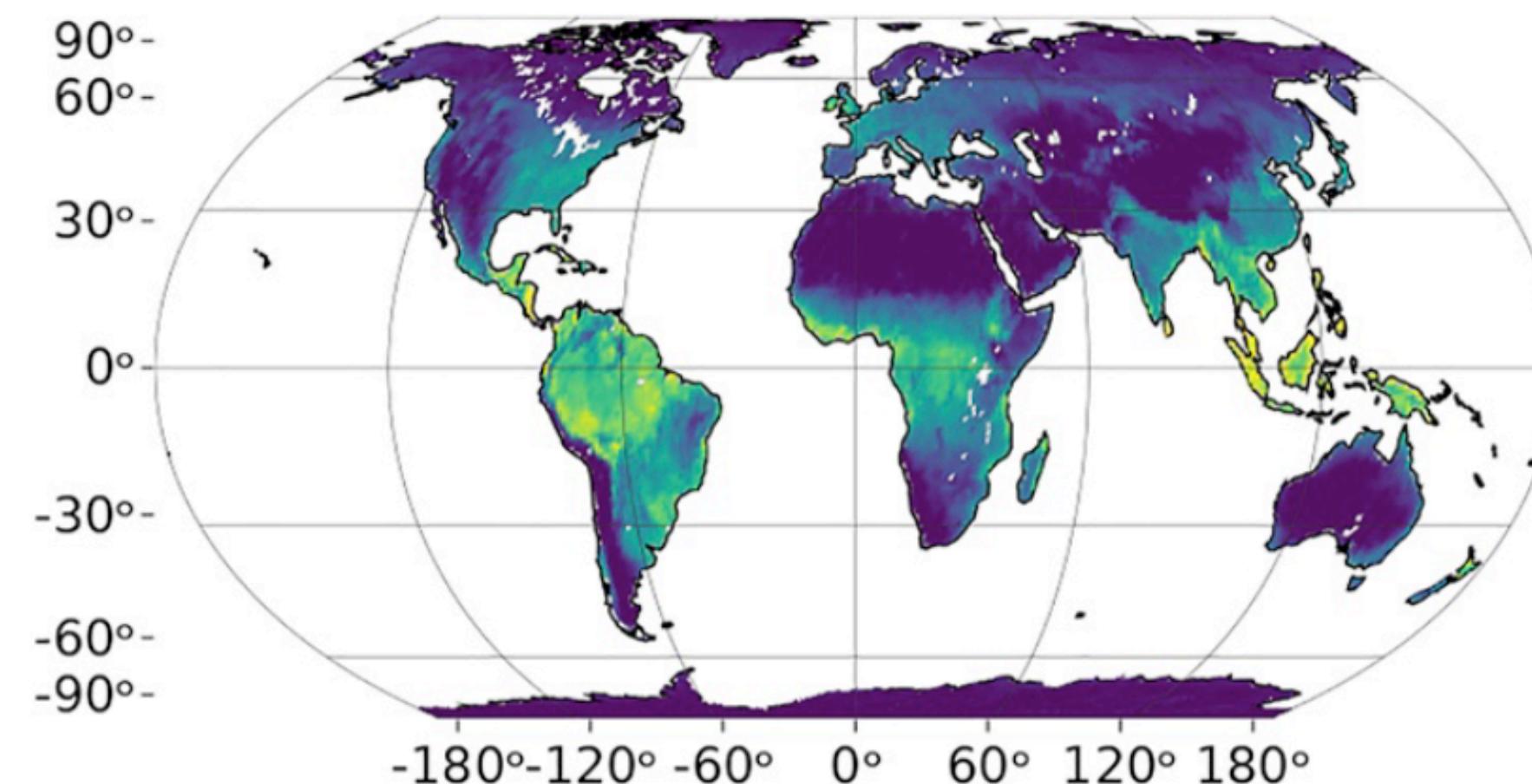
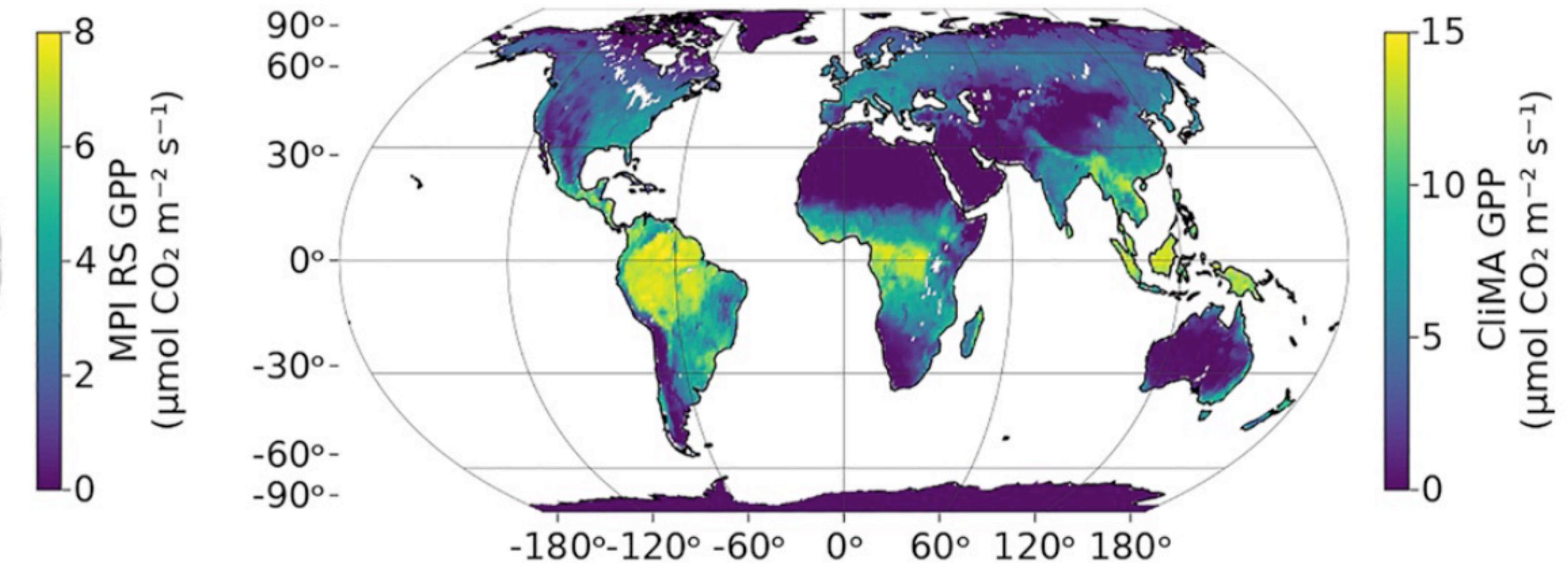
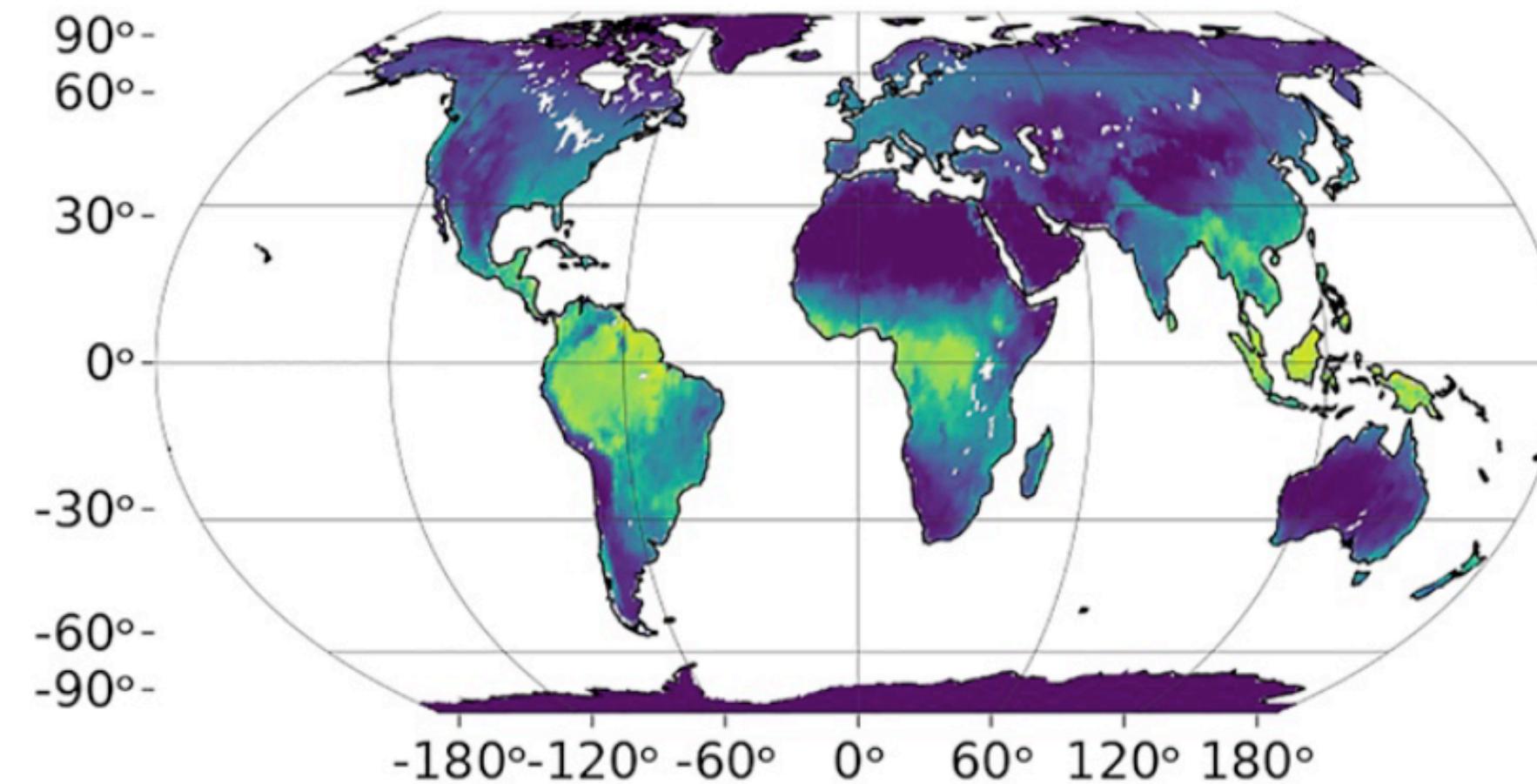


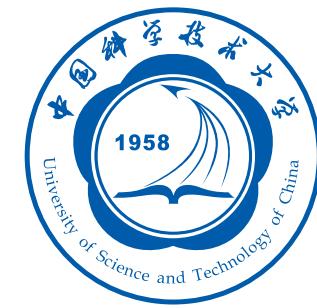
除了碳、水的通量模
拟，还包含了冠层光学
特征



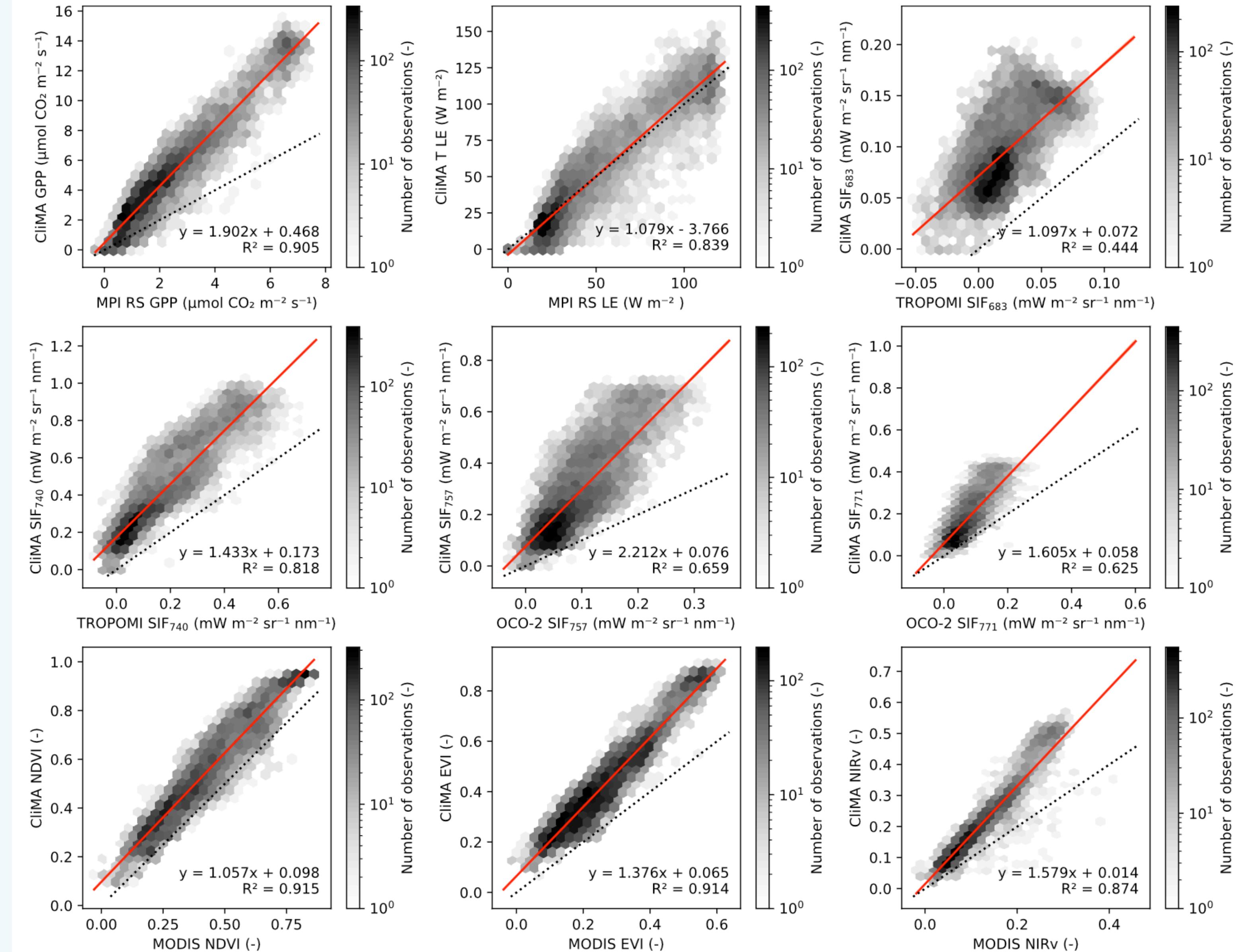
CLiMA Land SIF @ 740 nm







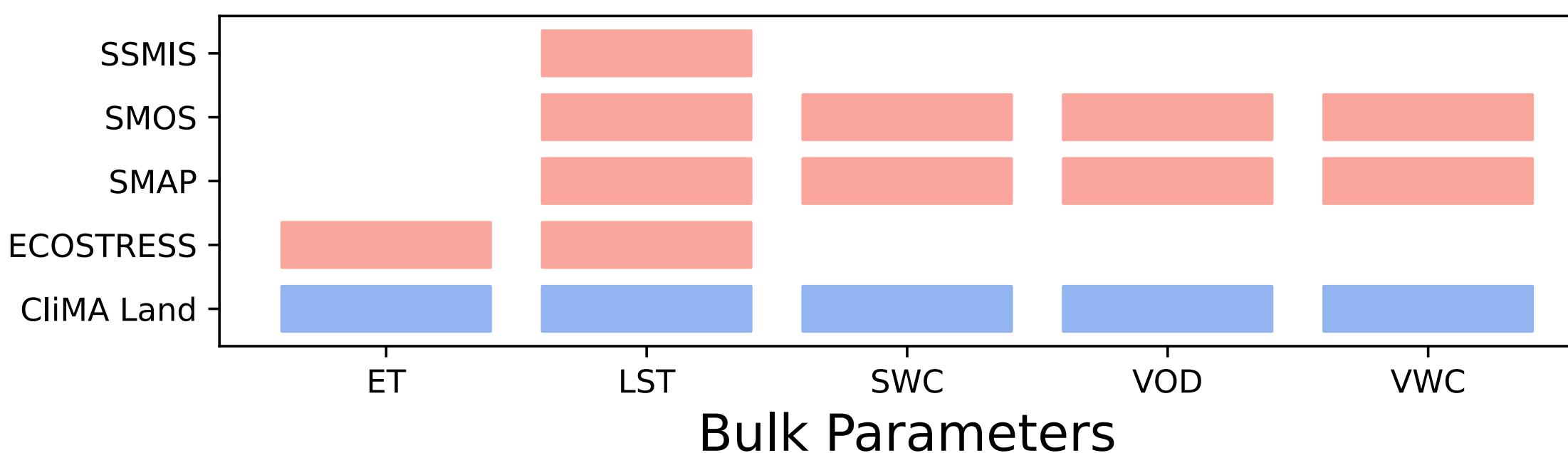
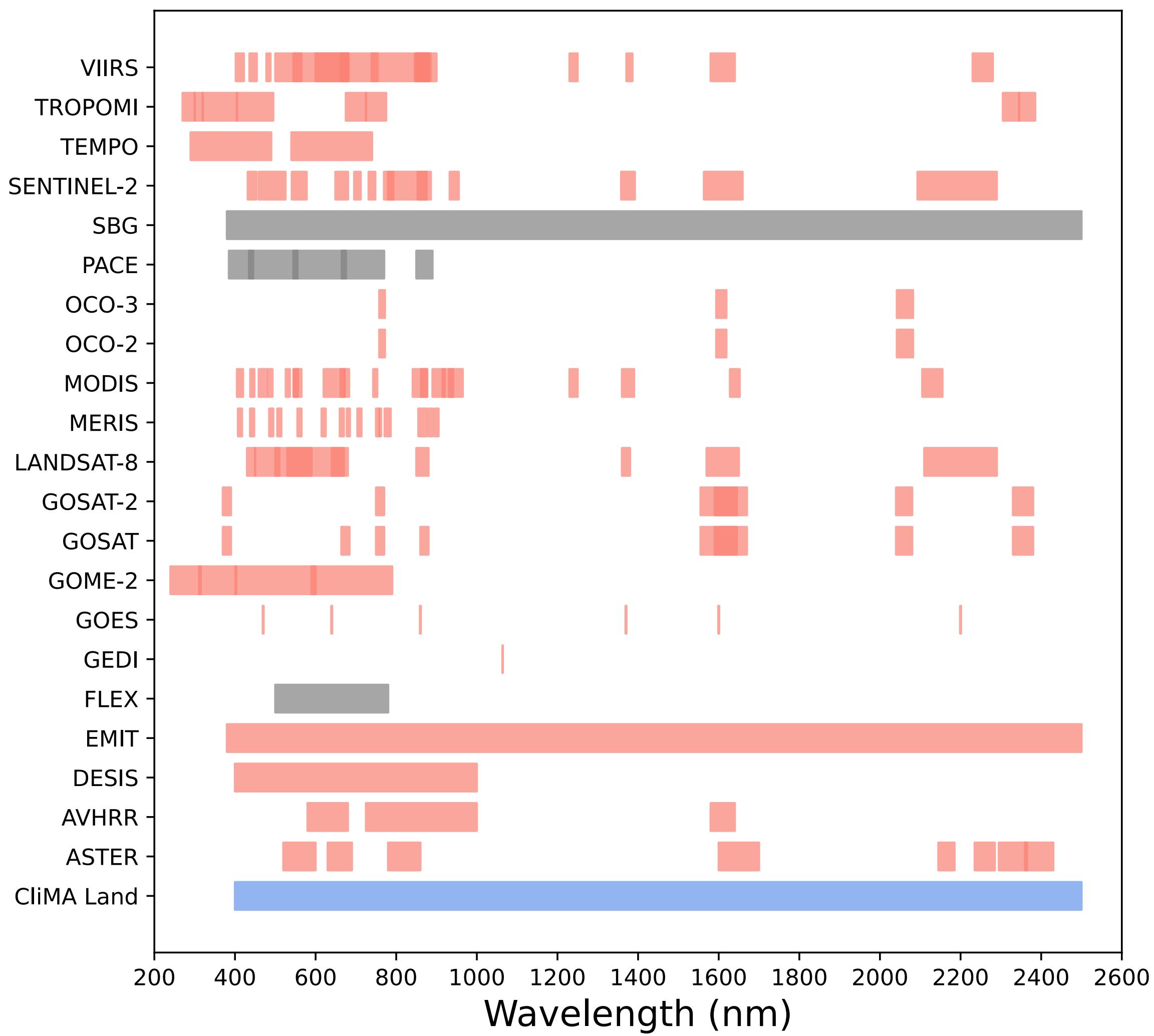
CLiMA Land还需要进一步的参数矫正





遥感数据

ClIMA Land能进行高光谱的辐射模拟，因此可以直接使用大多数卫星的L1、L2数据进行参数矫正



未来研究方向



1. 模式开发

改进土壤-植物-
大气连续体模
型，加入更多的
生理机制

- 引入更多机制模型
- 基于最优化理论的植被生长、繁殖、竞争、演替
- 拓展高光谱以覆盖TIR
- 考虑更加复杂的生态系统结构
-

未来研究方向



2. 模式设置

使用更合理的模式设置与组合，降低对经验模式的依赖

- 将陆面模式和大气、海洋模式耦合
- 测试更多的模型组合
- 添加更多的应用，如农业、林业
- 更多的模型示例，方便教学
-

未来研究方向



3. 参数矫正

使用更多、更系统的多来源数据
进行模型参数的
矫正

- 为GriddingMachine引入更多功能
- 进行CliMA Land的参数矫正
 - 叶面积指数 (进行中)
 - 叶绿素含量 (进行中)
 - 冠层结构 (进行中)
- 探索基于自然的应对气候变化的策略

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Tapio Schneider, Charles Kawczynski, Zhaoyi Shen, Eviatar Bach, Leilani Rivera-Dotson

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Martin Venturas, Kailiang Yu, Anna Trugman, Xiaonan Tai

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Melvin Tyree



陆地系统跨学科研讨会（待定）

1. 陆面模式开发、应用
2. 植物生理生态学
3. 土壤、水文学
4.

