# 基于功能指标预测生态系统状态转变

胡中民

海南大学

CellPress

Trends in Ecology & Evolution

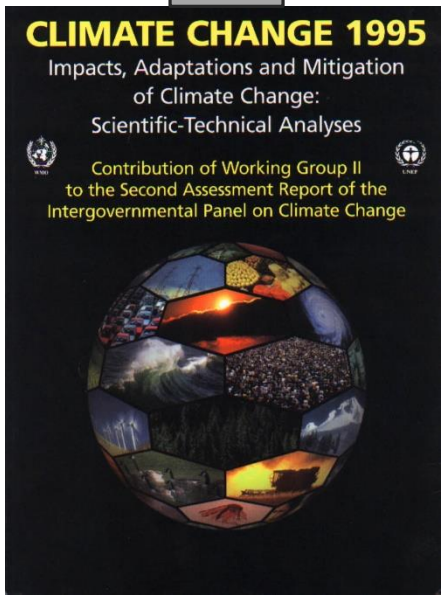
Opinion

## Using functional indicators to detect state changes in terrestrial ecosystems

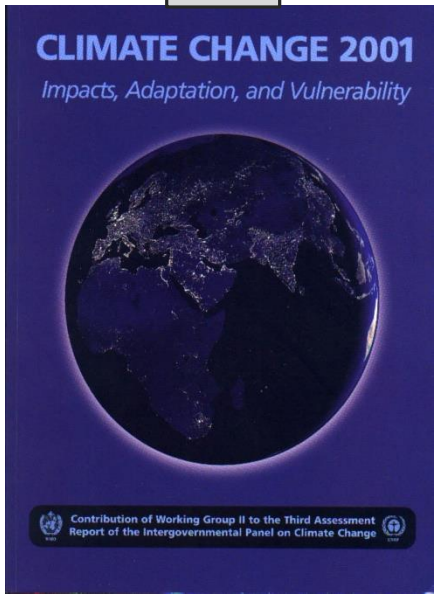
Zhongmin Hu [1,2,*] Vasilis Dakos,[3] and Max Rietkerk[4]

# IPCC Assessment Reports

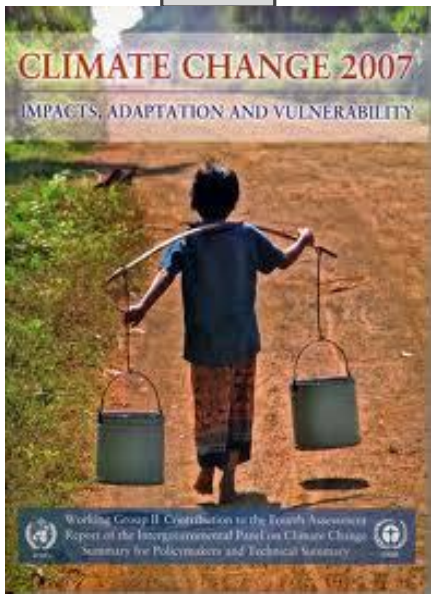
1995



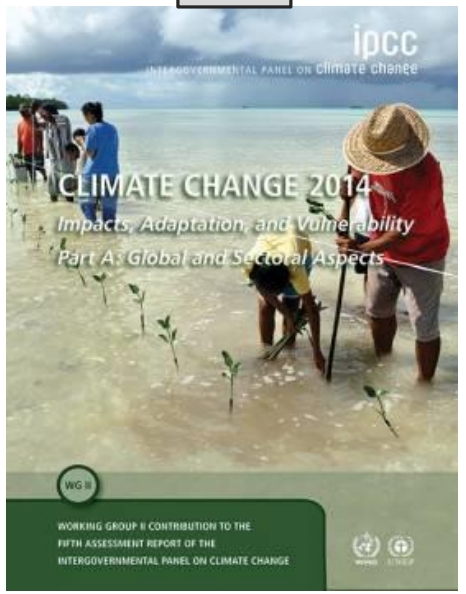

2001



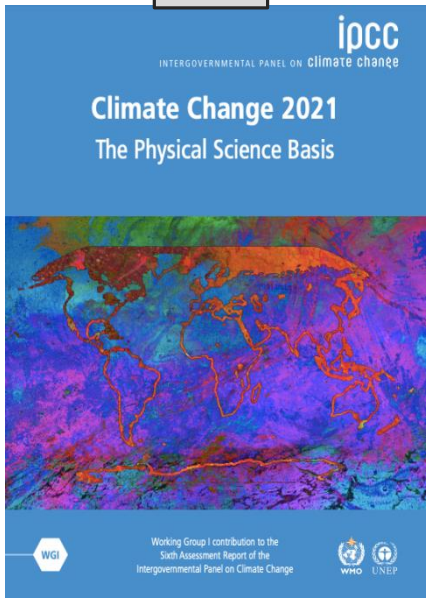

2007



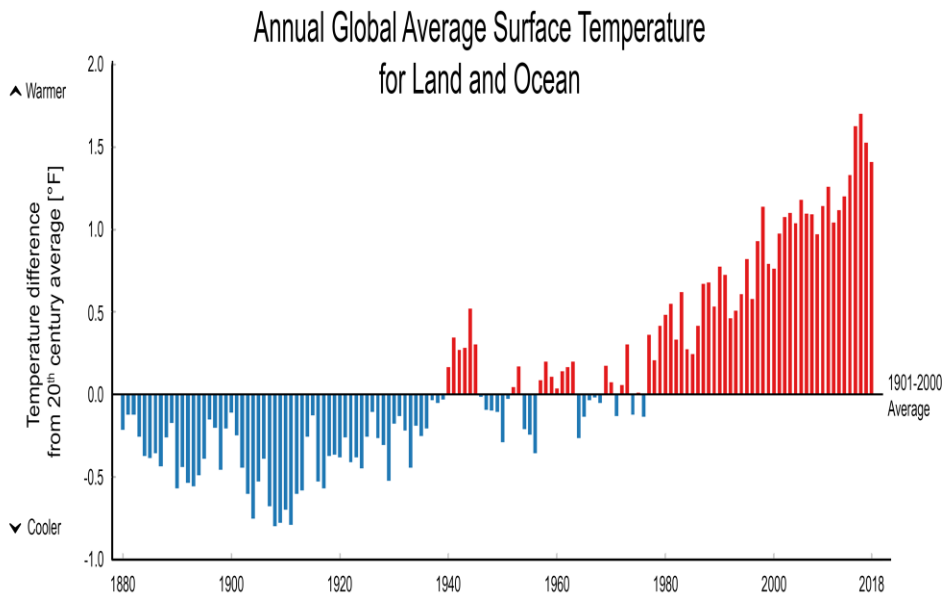

2013

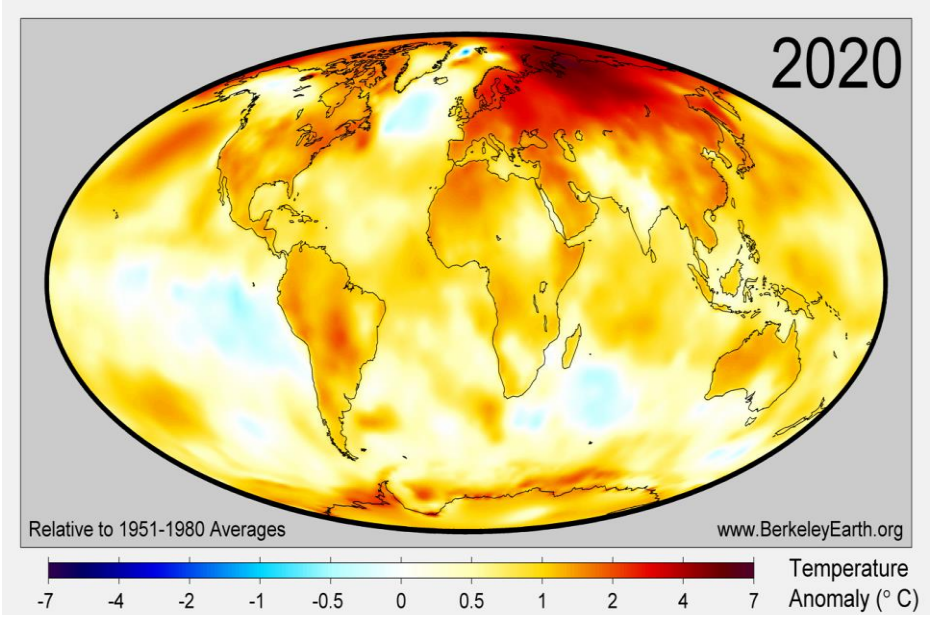


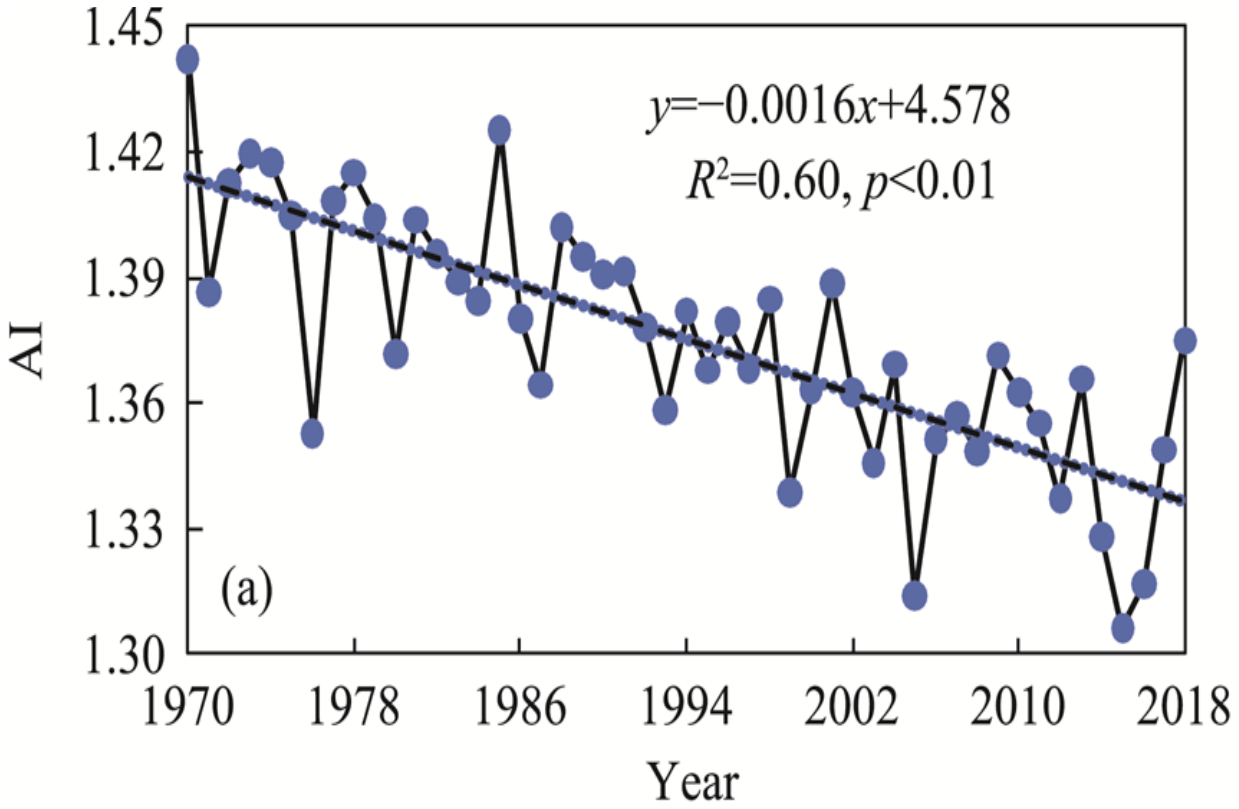

2022



# 全球气温变化


Annual Global Average Surface Temperature
for Land and Ocean
Warmer
Cooler
Temperature difference
from 20th century average [°F]
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1880
1900
1920
1940
1960
1980
2000
2018
1901-2000
Average

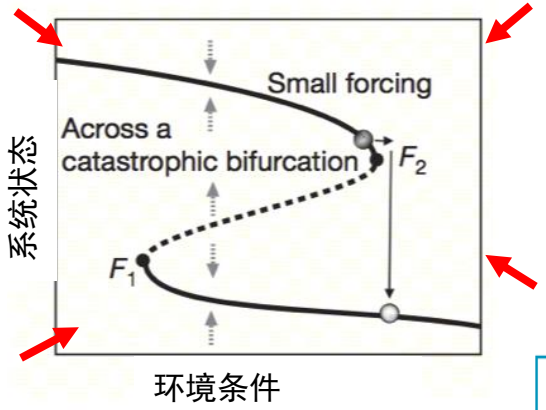

2020
Relative to 1951-1980 Averages
www.BerkeleyEarth.org
-7
-4
-2
-1
-0.5
0
0.5
1
2
4
7
Temperature
Anomaly (° C)


1.45
1.42
1.39
1.36
1.33
1.30
AI
y=−0.0016x+4.578
R²=0.60, p<0.01
(a)
1970
1978
1986
1994
2002
2010
2018
Year

# 全球变化影响下生态系统状态转变风险加剧

Science
AAAS

**Anticipating Critical Transitions**
Marten Scheffer *et al.*
*Science* **338**, 344 (2012);
DOI: 10.1126/science.1225244




nature
International journal of science

Review Article | Published: 03 September 2009

Early-warning signals for critical transitions

Marten Scheffer, Jordi Bascompte, William A. Brock, Victor Brovkin, Stephen R. Carpente
Dakos, Hermann Held, Egbert H. van Nes, Max Rietkerk & George Sugihara

nature
International journal of science

Letter | Published: 18 November 2012

Flickering gives early warning signals
critical transition to a eutrophic lake s

nature climate change

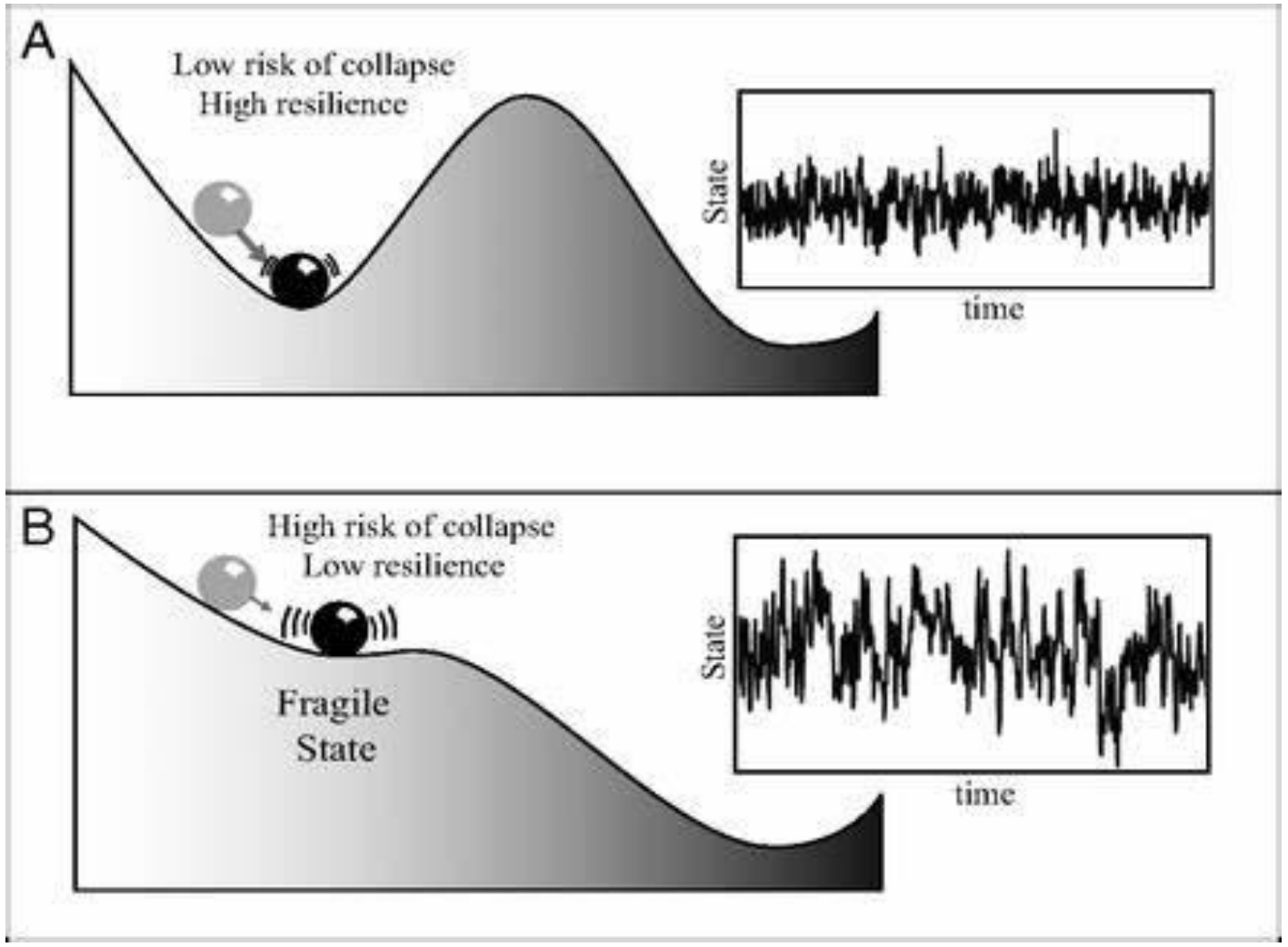
REVIEW

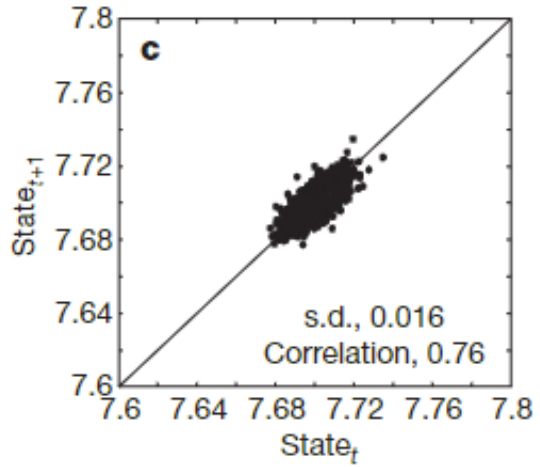
PUBLISHED ONLINE: 19 JUNE 2011 | DOI: 1

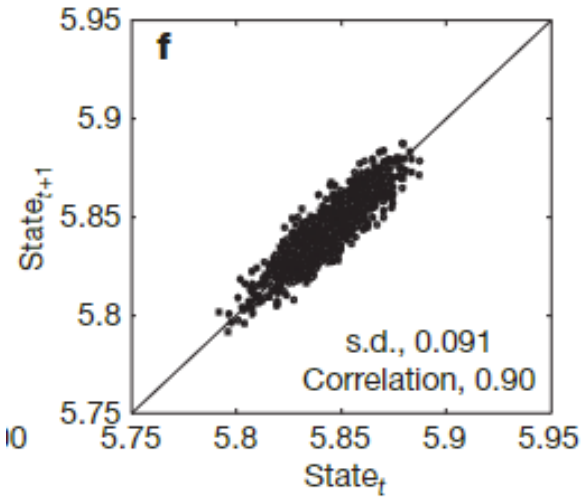
Early warning of climate tipping points

# 基于系统动力学的突变预警理论与指标

Critical Slowing Down (CSD) indicators　　变异性、偏度、自相关，恢复时间…

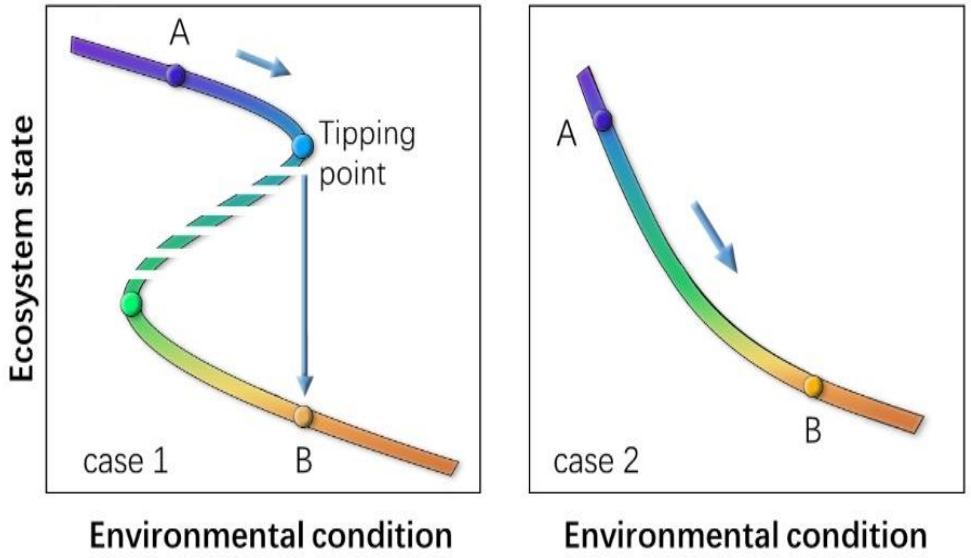


# 传统预警指标的不足

1. 要求基于生态“状态”变量构建；
2. 基于纯数学的推导，未能与生态系统过程建立联系，难于揭示机理；
3. 只服务于预测突变，不能预测渐变；



# 全球变化生态学领域，已经有不少基于“功能”的指标被广泛研究

**热点1：基于系统动力学理论发展的指标预警生态系统状态转变**

Nature

REVIEWS

Early-warning signals for critical transitions

Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1],

Science AAAS

Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment
S. R. Carpenter, *et al.*
*Science* **332**, 1079 (2011);
DOI: 10.1126/science.1203672

Science AAAS

Anticipating Critical Transitions
Marten Scheffer *et al.*
*Science* **338**, 344 (2012);
DOI: 10.1126/science.1225244

nature climate change

REVIEW ARTICLE
PUBLISHED ONLINE: 19 JUNE 2011 | DOI: 10.1038/NCLIMATE1143

Early warning of climate tipping points

**热点2：生产力的年际变异性、气候敏感性、对气候因子波动响应的非对称性的时空格局**

nature
International journal of science

Letter | Published: 17 February 2016

Sensitivity of global terrestrial ecosystems to climate variability

REPORT

The dominant role of semi-arid ecosystems in the trend and variability of the land $CO_2$ sink

Anders Ahlström[1,2,*], Michael R. Raupach[3,†], Guy Schurgers[4], Benjamin Smith[1], Almut Arneth[5], Martin Jung[6], Markus Reich...
+ See all authors and affiliations

REPORT

Variation Among Biomes in Temporal Dynamics of Aboveground Primary Production

Alan K. Knapp, Melinda D. Smith
+ See all authors and affiliations

*Science* 19 Jan 2001:

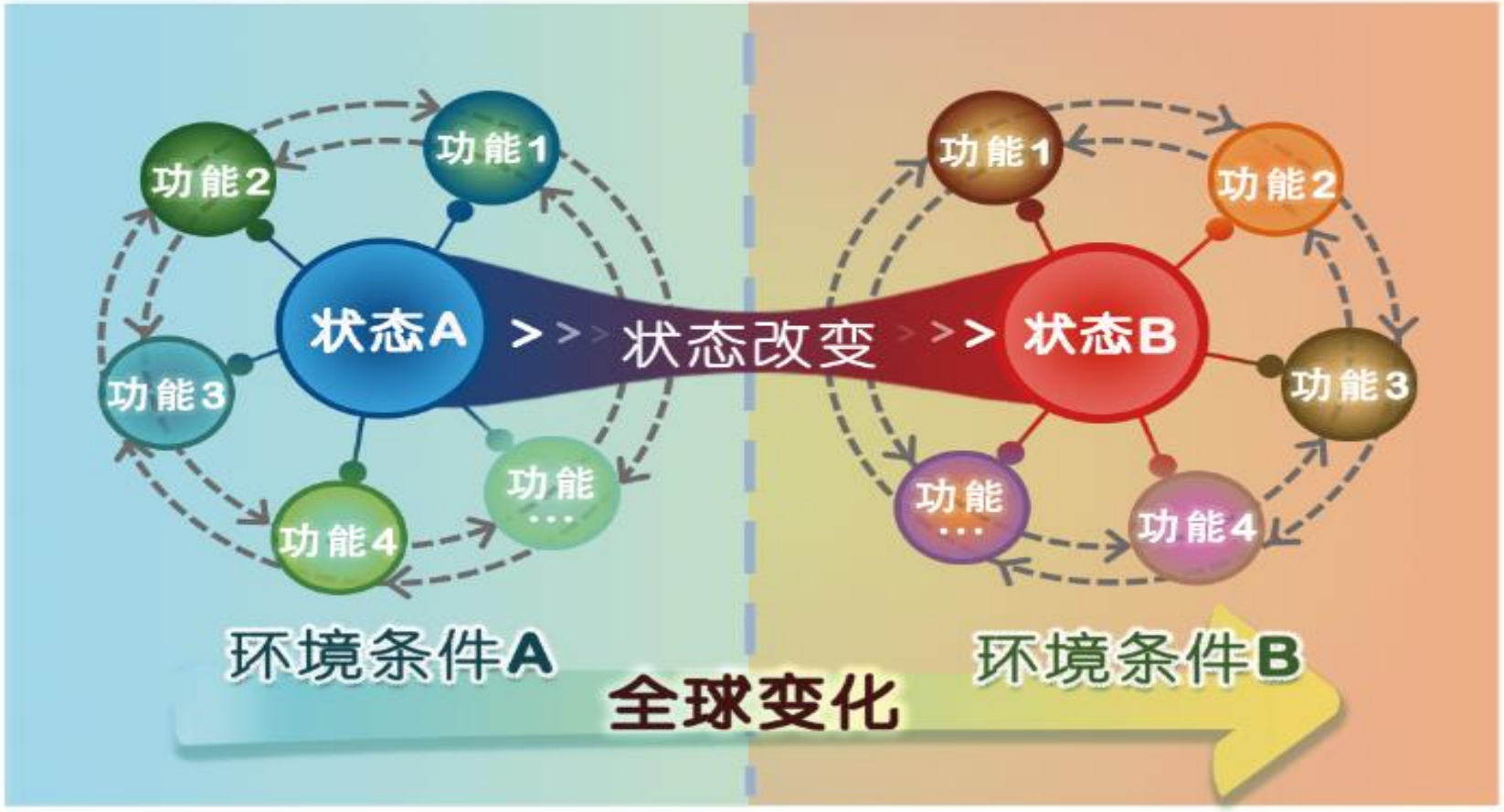
New Phytologist

Tansley insight | Free Access

Reconciling inconsistencies in precipitation–productivity relationships: implications for climate change

Alan K. Knapp, Philippe Ciais, Melinda D. Smith

基于生态系统“功能”的“关系”指标也可能可以用于预测系统转变




生态系统功能=生态系统过程　　生态系统功能≠生态系统服务

# 候选指标体系1

| Category | Indicator | Definition | Usage | Caveat | Case study |
|---|---|---|---|---|---|
| **CSD function-based indicators** | variance, autocorrelation, skewness, recovery rate, etc. | Instead of state variables, functional variables, e.g., NPP or GPP are used to construct CSD indictors for predicting catastrophic state change | Increase in variance, autocorrelation skewness, recovery rate, etc. when approaching the tipping point | Context information, e.g., driver characteristic, soil, climate, temporal scale etc. may affect the robustness[17] | [15, 17, 46] |

以水分为主导限制因子的生态系统为例

# 候选指标体系2

| Category | Indicator | Definition | Usage | Caveat | Case study |
|---|---|---|---|---|---|
| **Function-environment relation (the indicators are constructed from the relationships between environmental factors, e.g., precipitation, and ecosystem functions, e.g., vegetation precipitation)** | Climate sensitivity (here precipitation sensitivity is used as examples) | Slope of the environmental-function relationship or the relative response of ecosystem function to an environmental change[21] | Increase in precipitation sensitivity when ecosystem shifts from forest to grassland, and to desert | Interactions of other enviromental factors may strenghen or weaken the sensitivity | [15, 21, 30, 47] |
| | Precipitation-use efficiency | Ratio of vegetation productivity to annual precipitation[22] | Lower PUE in degraded ecosystems, or lower-complexity ecosystems | Intra-species phyiological flexibility may cause temporal variations in PUE without state change | [24, 39, 44] |

以水分为主导限制因子的生态系统为例

# 候选指标体系3

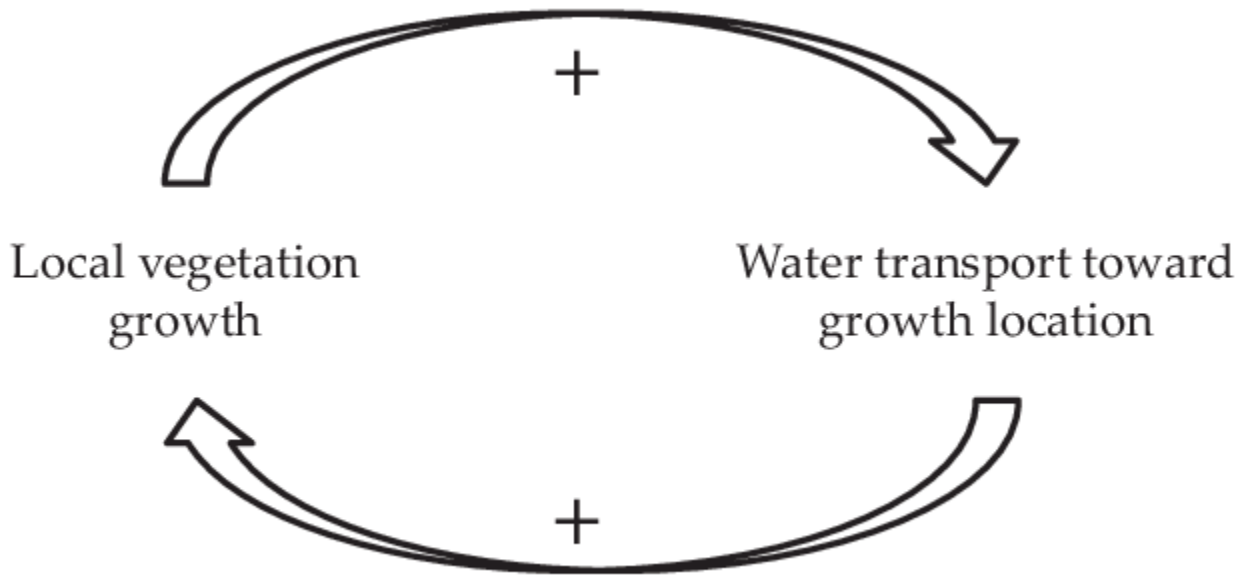
| Category | Indicator | Definition | Usage | Caveat | Case study |
|---|---|---|---|---|---|
| **Function-function relation (the indicators are constructed from the relationships between ecosystem functions, e.g., the relationship between vegetation productivity and water consumption)** | Ecosystem level water use efficiency (WUE) | The ratio of vegetation productivity to ecosystem evapotranspiration[48] | Lower WUE in degraded ecosystems, or lower-complexity ecosystems | High intra-species variations in plant water-use strategy may make ecosystem WUE quite variable within the same ecosystem types[49] | [45, 48] |
| | Transpiration fraction (T/ET) | The ratio of plant transpiration to whole ecosystem evapotranspiration[26] | Lower T/ET in degraded ecosystems, or lower-complexity ecosystems | Intra-species physiological flexibility may cause temporal variatoins in T/ET without state change | [25] |

以水分为主导限制因子的生态系统为例

# 理论模型验证

$$\frac{dP}{dt} = g(W)P - (d + b)P \qquad (1)$$

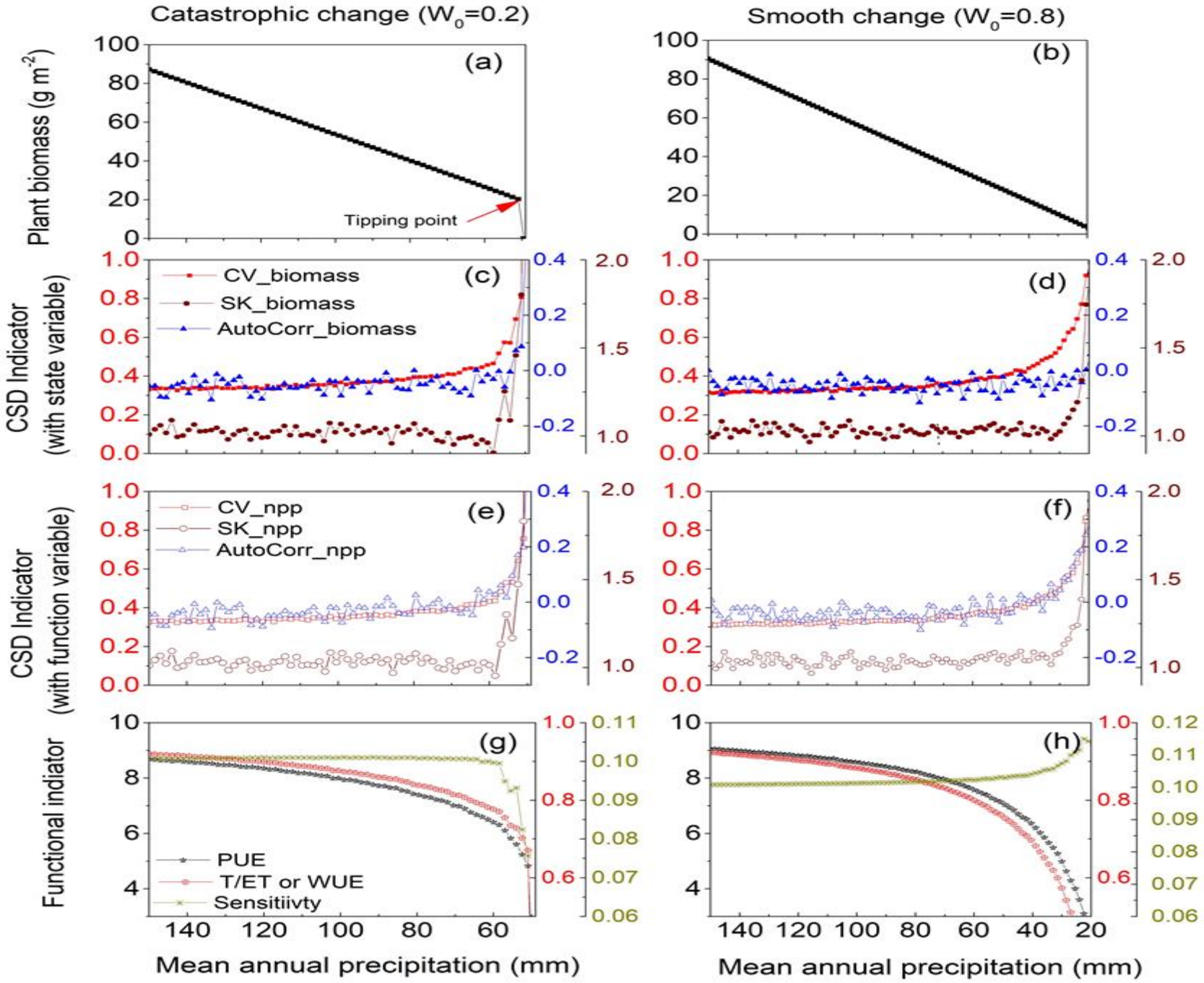
$$\frac{dW}{dt} = W_{in}(P) - c(W)P - r_w W \qquad (2)$$




植被越多，更多水分下渗到土壤中被用于植物生长，导致更多植被和更多水分下渗吸收

植被越少，更多水分以地表径流流失，导致植物更少和更多径流损失

Rietkerk et al., 2004, Science



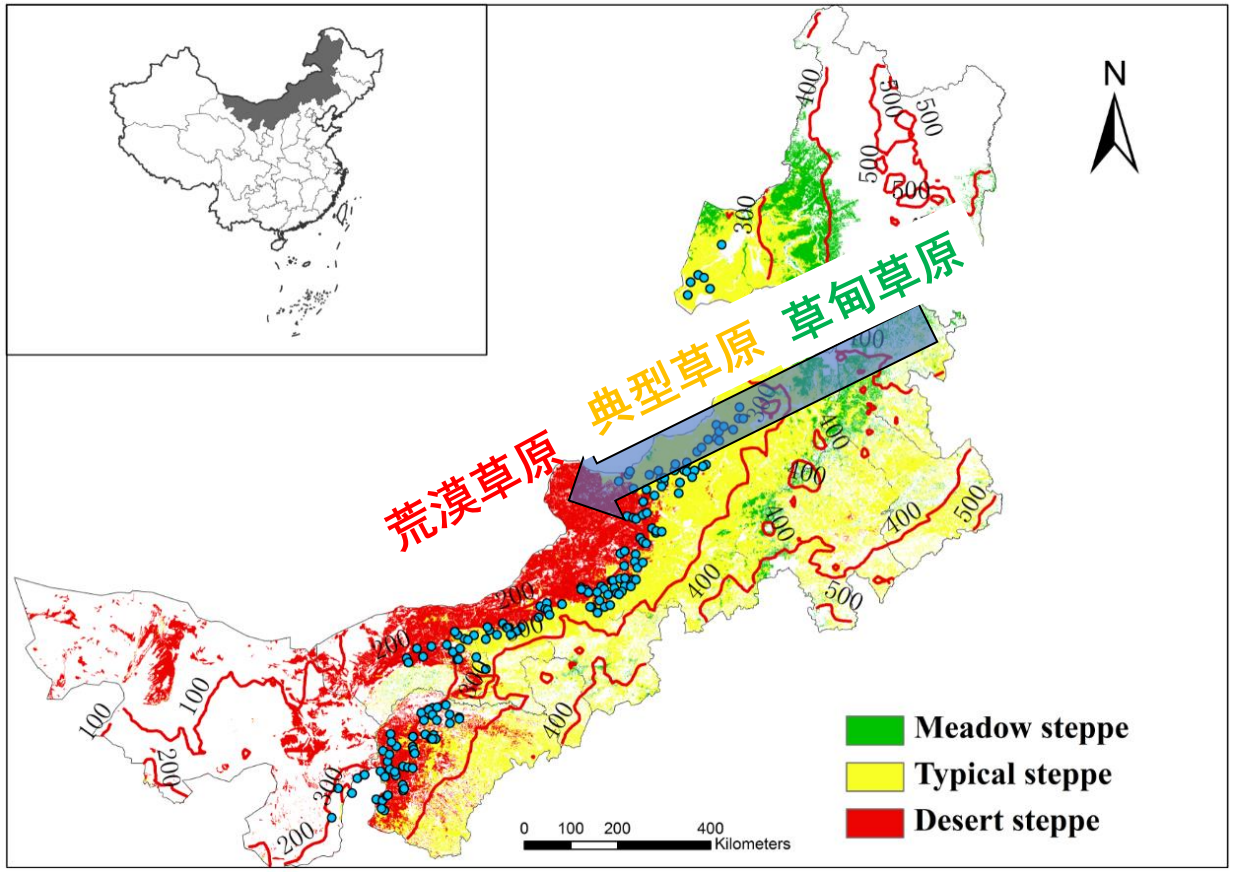

## 理论模型验证

不仅基于生产力计算得到的CSD指标，气候敏感性、降水利用效率，生态系统水分利用效率，蒸腾蒸散比等基于生态系统功能得到的指标均可能用于系统状态转变，甚至系统渐变

# 验证1

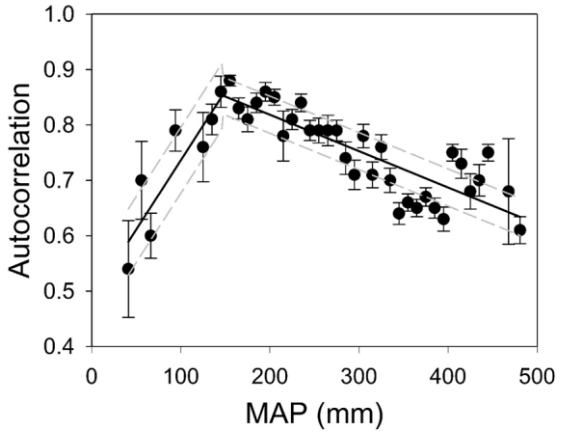
以空间代替时间的分析

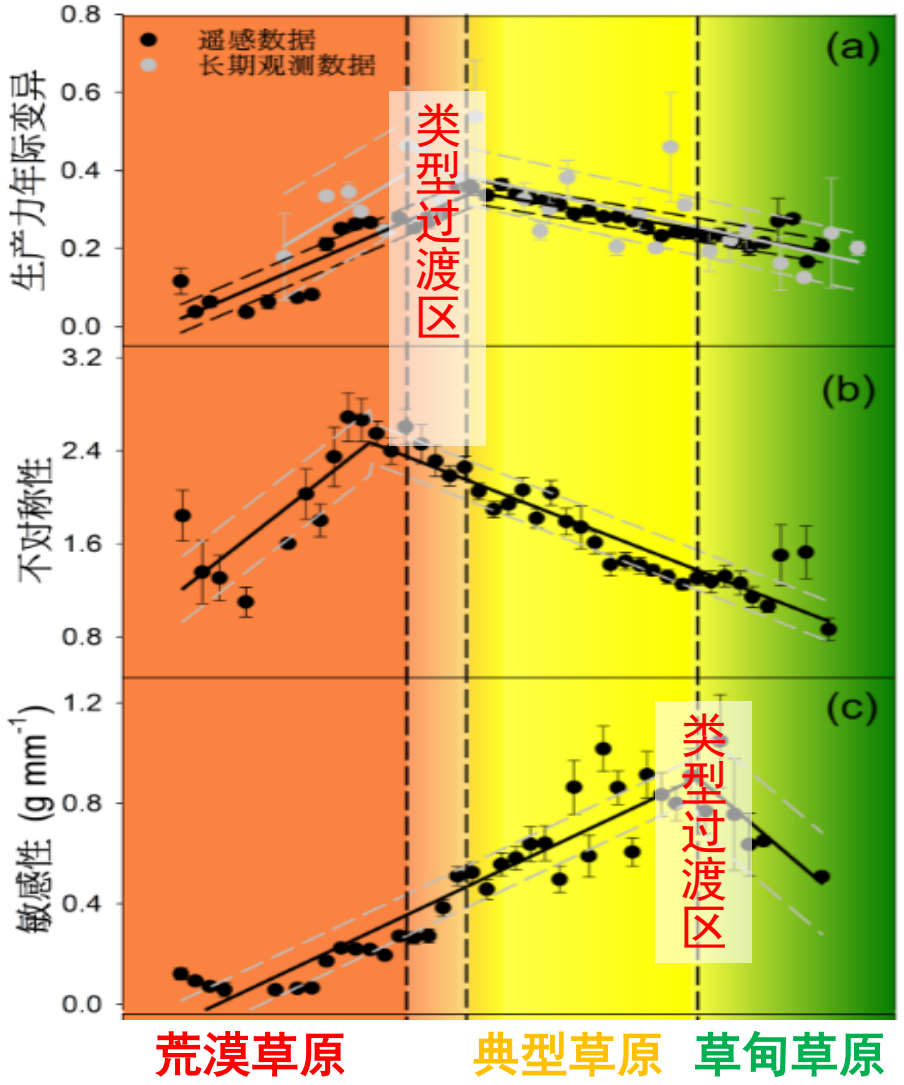
# 沿气候梯度所呈现的不同草地类型提供了天然实验室




用120个地面站连续多年的监测数据进行验证

# 验证了生产力动态指标预测群落类型转变的有效性



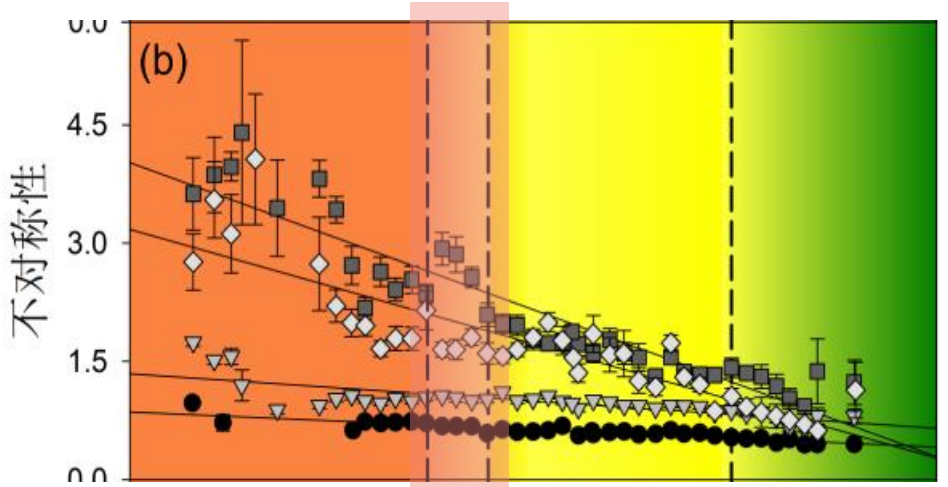




- 生产力变异性和非对称性在荒漠草原与典型草原过渡区达到峰值。
- 敏感性在典型草原与草甸草原过渡区达到峰值。

■ 生产力动态指标能有效的预测不同草原类型之间的转变

# 模型存在的问题：不能捕捉生态系统的状态转变

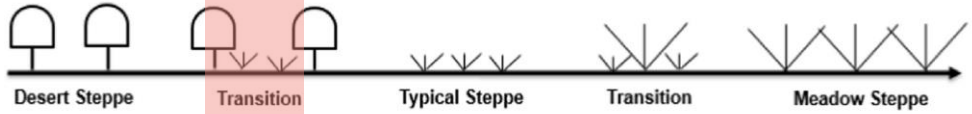
- 四个国际主流模型均无法预测转变（即转折点）




模型模拟结果

荒漠草原　典型草原　草甸草原

非对称性峰值　变异性峰值　非对称性峰值




群落学机制


√ 养分驱动机制

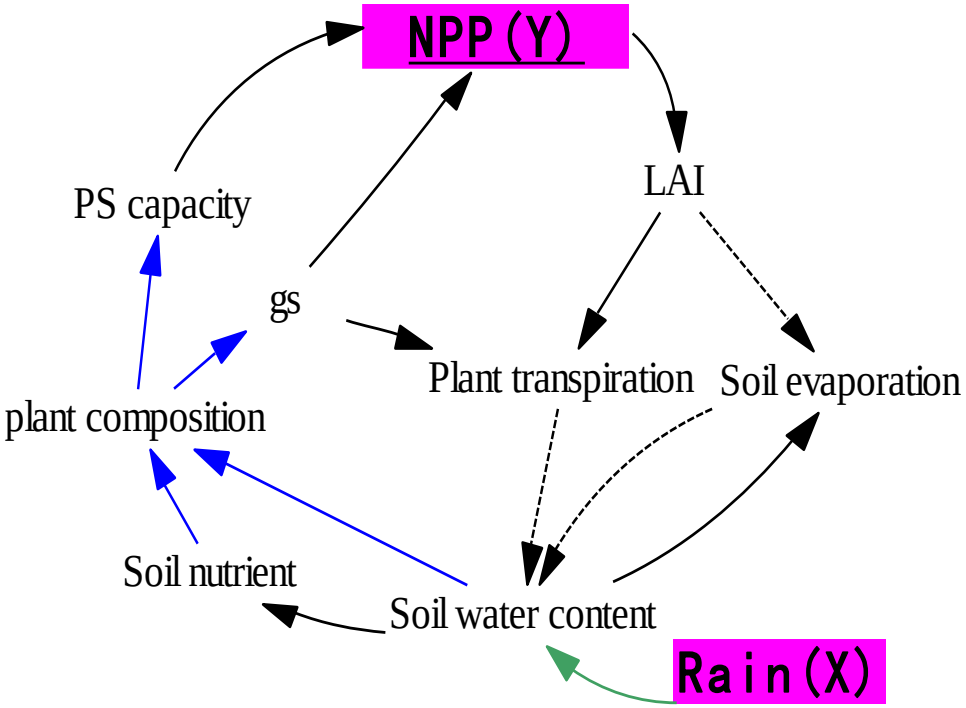

√ 水分驱动机制


Hu et al. 2018. Ecology Letters

# 对理论机理的验证

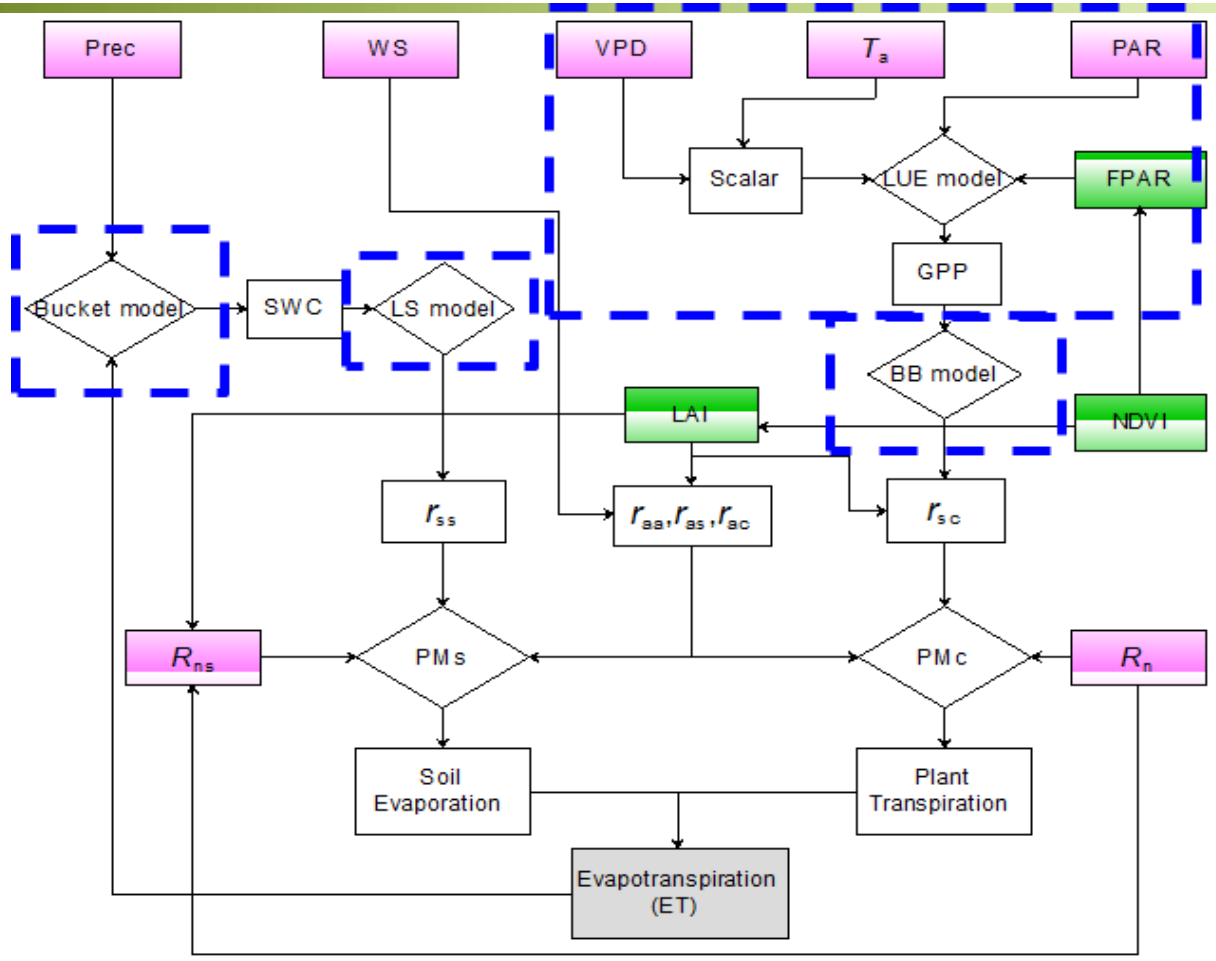
所提出的正反馈机制是否起主导作用?

# 降水影响植被生产力的内部过程复杂




To clarify the preci-NPP relation, we need study the internal processes at multiple spatiotemporal scales

# 研发了蒸腾蒸发估算模型




Hu et al. 2009. Agricultural and Forest Meteorology

Wu et al. 2020. Journal of Hydrology

Zhang et al. 2015. Ecological Modelling

Hu et al. 2013. Journal of Hydrology

Wu et al. 2021. JGR-Biogeosciences

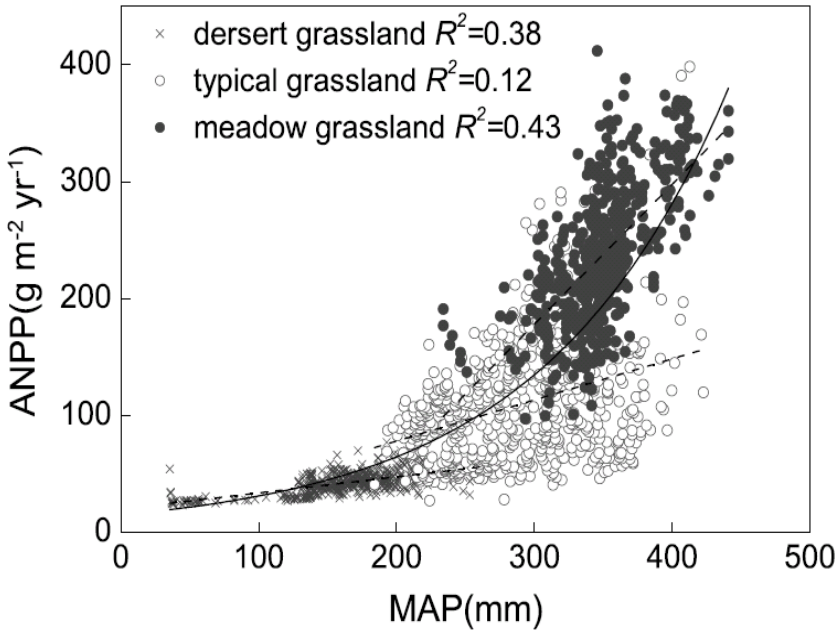
Hu et al. 2014. JGR-Biogeosciences

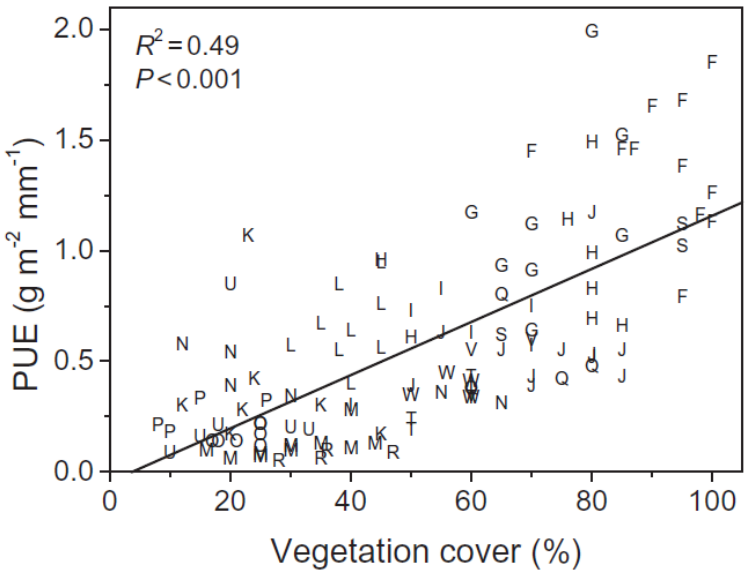
Cao et al. 2021, 2022, AFM

Hu et al. 2017. Remote Sensing

量化蒸腾蒸散比

# 降水利用效率空间变化格局与机理



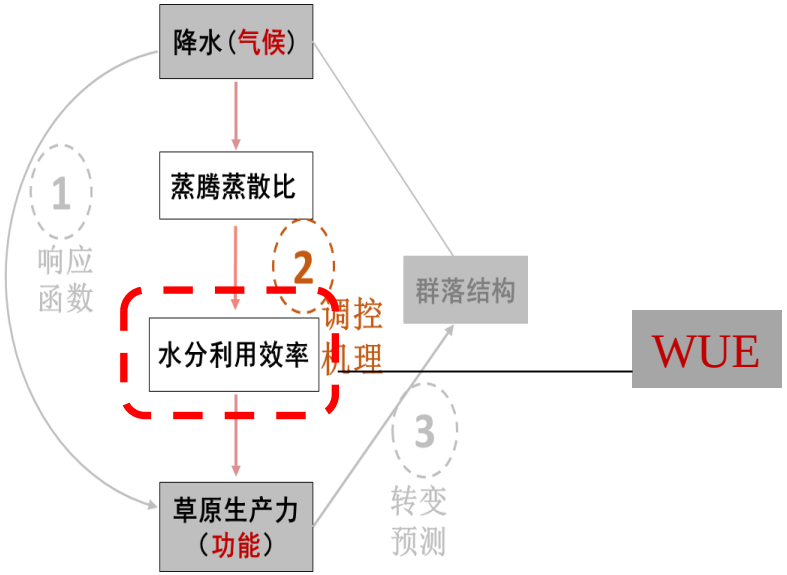




ANPP increased exponentially with MAP

Increase in vegetation cover reduce the runoff and soil evaporation, resulting higher PUE

Hu et al. 2010. Global Ecology and Biogeography

# LAI对生态系统水分利用效率（WUE）的调控机制

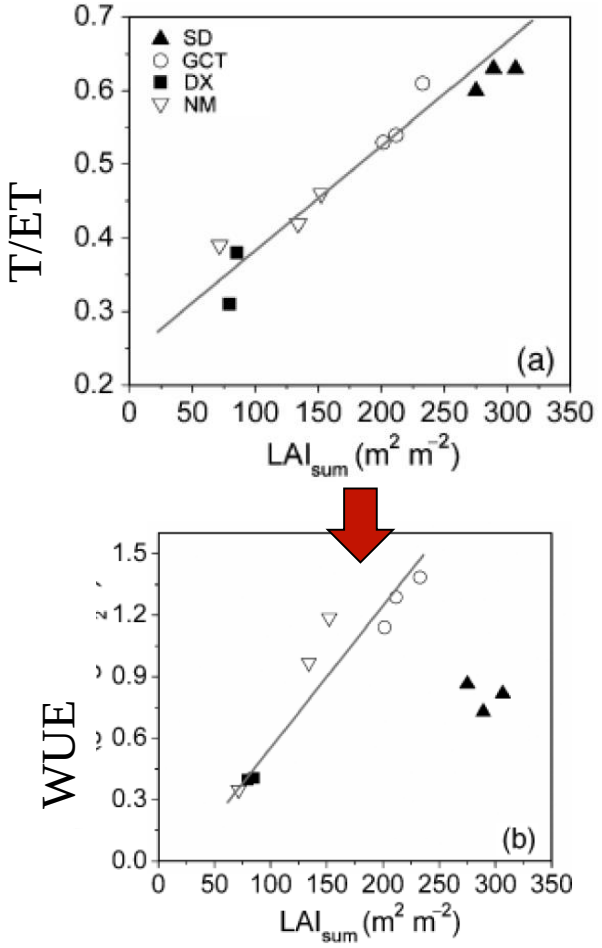



生理调控过程

$$\frac{GPP}{T}$$

$$\frac{T}{ET}$$

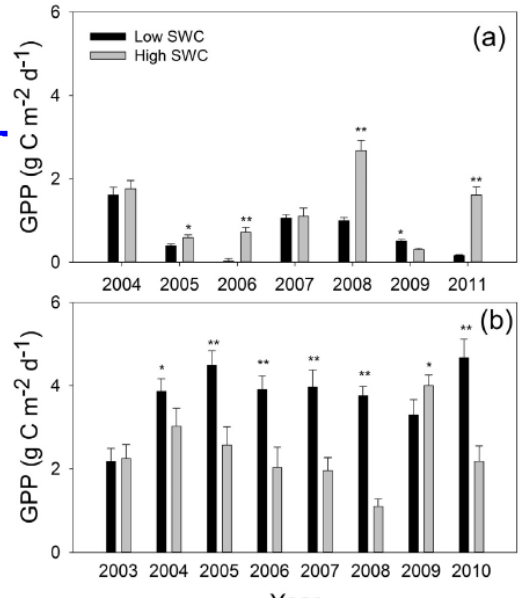
物理调控过程




Hu et al. 2008. Global Change Biology

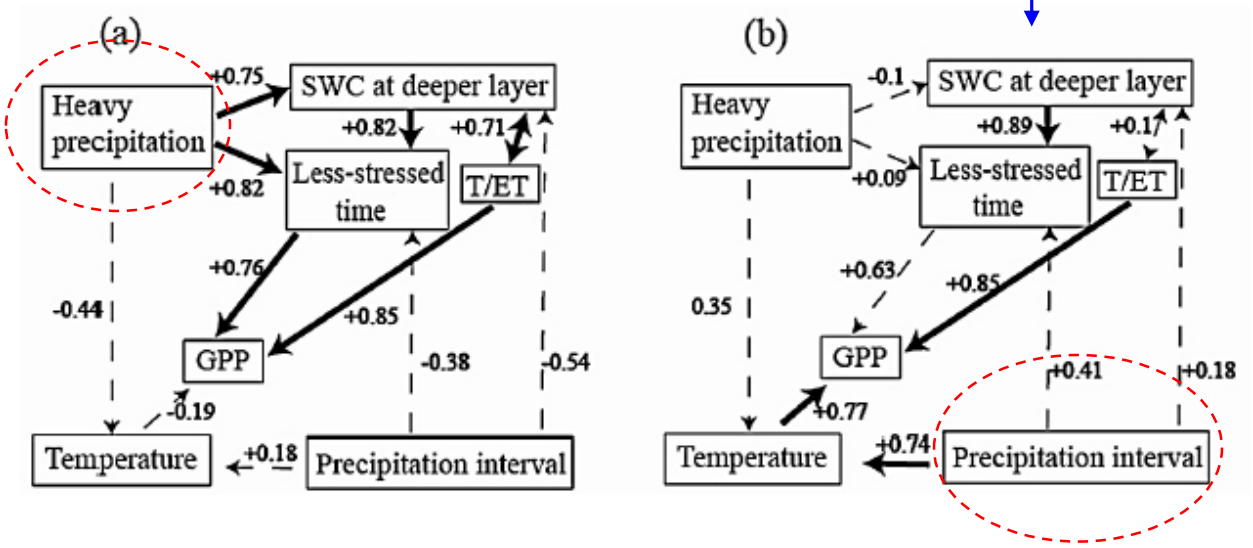
# Effects of rainfall characteristics on annual GPP

Temperate grassland




The VWC-GPP relation was contrast between two ecosystems

Alpine grassland




Guo et al., 2015. Agriculture and Forest Meteorology

# 功能指标的潜在优势

1. 大量遥感数据、地面长期监测数据对预测生态系统状态转变具有巨大潜力;
2. 容易与生态系统过程建立联系，有助于揭示导致状态转变的生态学机理;
3. 容易与生态系统过程模型建立联系，从而提升模型对于预测状态转变的能力;
4. 可预测生态系统突变和渐变。

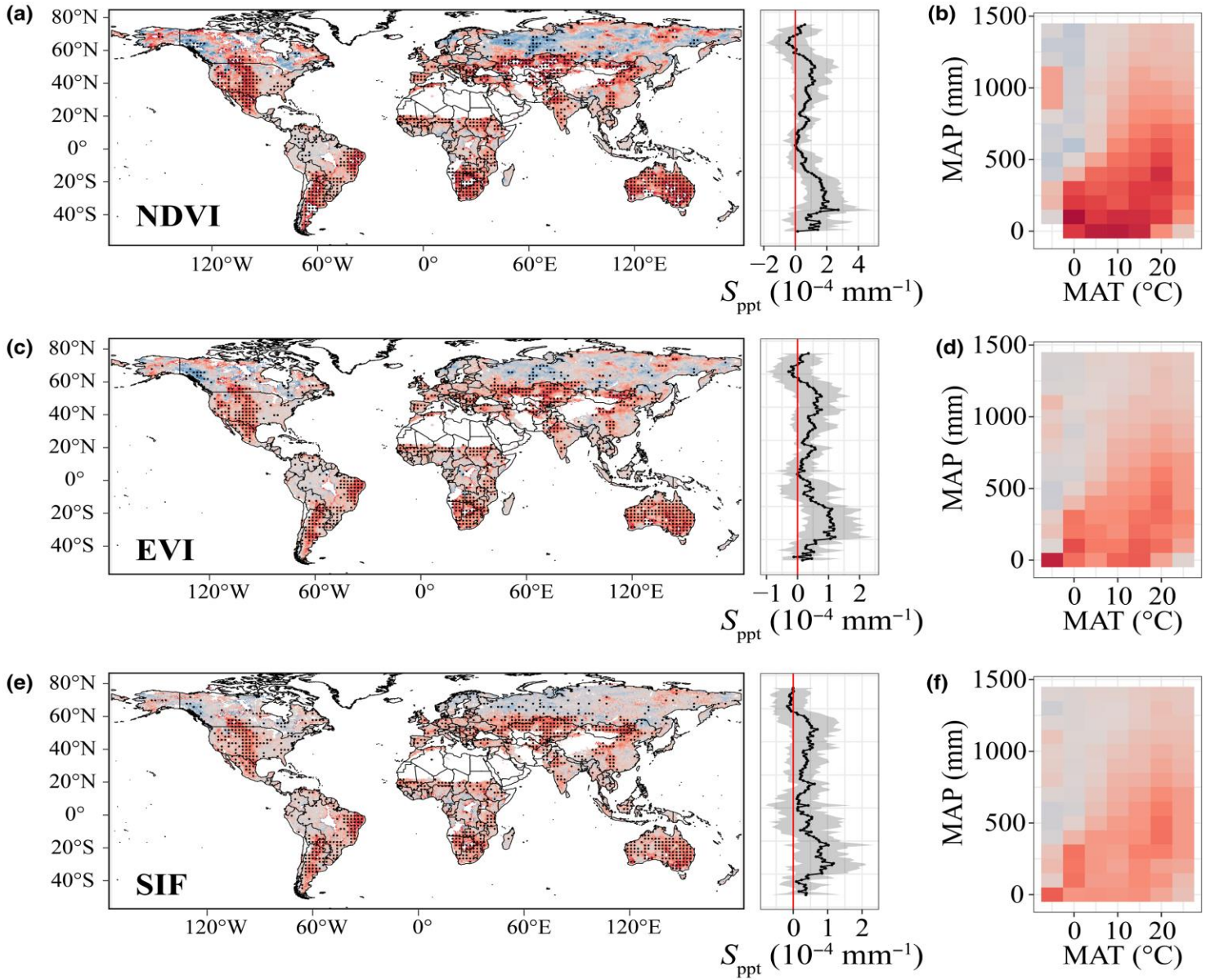
# 待进一步回答的问题

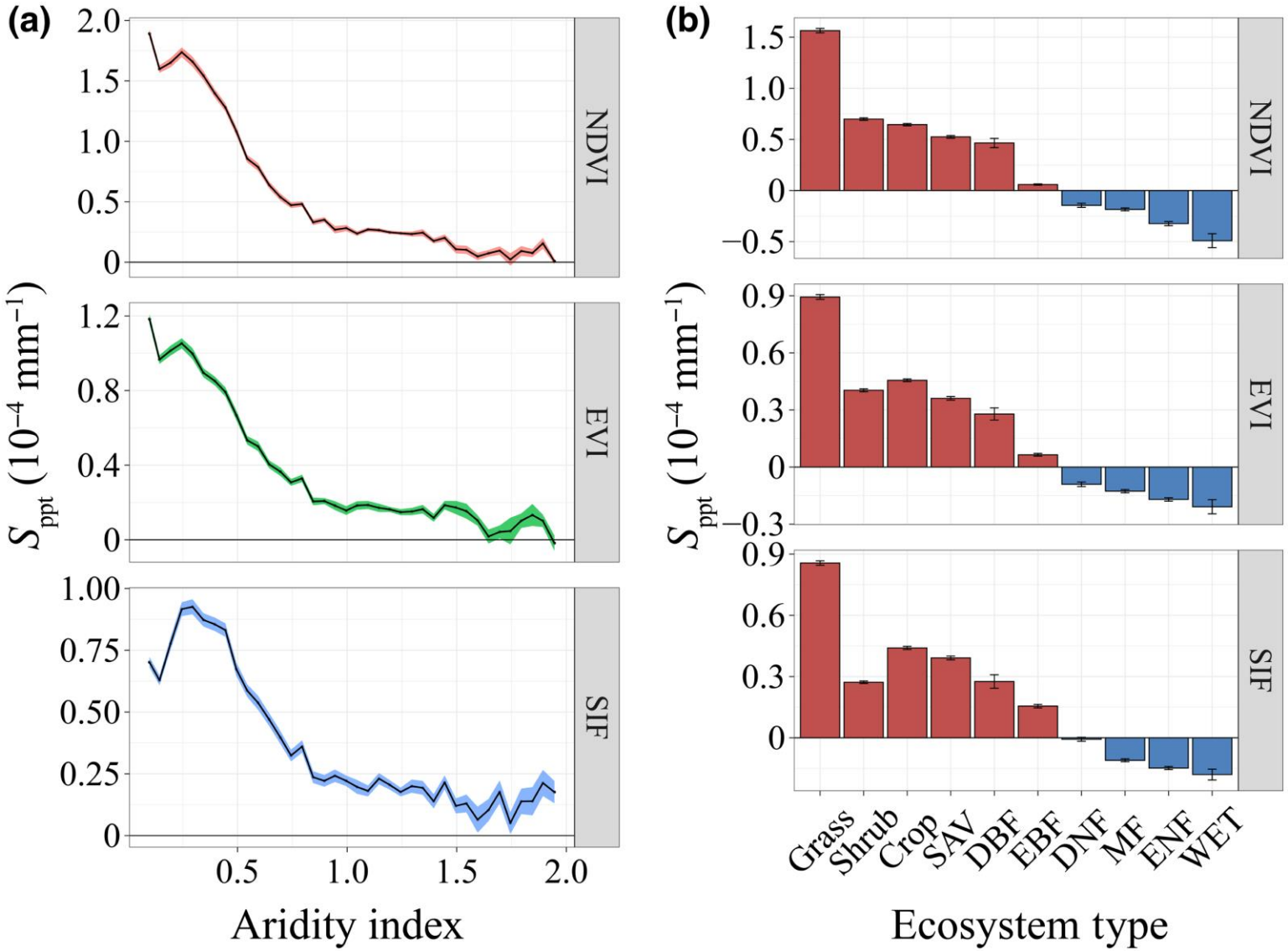
◆基于现有指标对陆地生态系统恢复力（Resilience）的评估;

◆对于非水分为主导限制因子的生态系统类型，如何构建指标体系：围绕主导限制因子设计;

◆如何提升生态系统过程模型预测状态转变的能力：以功能指标为参照，明确关键反馈过程和参数

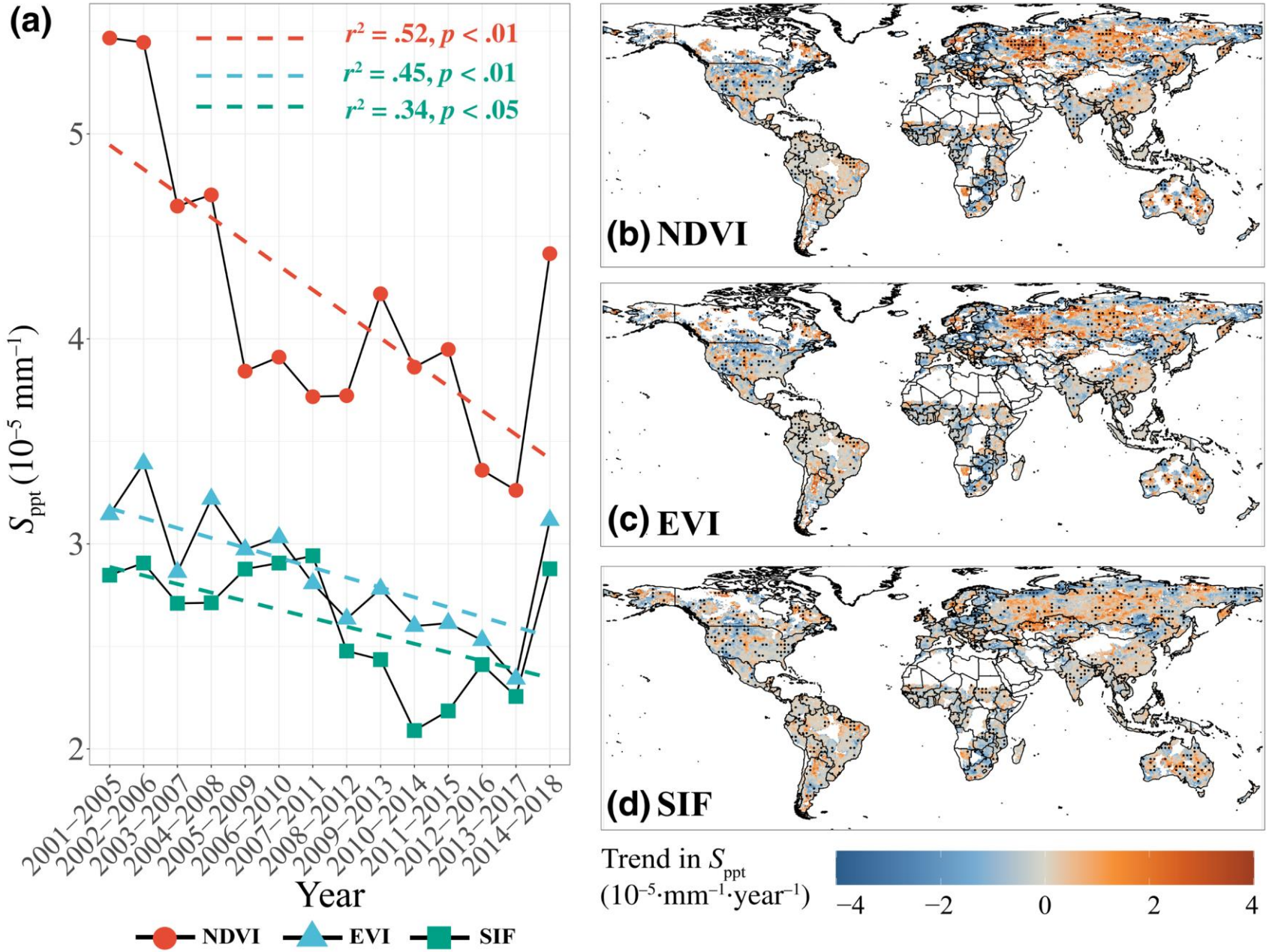
# 降水敏感性的空间格局


(a)
NDVI
(b)
(c)
EVI
(d)
(e)
SIF
(f)
80°N
60°N
40°N
20°N
0°
20°S
40°S
120°W
60°W
0°
60°E
120°E
MAP (mm)
1500
1000
500
0
MAT (°C)
0 10 20
$S_{ppt}$ ($10^{-4}$ mm$^{-1}$)
−2 0 2 4
−1 0 1 2
0 1 2
−3 −2 −1 0 1 2 3




Zeng, Hu* et al., 2022, GCB

# 全球植被生产力的降水敏感性总体呈下降趋势



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◆基于现有指标对陆地生态系统恢复力（Resilience）的评估;

◆对于非水分为主导限制因子的生态系统类型，如何构建指标体系：围绕主导限制因子设计;

◆如何提升生态系统过程模型预测状态转变的能力：以功能指标为参照，明确关键反馈过程和参数

敬请指正!