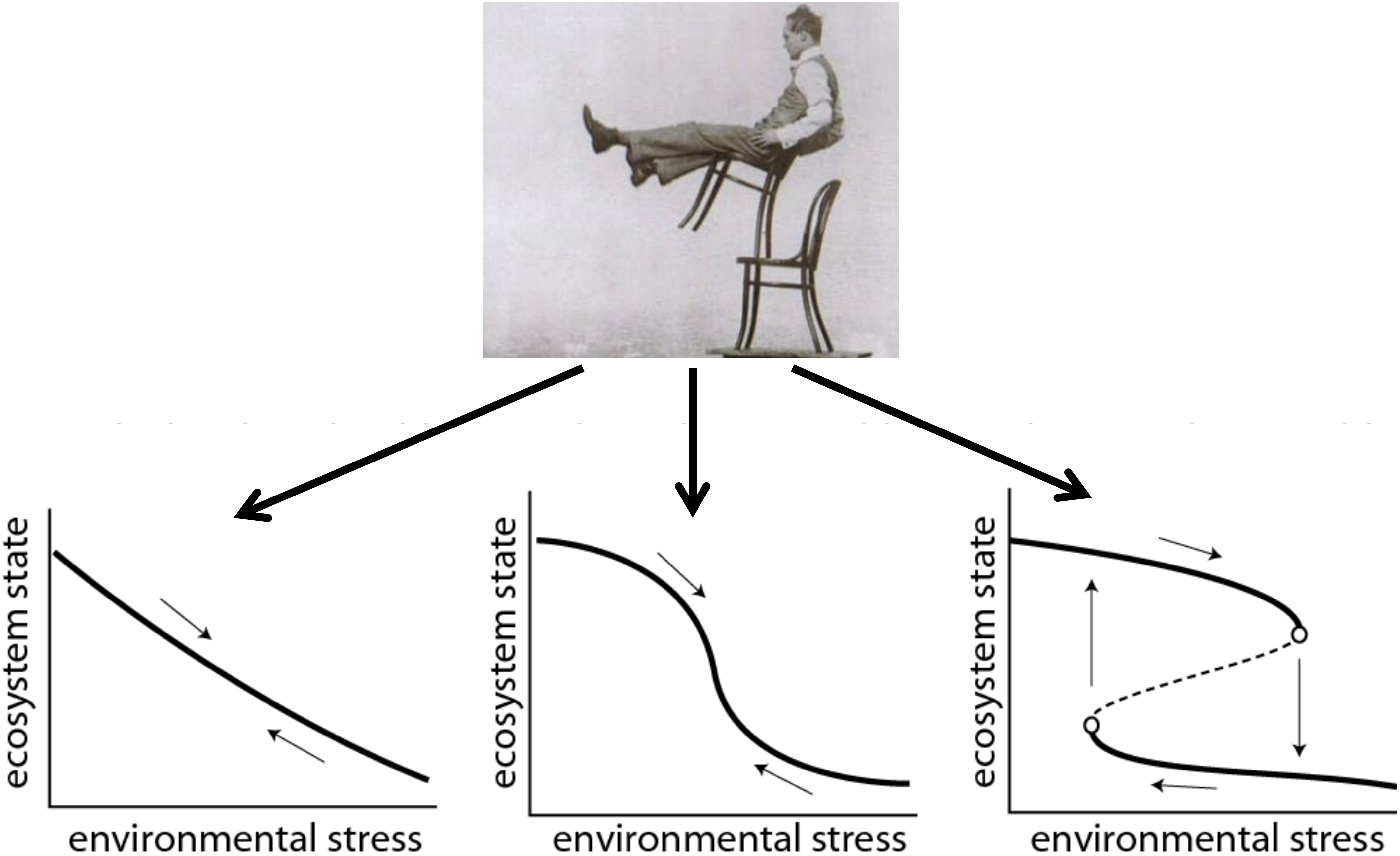
Is he stable?

What keeps him from falling?

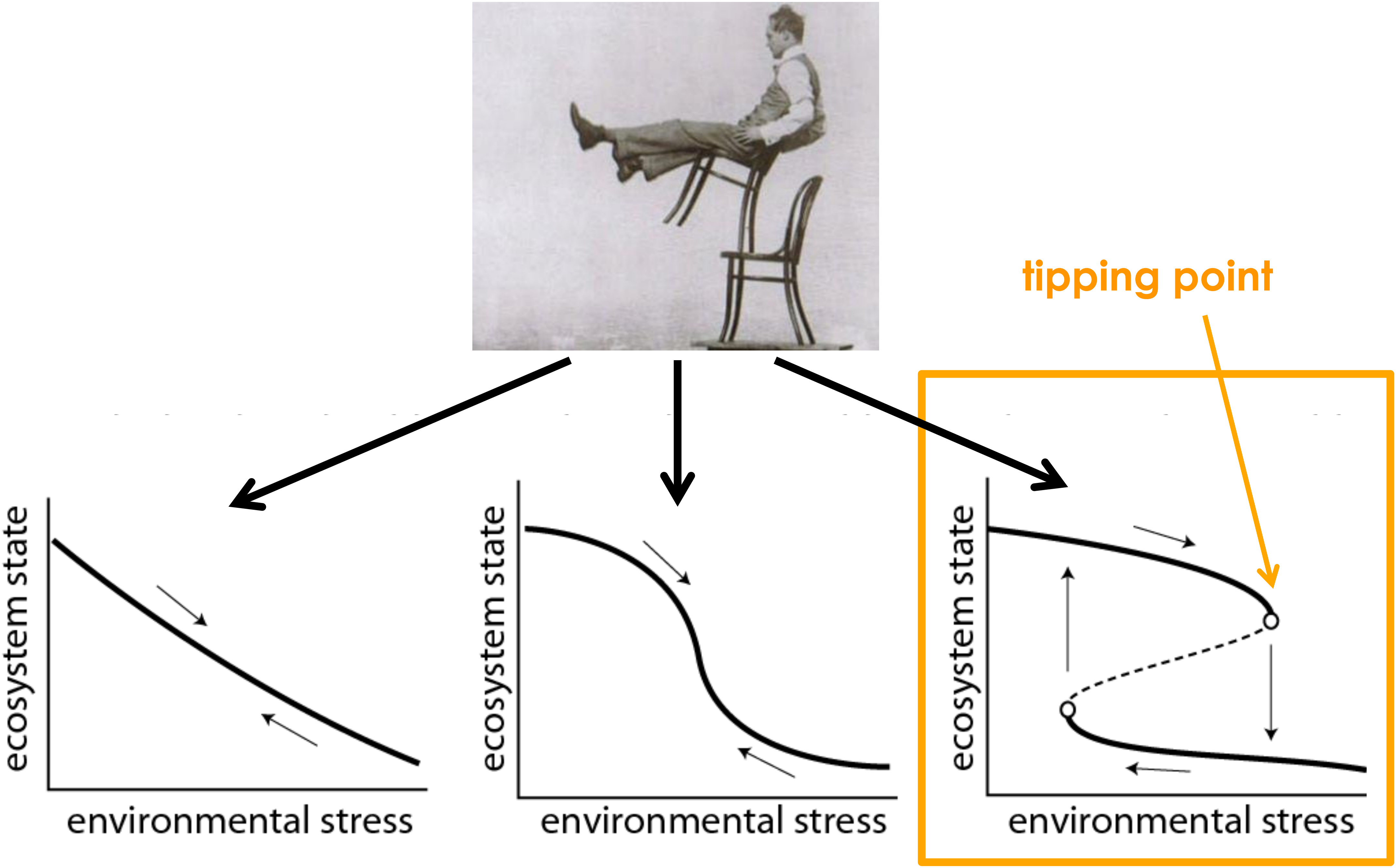
How did he get there in the first place?

**When** and **where to** is he going to fall?

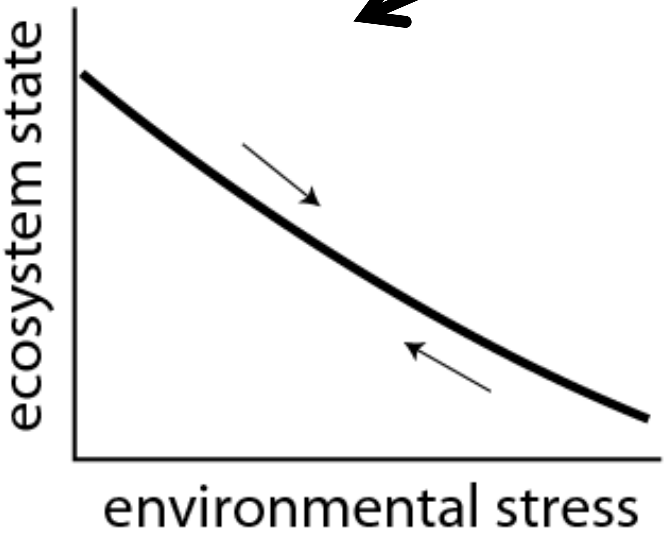
# How will ecosystems respond to environmental stress?

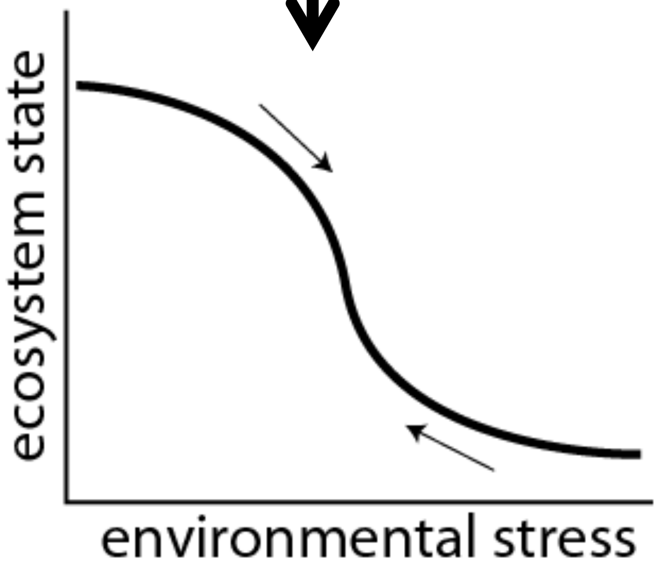


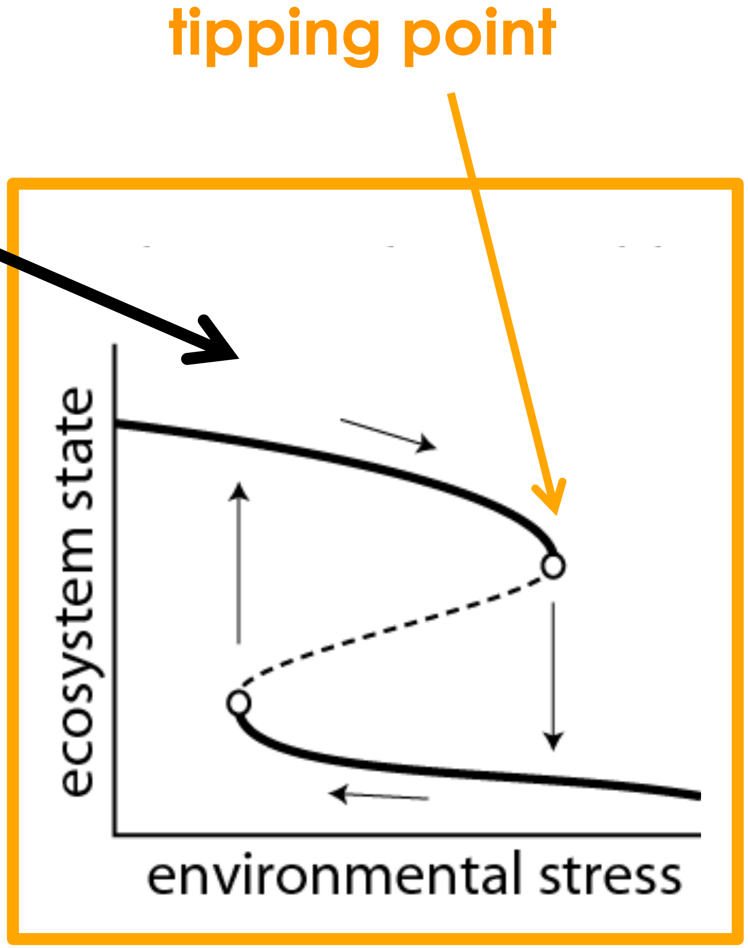
# How will ecosystems respond to environmental stress?



# How will ecosystems respond to environmental stress?

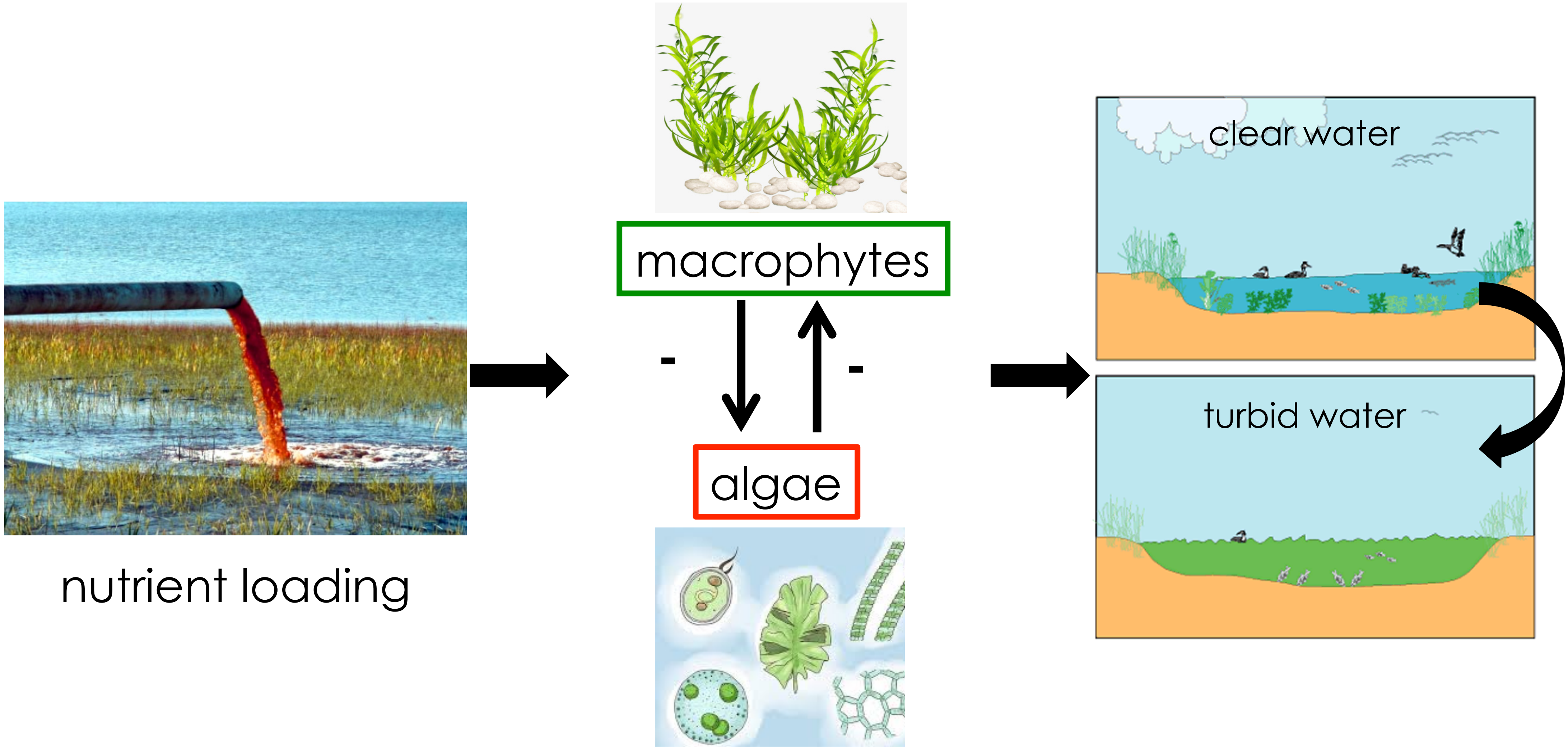


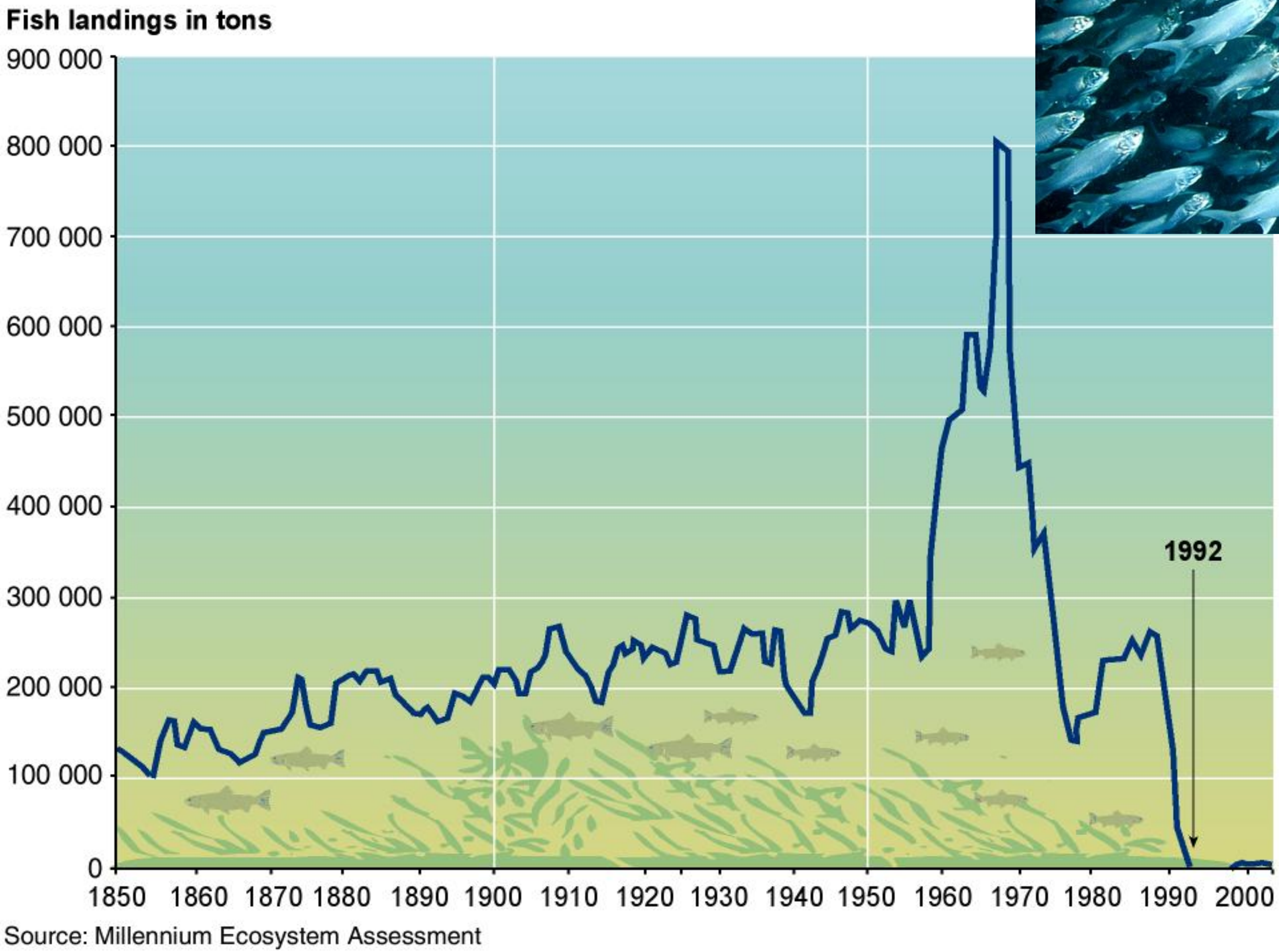
# tipping points to lake eutrophication

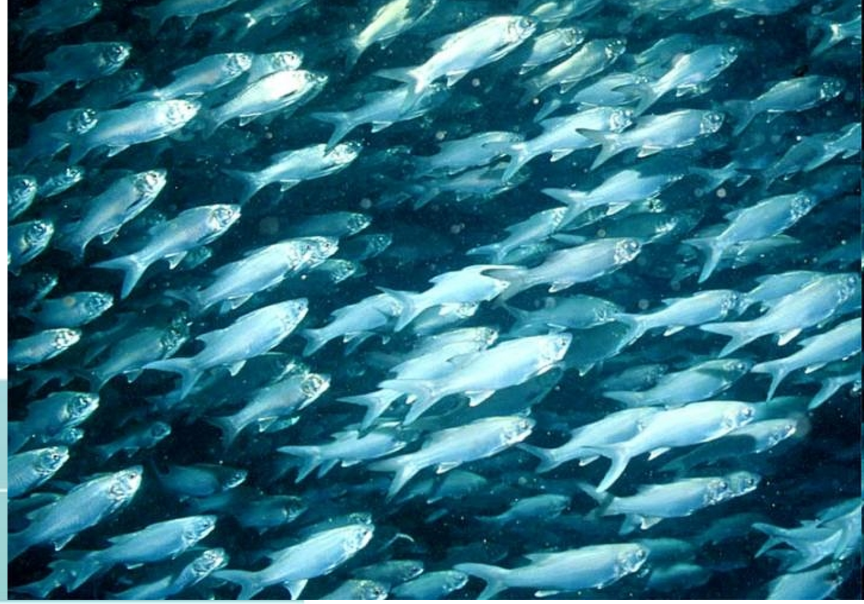
# shallow lake tipping points to eutrophication



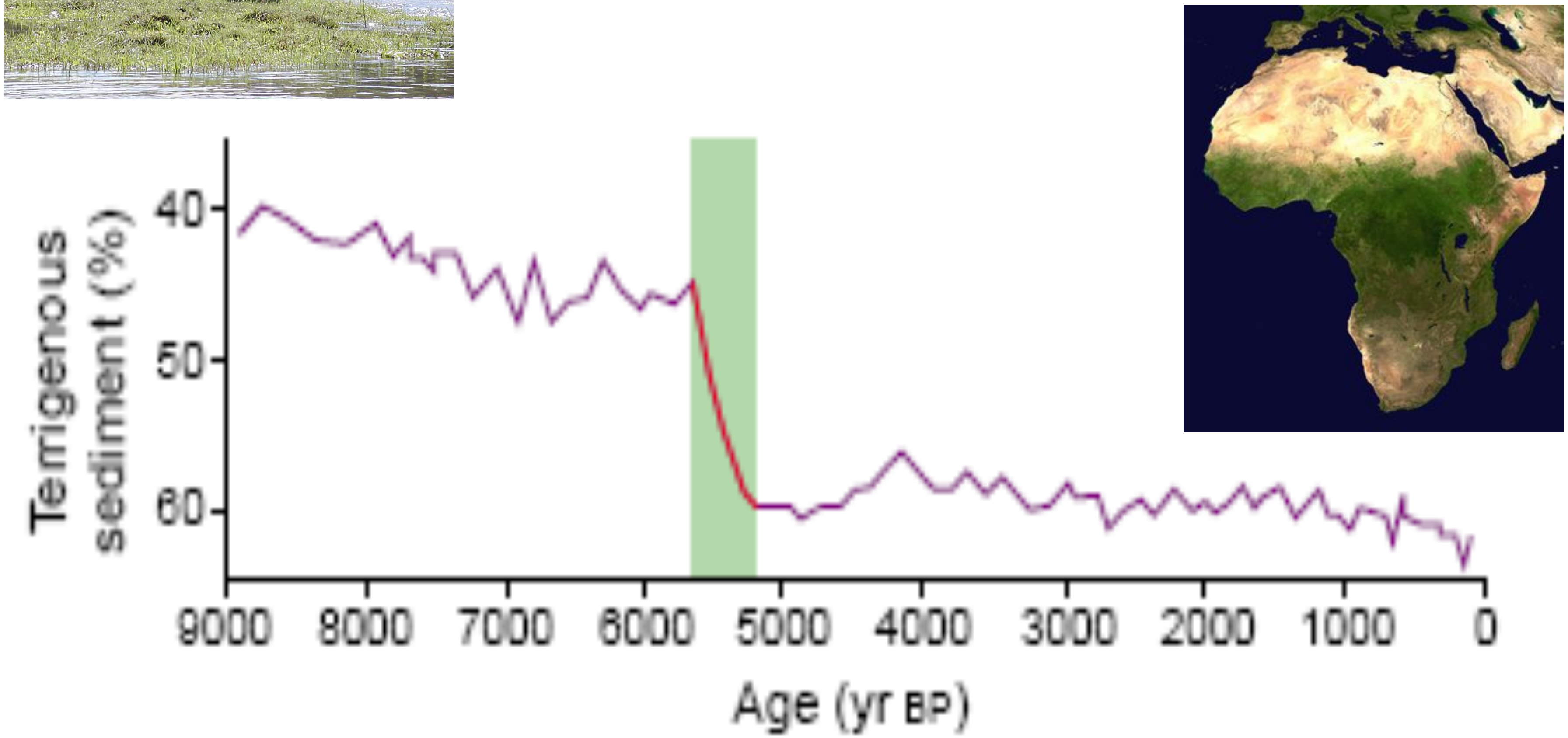

Uhlmann 1980, Developments in Hydrobiology

# populations collapse



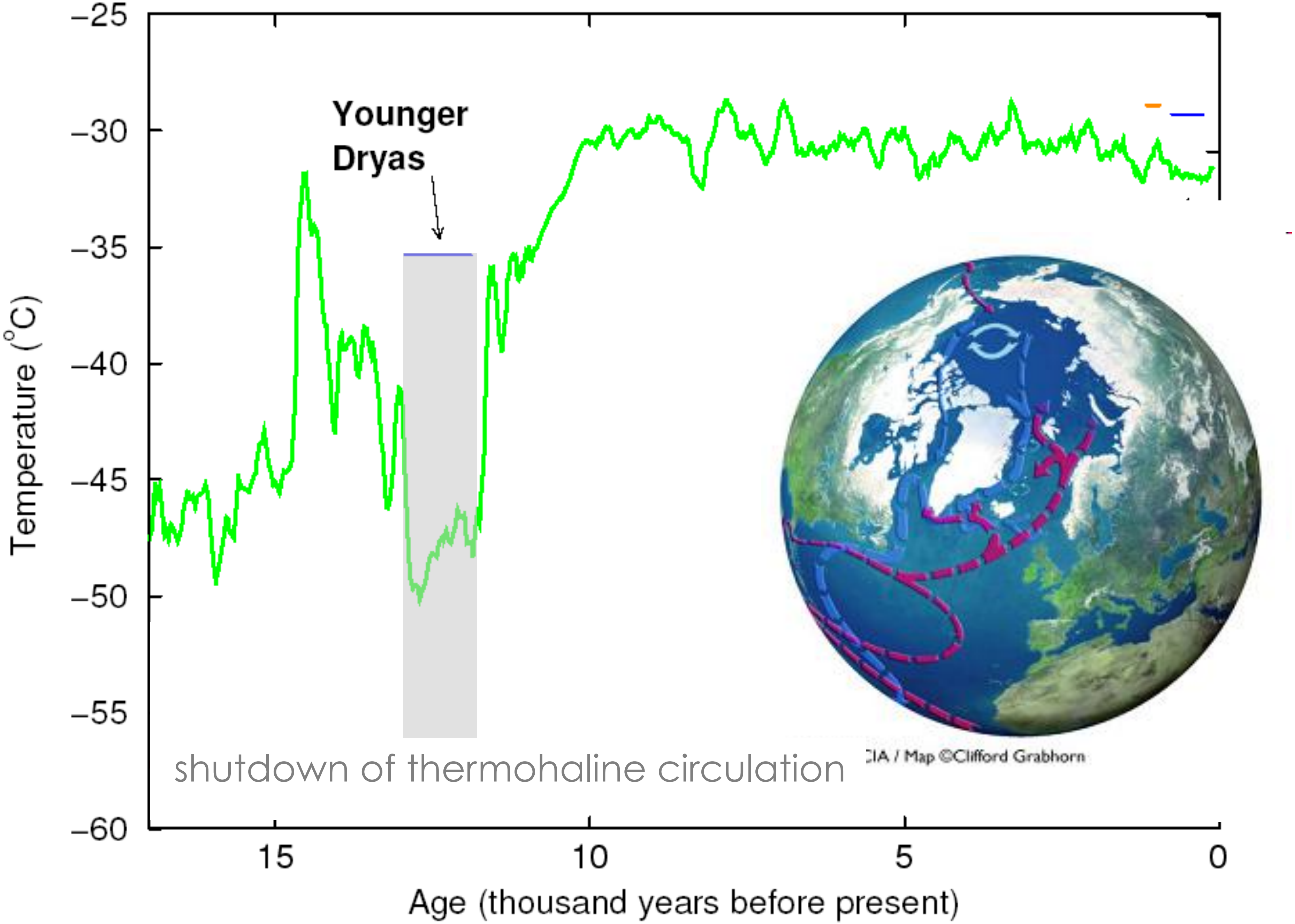



# biomes may shift to a desert state

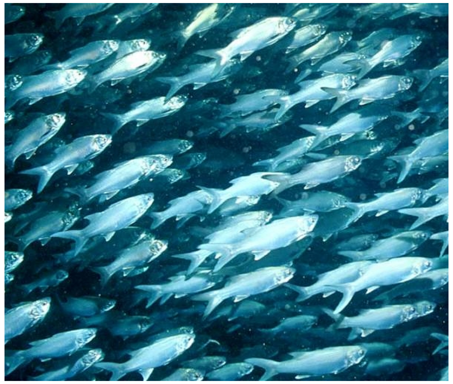

deMenocal et al (2000), Science

# climate systems can change abruptly

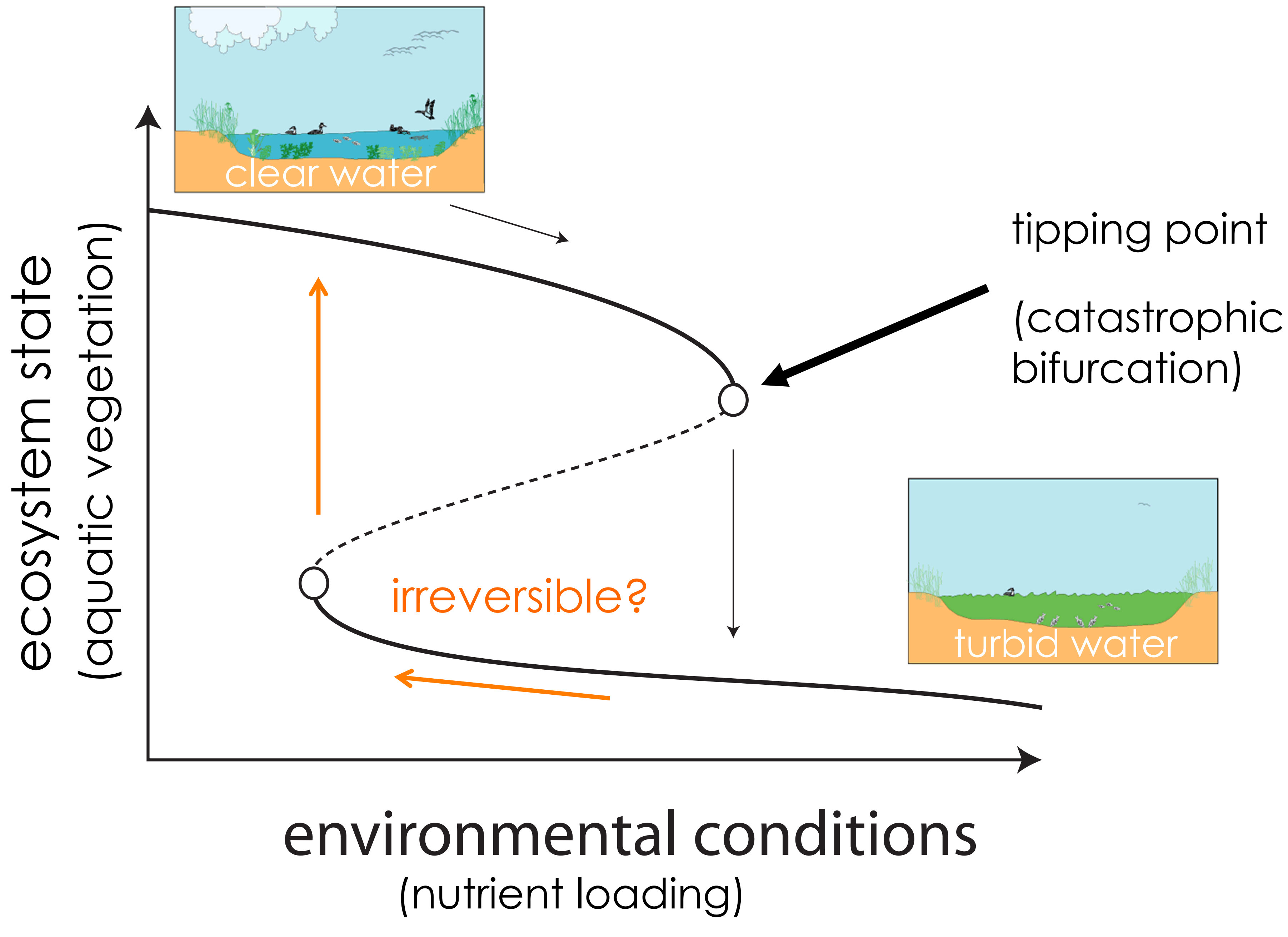


understand and detect

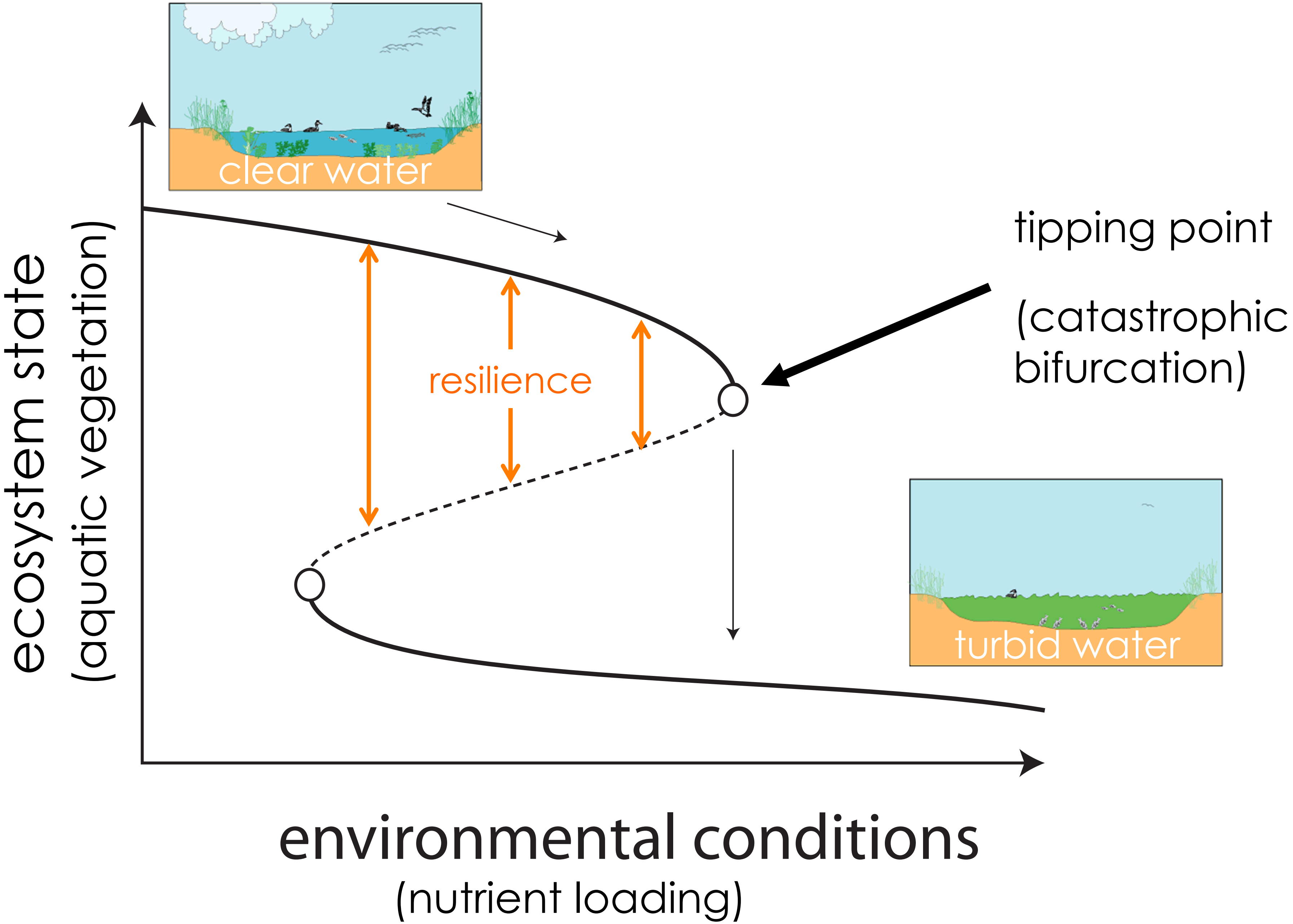
**abrupt** ecosystem responses to stress

# tipping point and alternative stable states

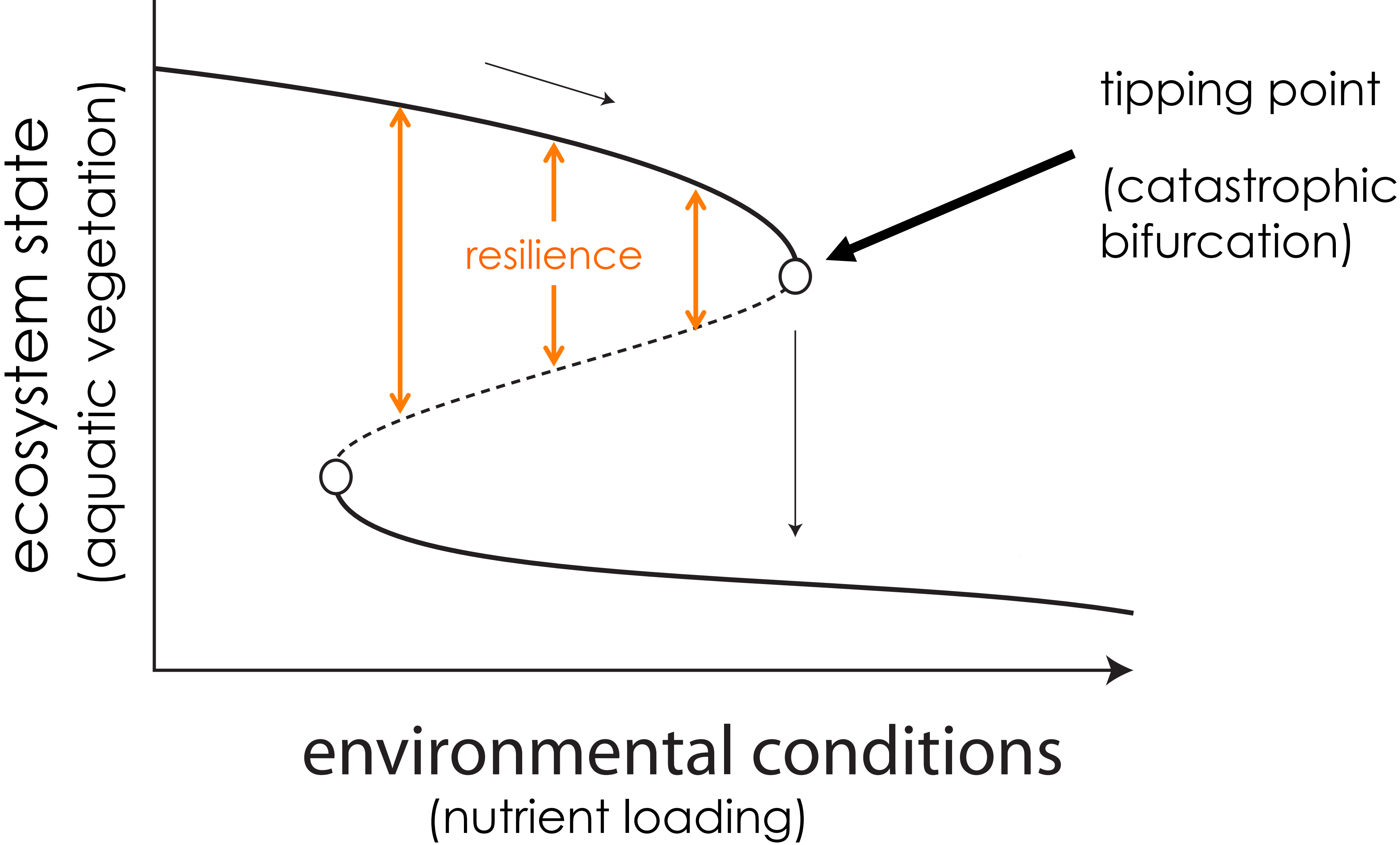


# tipping point and alternative stable states



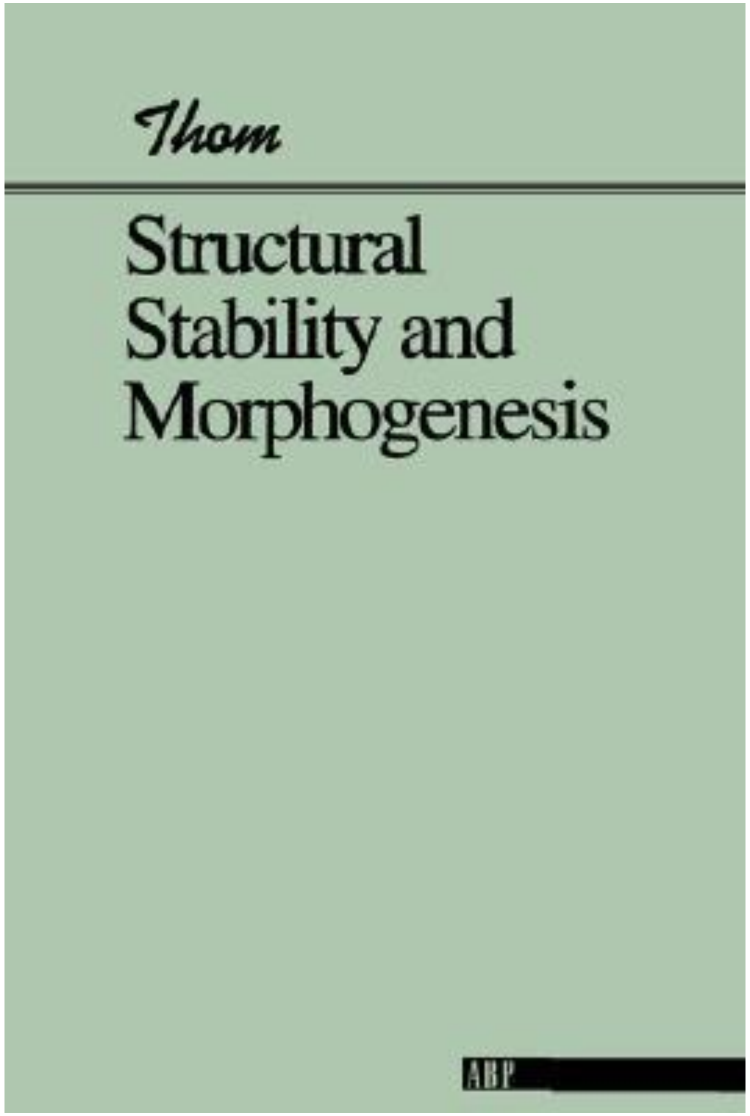
# Can we detect tipping points in advance?



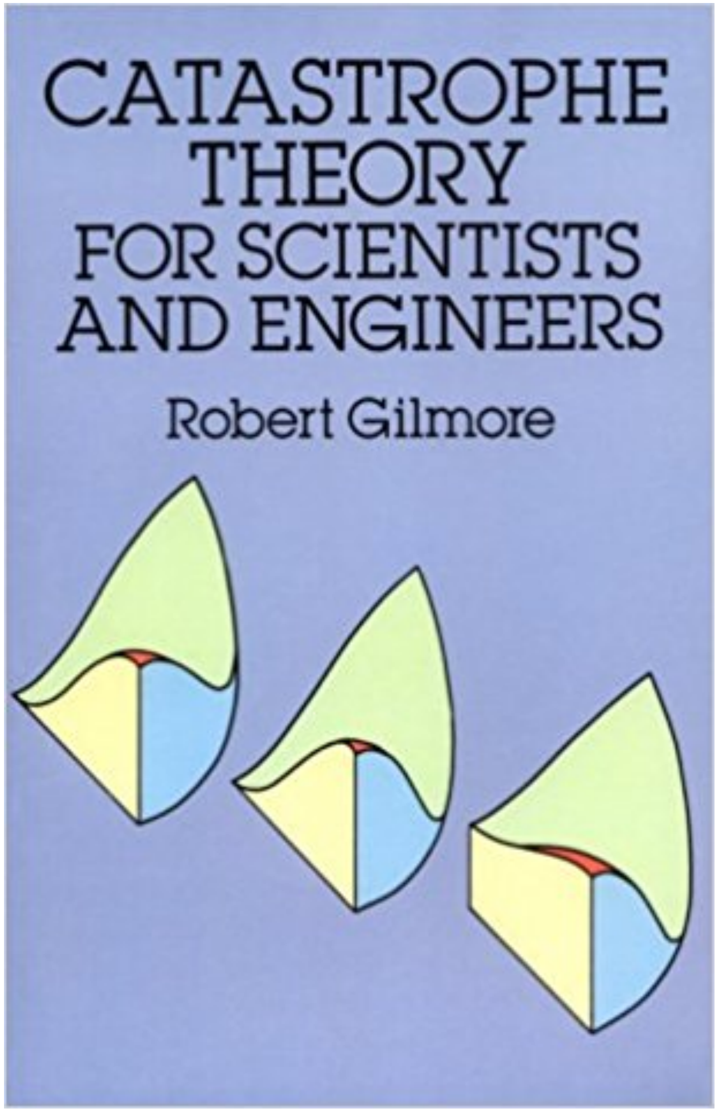



# systems prior to tipping points slow down

# catastrophe theory and catastrophe flags

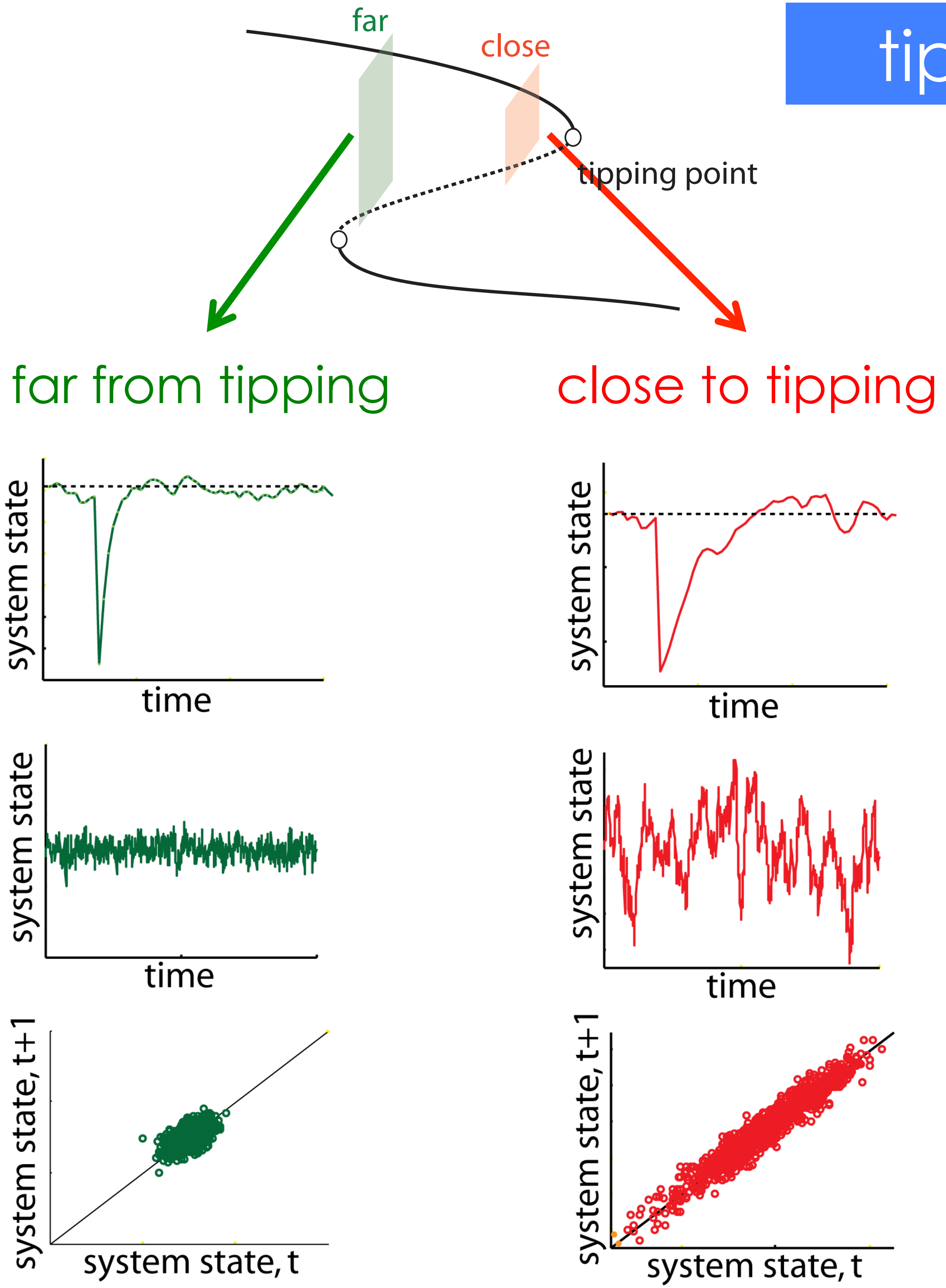



Thom 1976




Gilmore 1981

# tipping point detection




leading indicators

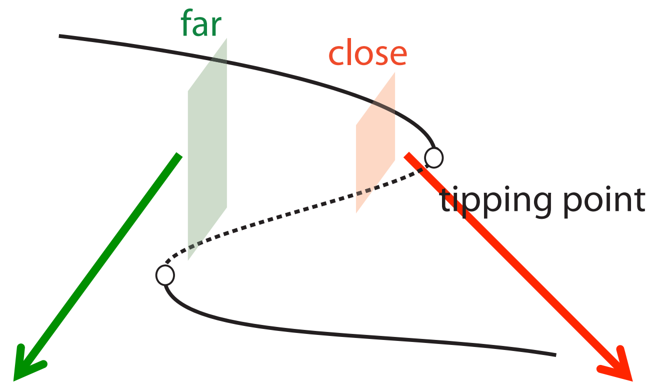
recovery time increases

variance increases

autocorrelation rises

Scheffer et al 2009, Nature

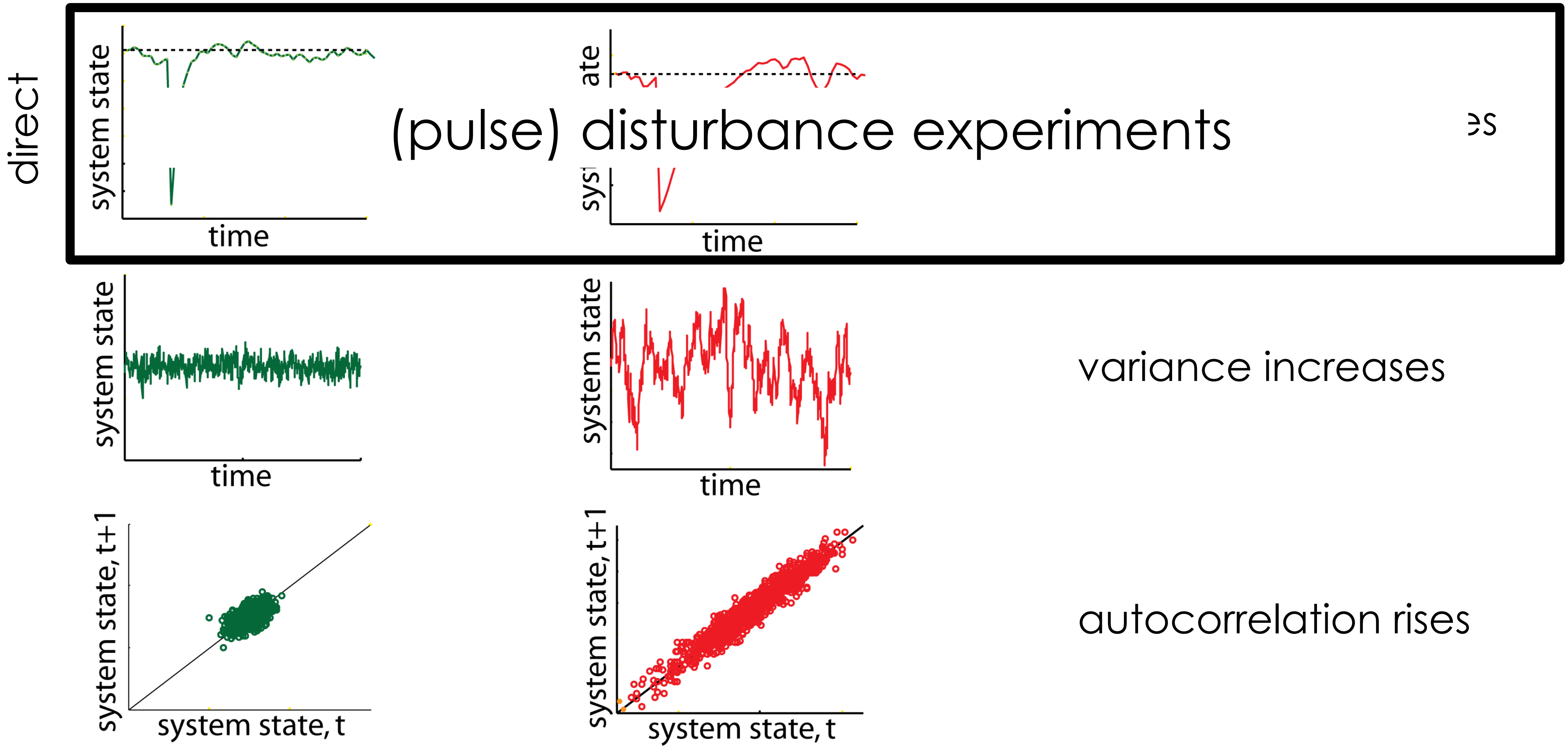
# tipping point detection




far from tipping

close to tipping

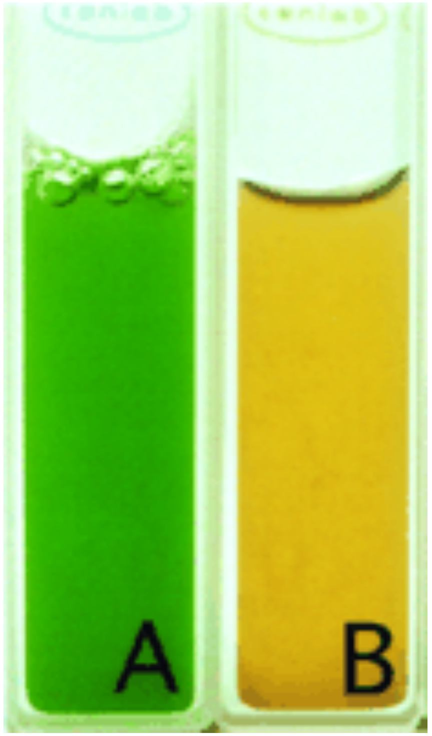
leading indicators




Scheffer et al 2009, Nature

# direct indicators: disturbance experiments

phytoplankton collapse due to photoinhibition

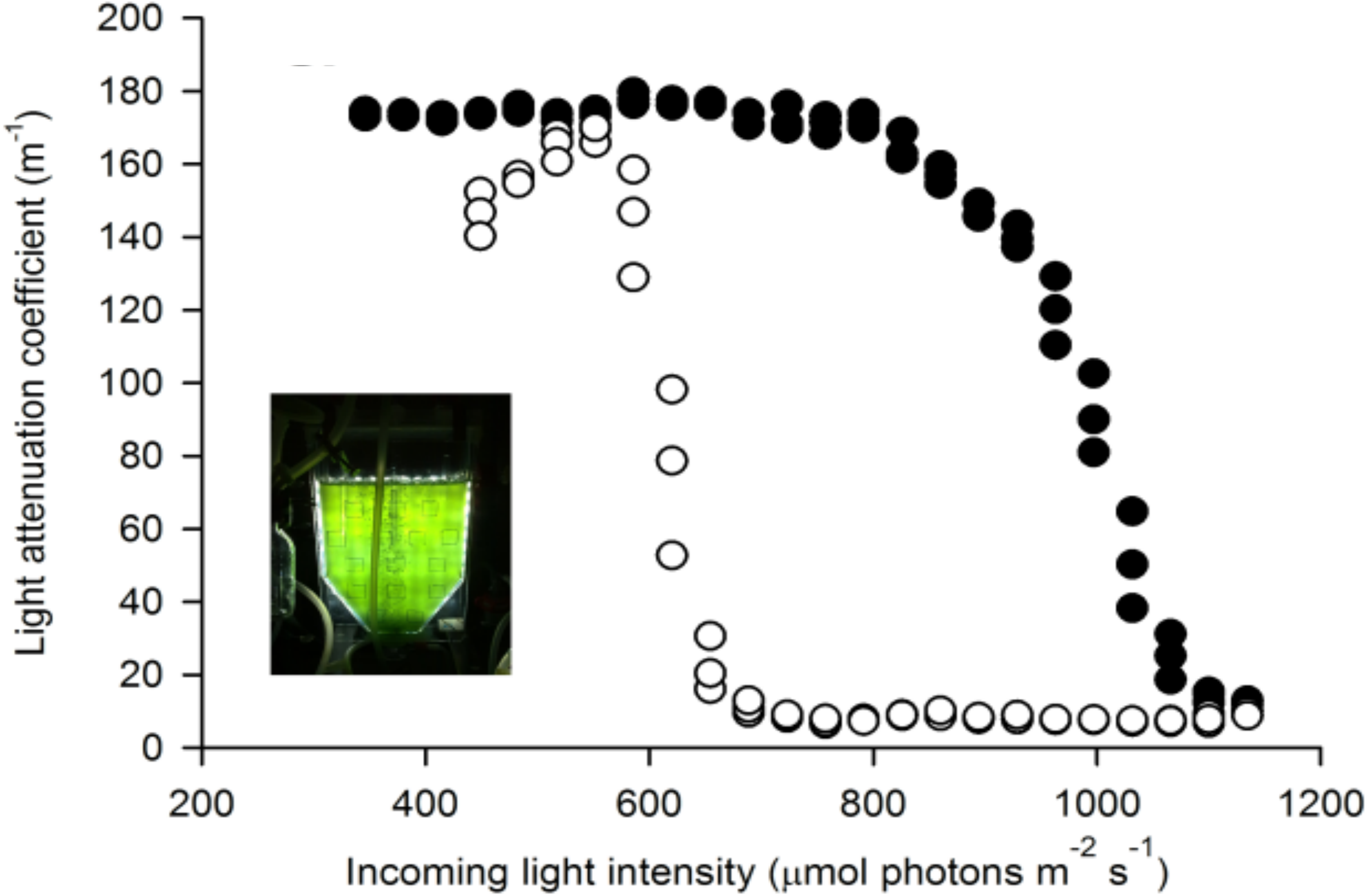


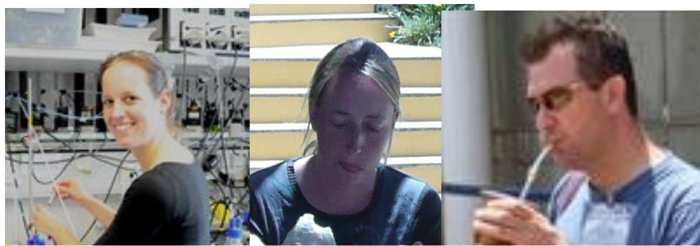


eg Long et al 1994

# direct indicators: disturbance experiments

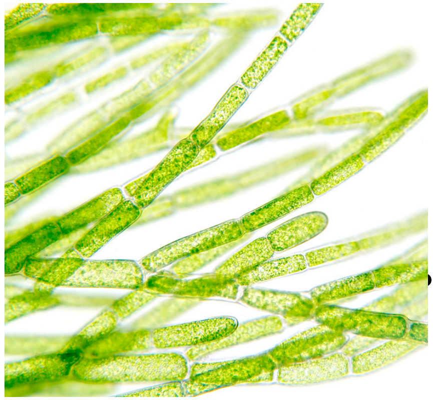
phytoplankton collapse due to photoinhibition



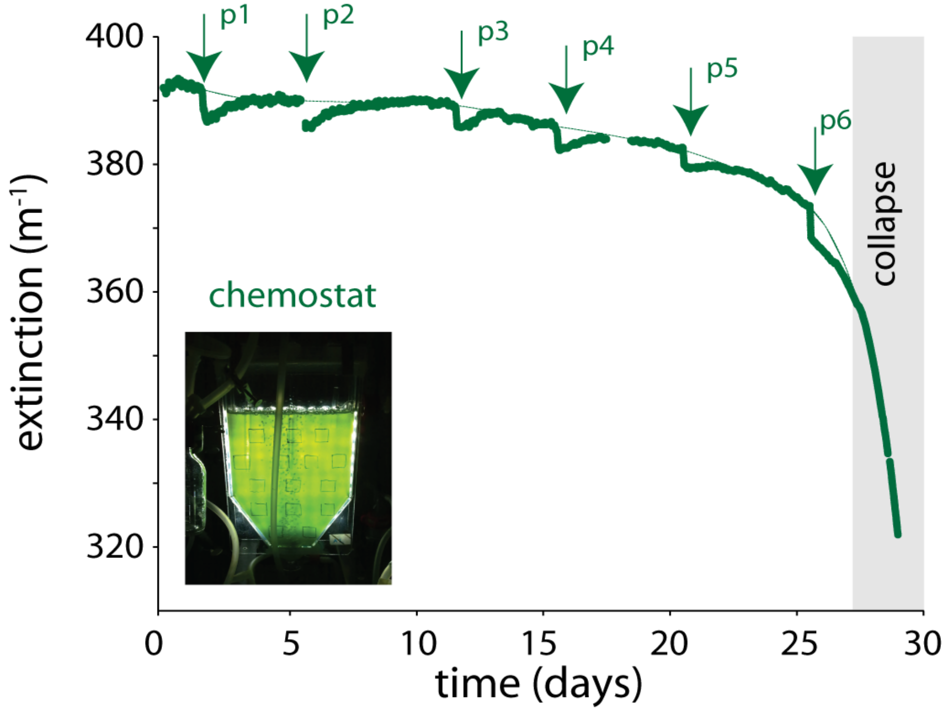
Faasen, Veraart, van Nes, Dakos, Lurling, Scheffer 2015, Oikos

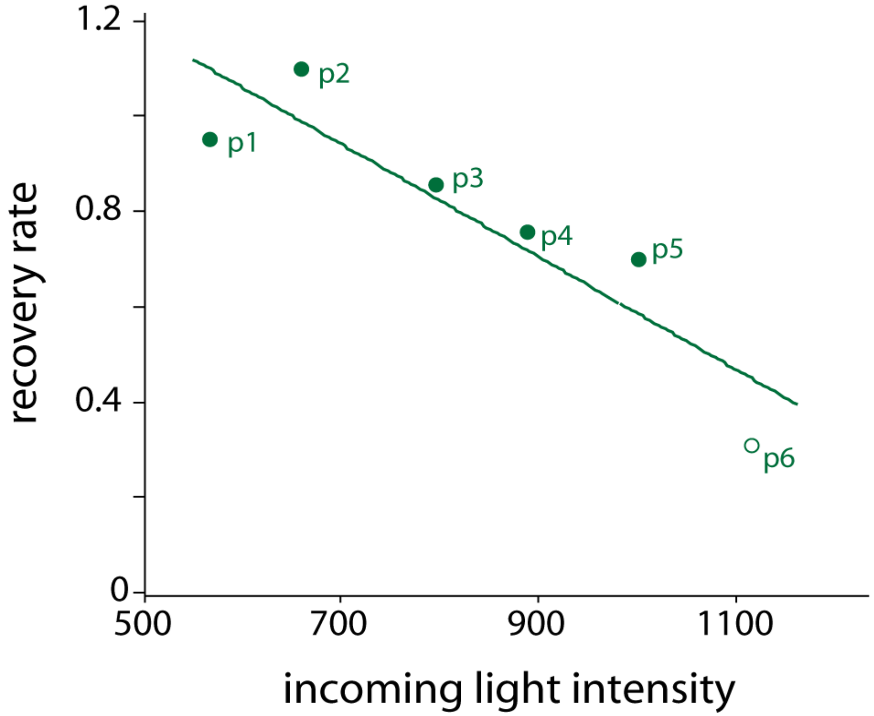
# direct indicators: disturbance experiments



phytoplankton collapse due to photoinhibition

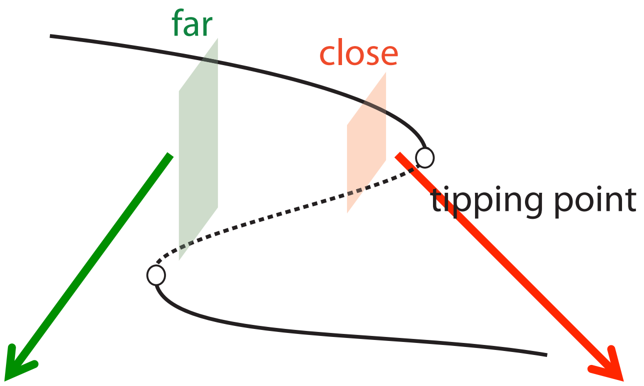
- removal of 10% of standing stock through dilution



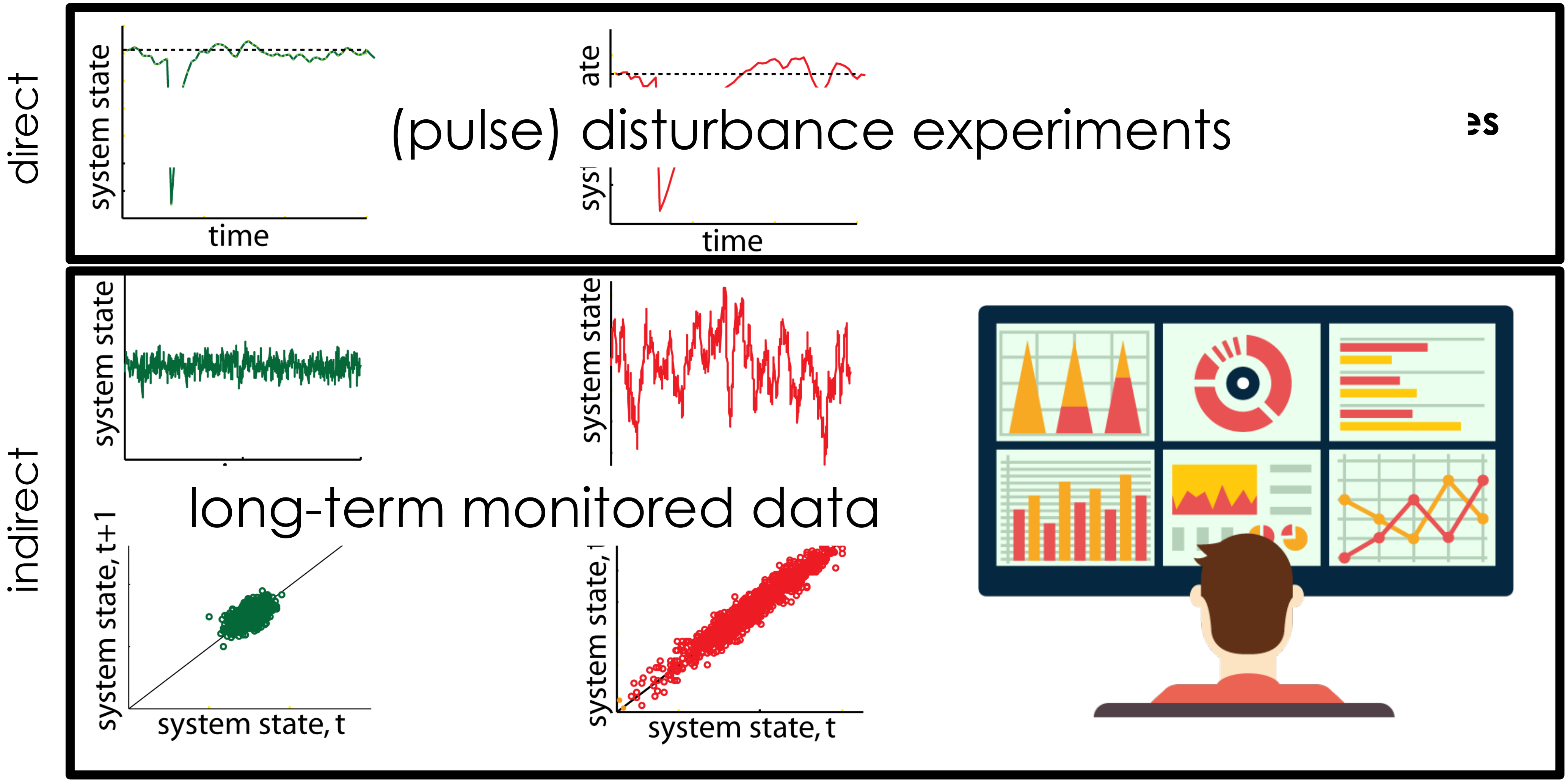




Veraart et al 2012, Nature

# tipping point indicators



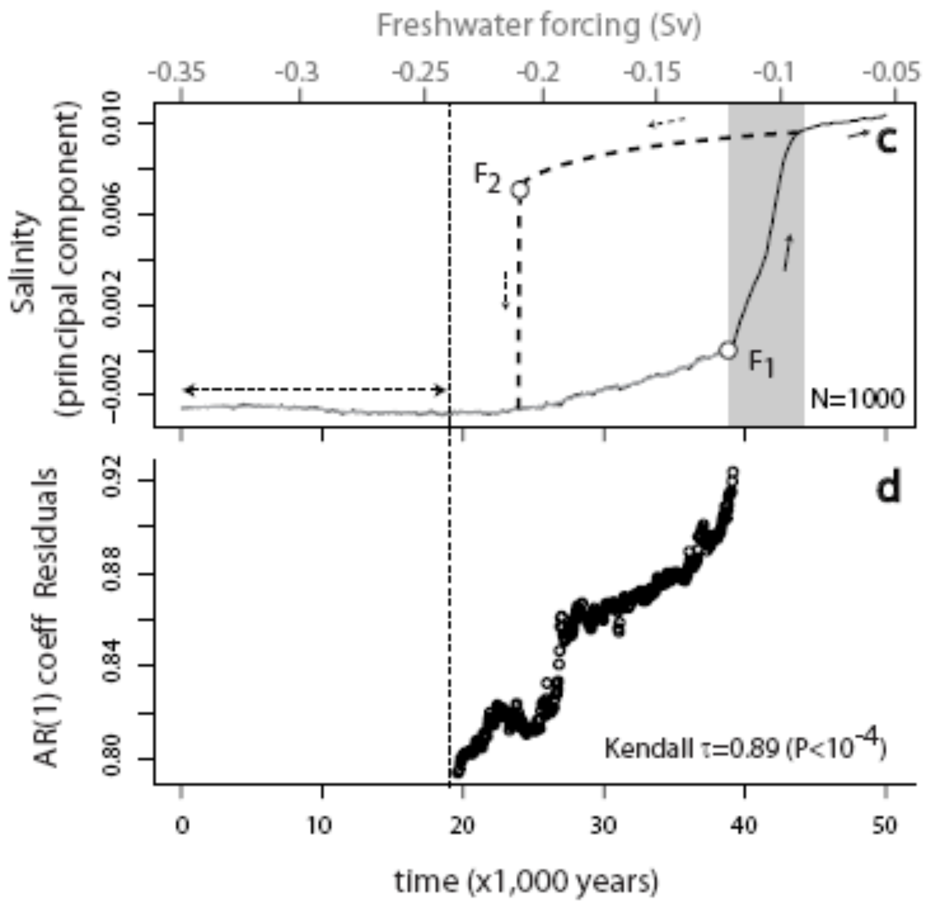

**far from tipping** | **close to tipping** | **leading indicators**




Scheffer et al 2009, Nature

# slowing down before past climate shifts

**Shutdown of thermohaline circulation**



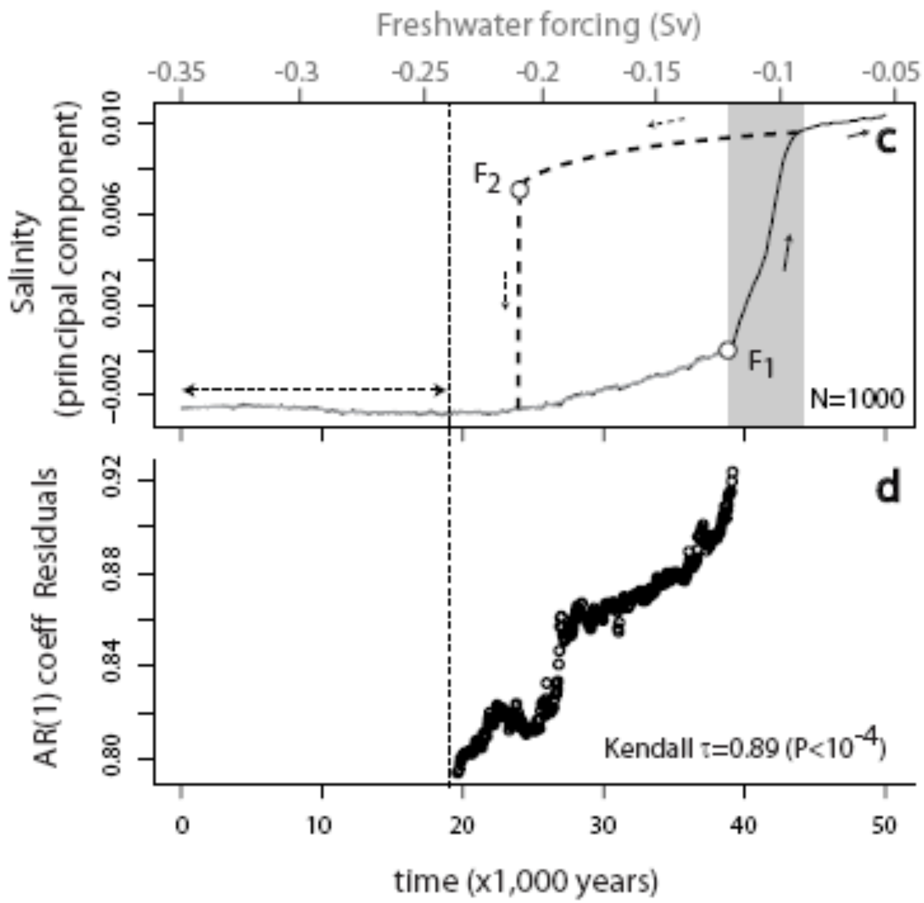

Model data

©2004, ACIA / Map ©Clifford Grabhorn

Dakos et al 2008, PNAS

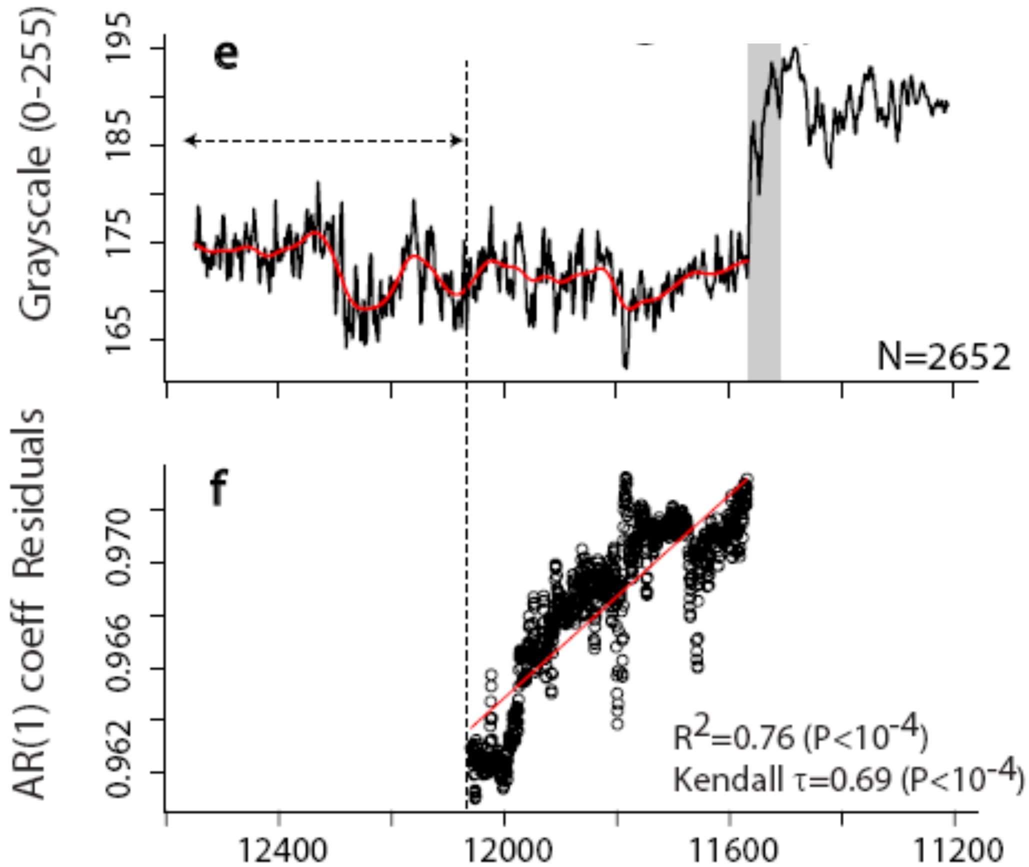
# slowing down before past climate shifts

**Shutdown of thermohaline circulation**



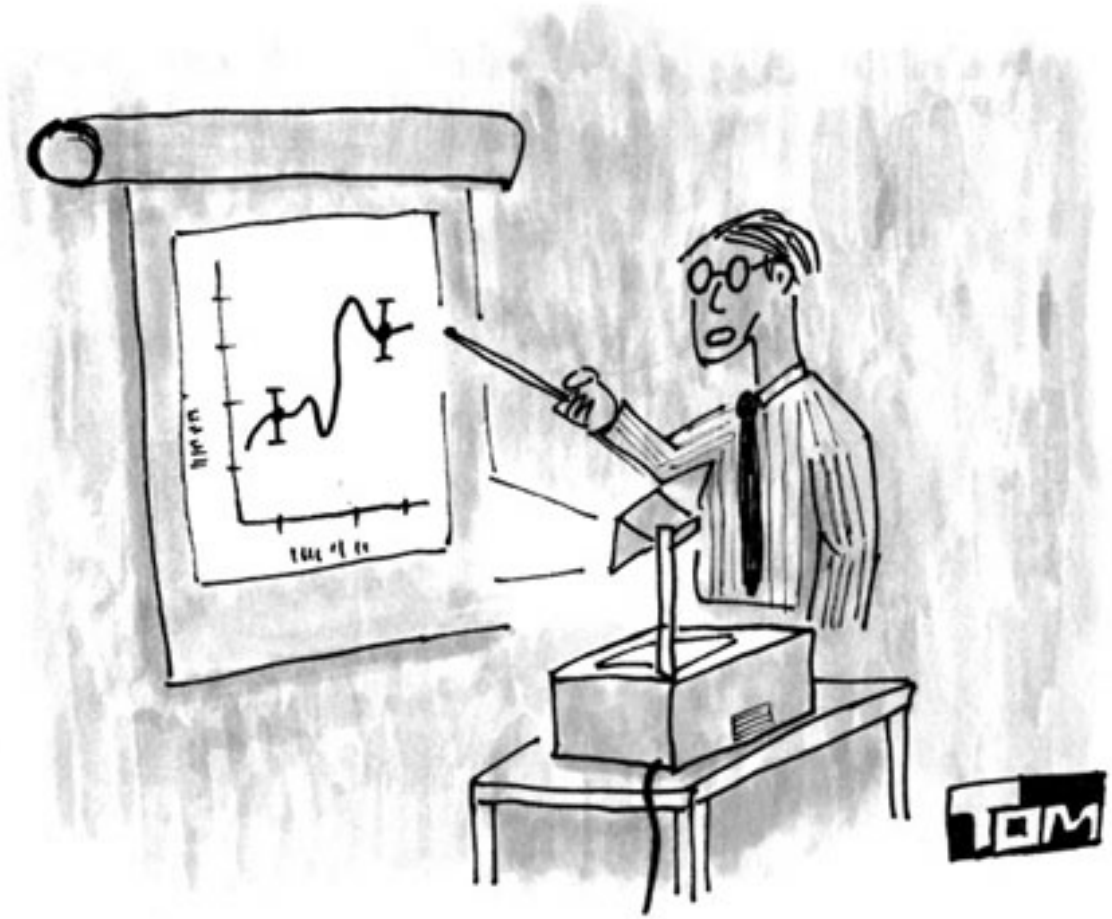

Model data

**end of Younger Dryas**




Paleo-climate data

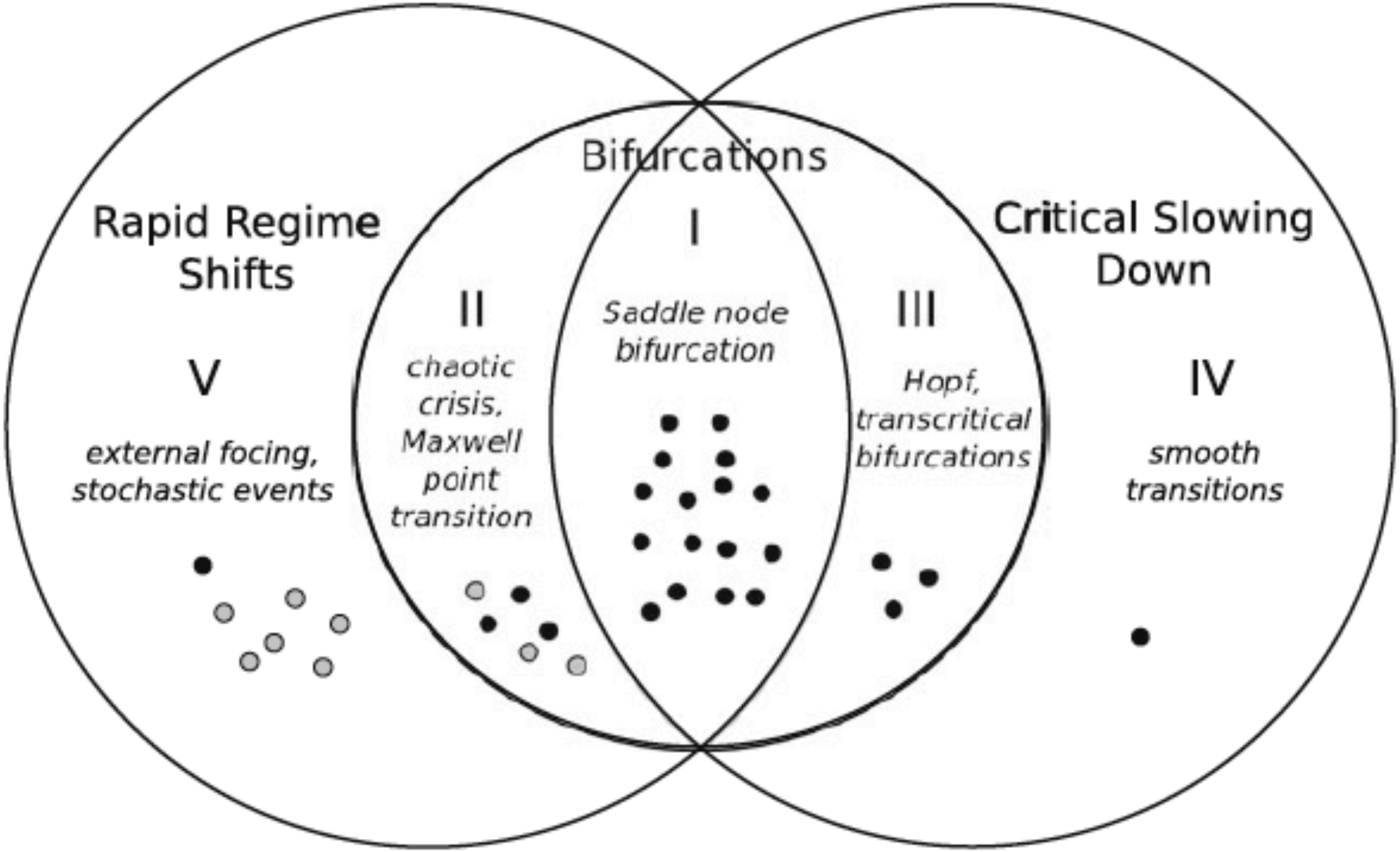
Dakos et al 2008, PNAS




"WE CAN SEE HERE THAT THE AGREEMENT WITH THEORY IS EXCELLENT"

©2000 Tom Swanson

# theoretical challenge - too generic?




There can be tipping points without warning (no alarms)

There can be warnings without tipping points (false alarms)

Boettiger et al. 2013

# practical application too difficult?

- noise, measurement error
- low resolution (gaps, irregular)
- data availability

**Journal of Applied Ecology**

British Ecological Society

*Journal of Applied Ecology* 2016, **53,** 666–676 doi: 10.1111/1365-2664.12519

**QUANTIFYING RESILIENCE**

## Do early warning indicators consistently predict nonlinear change in long-term ecological data?

Burthe et al 2016

# methods for tipping point detection – in time and space

| Method |
|---|
| **Metric-based** |
| Autocorrelation at-lag-1 |
| Autoregressive coefficient of AR(1) model |
| Return rate (inverse of AR(1) coefficient) |
| Detrended fluctuation analysis |
| Spectral density |
| Spectral ratio (of low to high frequencies) |
| Spectral exponent |
| Standard deviation |
| Coefficient of variation |
| Skewness |
| Kurtosis |
| Conditional heteroskedasticity |
| BDS test |
| **Model-based** |
| Time-varying AR(p) models |
| Nonparametric drift-diffusion-jump models |
| Threshold AR(p) models |
| Potential analysis (potential wells estimator) |

Early Warning Signals Toolbox

early-warning-signals.org

**earlywarnings**

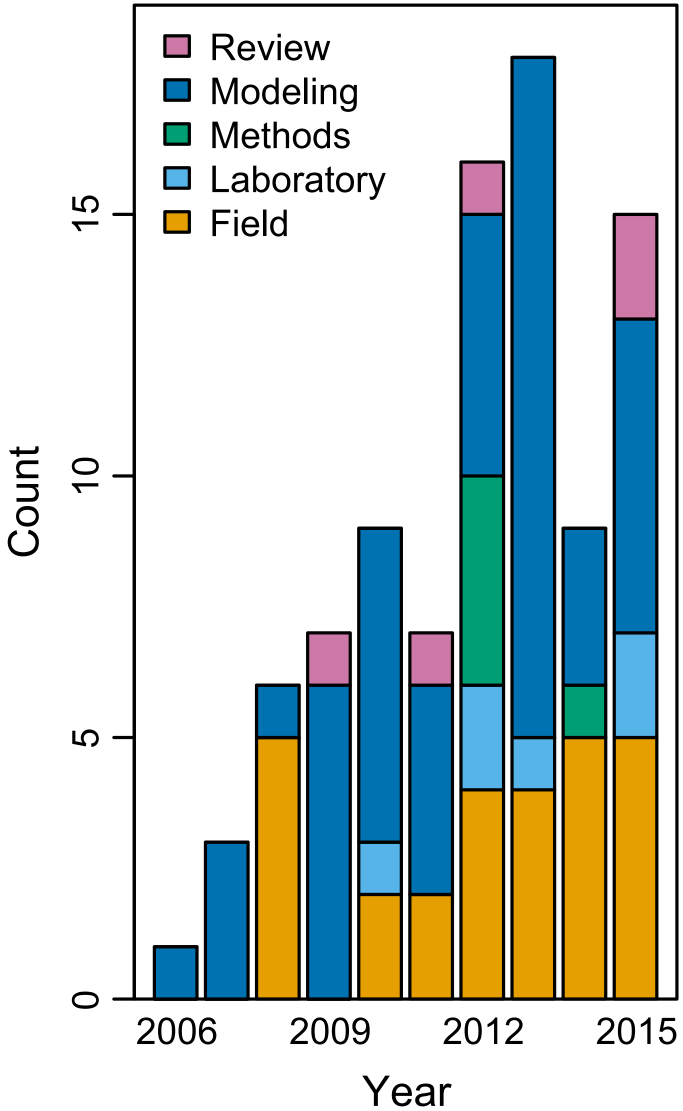
github.com/earlywarningtoolbox
github.com/spatial-ews/spatialwarnings

Dakos et al 2012, PLoS One
Ives & Dakos 2012, Ecosphere
Boettiger & Hastings 2013, J R Soc Int
Kéfi et al 2014, PLoS One
Seekel & Dakos 2015, Ecology & Evolution

PHILOSOPHICAL TRANSACTIONS B

Dakos et al 2015

# Resilience indicators: prospects and limitations for early warnings of regime shifts




- **Ecology**
  (desertification, lake eutrophication, population collapse, community shifts)
- **Climate** (paleoclimatic shifts)
- **Engineering**
  (power grid, material science)
- **Medicine**
  (cardiac instability, depression, geriatrics, disease epidemics, gut microbiome)
- **Social systems**
  (social unrest, finance)

Litzow & Hunsicker Ecosphere 2016, Scheffer et al 2015 AREES

# Quantifying resilience

monitor changes in resilience within a system (warnings)

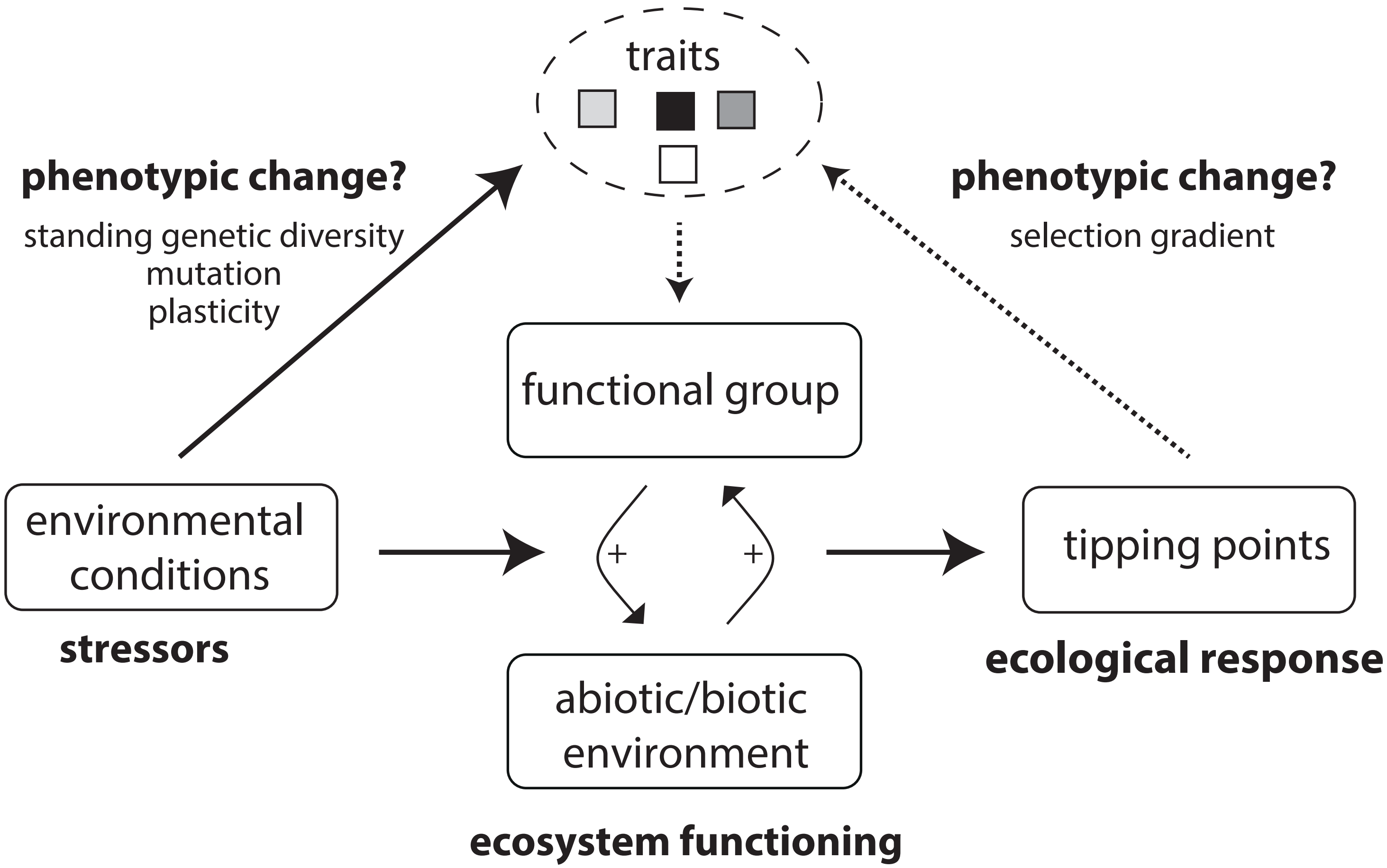
rank resilience across systems/sites/species (identify hotspots)

# understand and detect tipping points in a changing but evolving world

nature ecology & evolution
PERSPECTIVE
https://doi.org/10.1038/s41559-019-0797-2

# Ecosystem tipping points in an evolving world

Vasilis Dakos[1*], Blake Matthews[2*], Andrew P. Hendry[3], Jonathan Levine[4], Nicolas Loeuille[5], Jon Norberg[6], Patrik Nosil[7], Marten Scheffer[8] and Luc De Meester[9]



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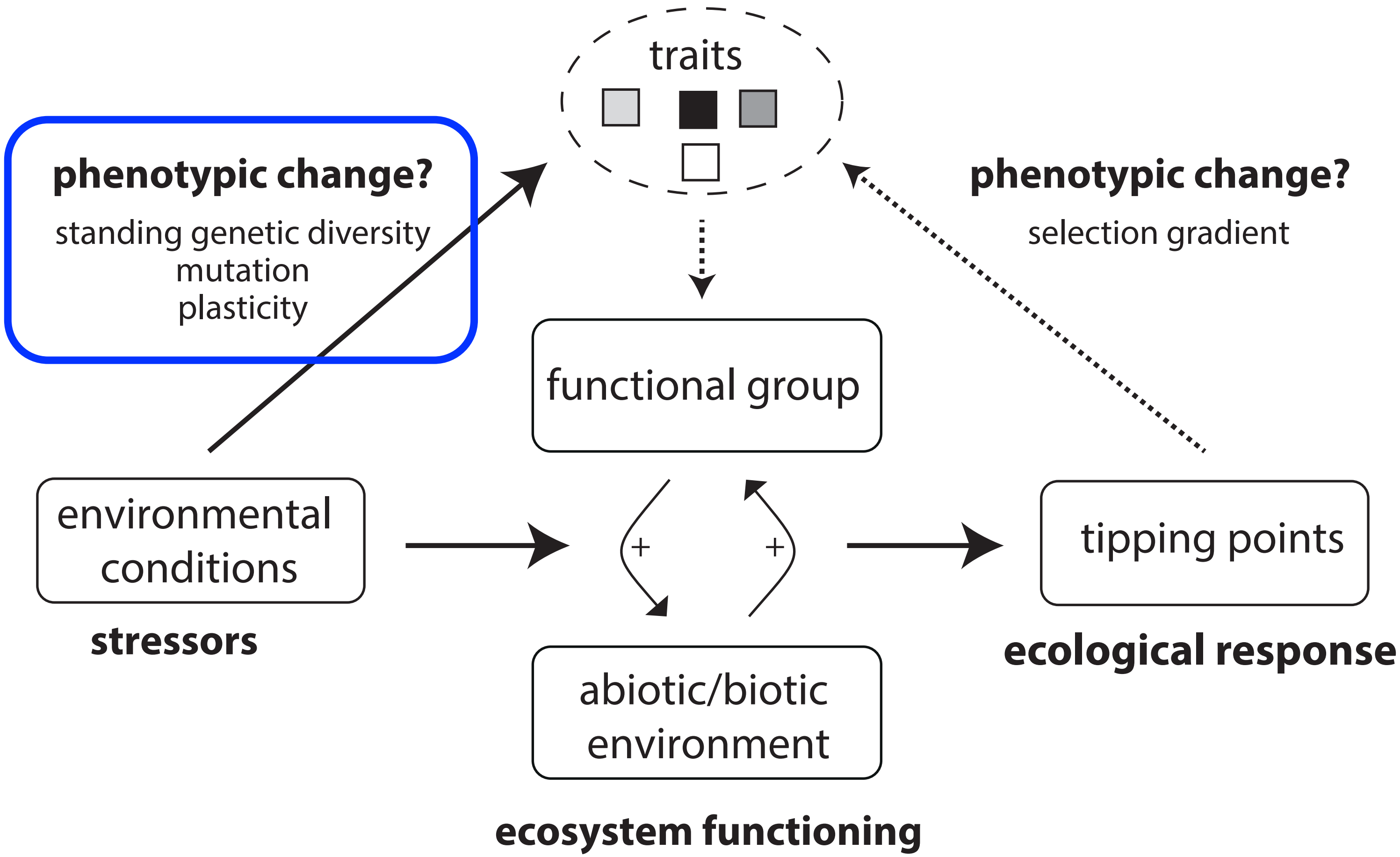
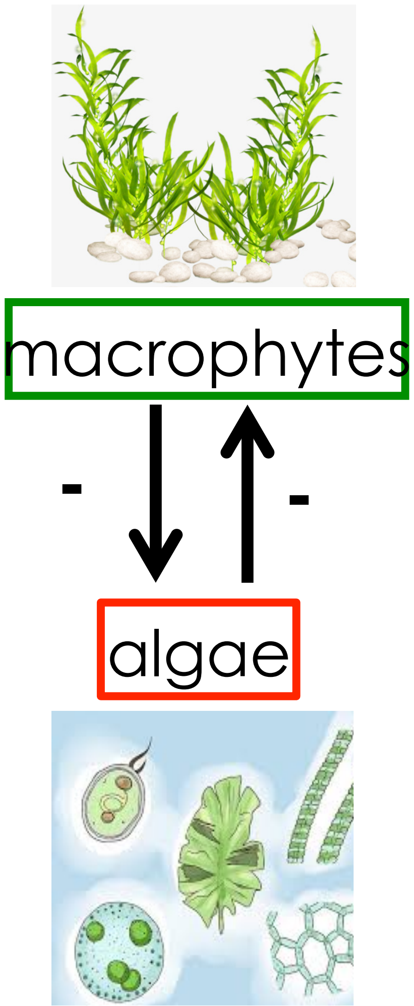


# effects of trait variation?

trait variation

Dakos et al Nat Ecol & Evol 2019

# Trait variation in a shallow lake

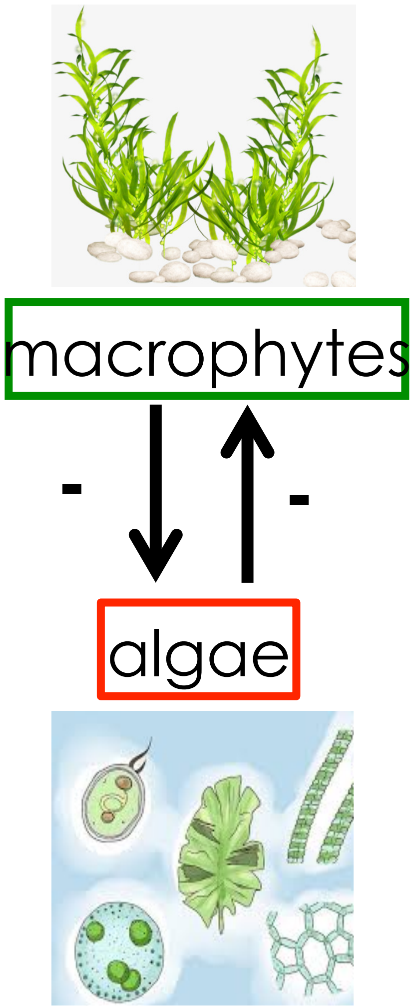




$$\frac{dT}{dt} = r_T\, T\left(1 - \frac{T}{T_o\, \frac{h_M}{h_M + M}}\right)$$

$$\frac{dM}{dt} = r_M\, M\left(1 - \frac{M}{K}\left(\frac{{h_T}^4 + T^4}{{h_T}^4}\right)\right)$$

Dakos et al Nat Ecol & Evol 2019

# Trait variation in a shallow lake

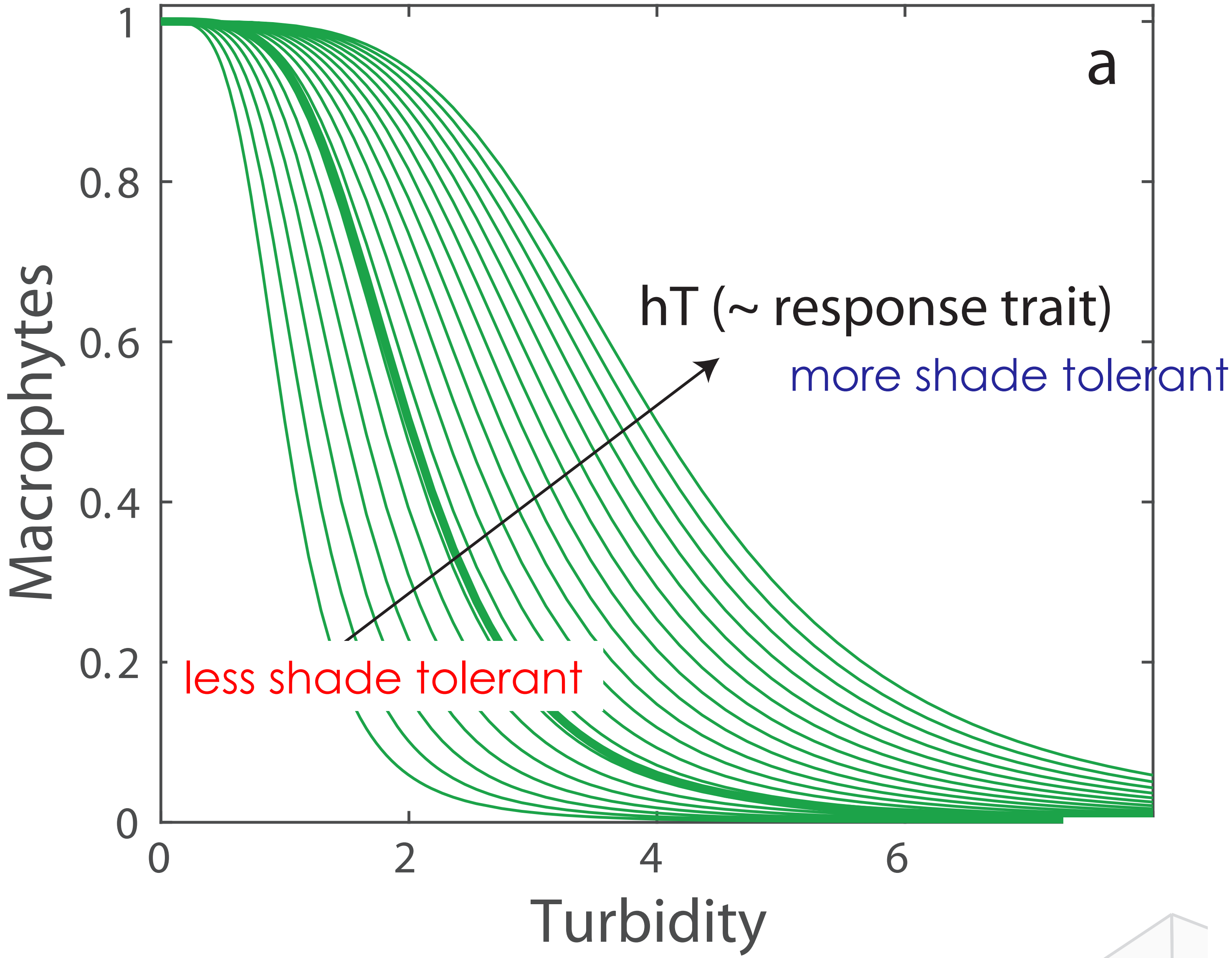

$$\frac{dT}{dt} = r_T\, T\left(1 - \frac{T}{T_o\, \frac{h_M}{h_M + M}}\right)$$

$$\frac{dM}{dt} = r_M\, M\left(1 - \frac{M}{K}\left(\frac{{h_T}^4 + T^4}{{h_T}^4}\right)\right)$$

**Response** trait - Shade tolerance

Dakos et al Nat Ecol & Evol 2019

# **Response** trait - Shade tolerance

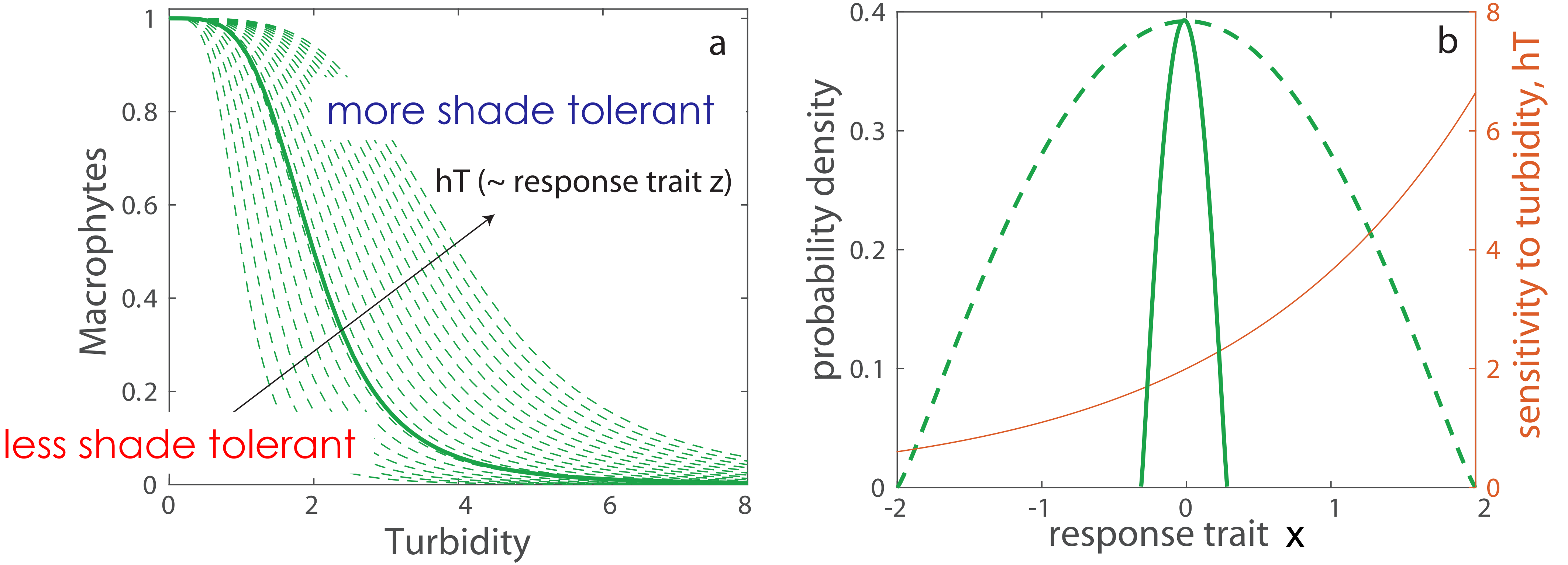




$$M' = \frac{{h_T}^4}{{h_T}^4 + T^4}$$

Dakos et al Nat Ecol & Evol 2019

# **Response** trait - Shade tolerance

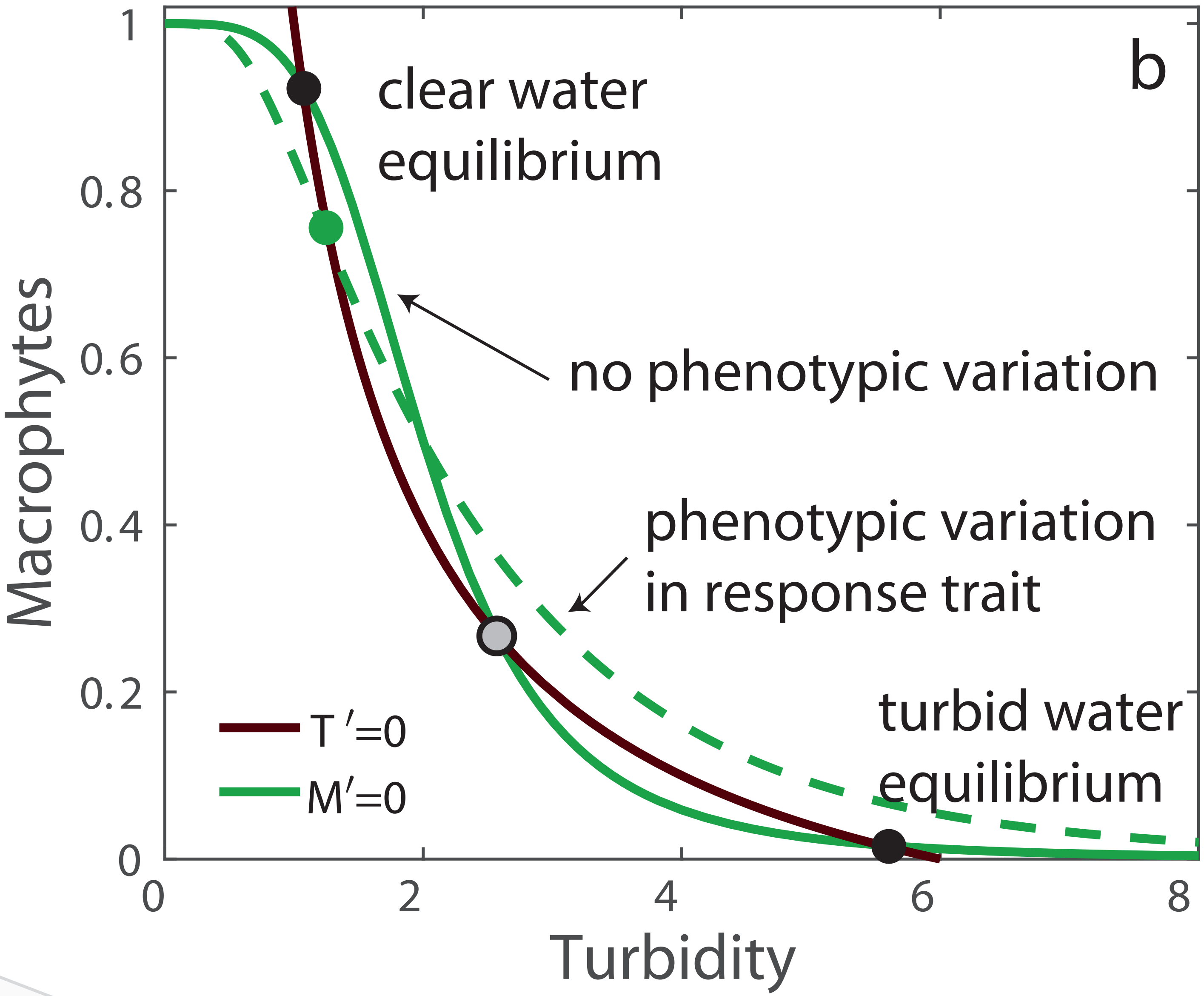
trait variation




$$h_T(x) = h_{T0}e^{\lambda x}$$

Dakos et al Nat Ecol & Evol 2019

# **Response** trait - Shade tolerance

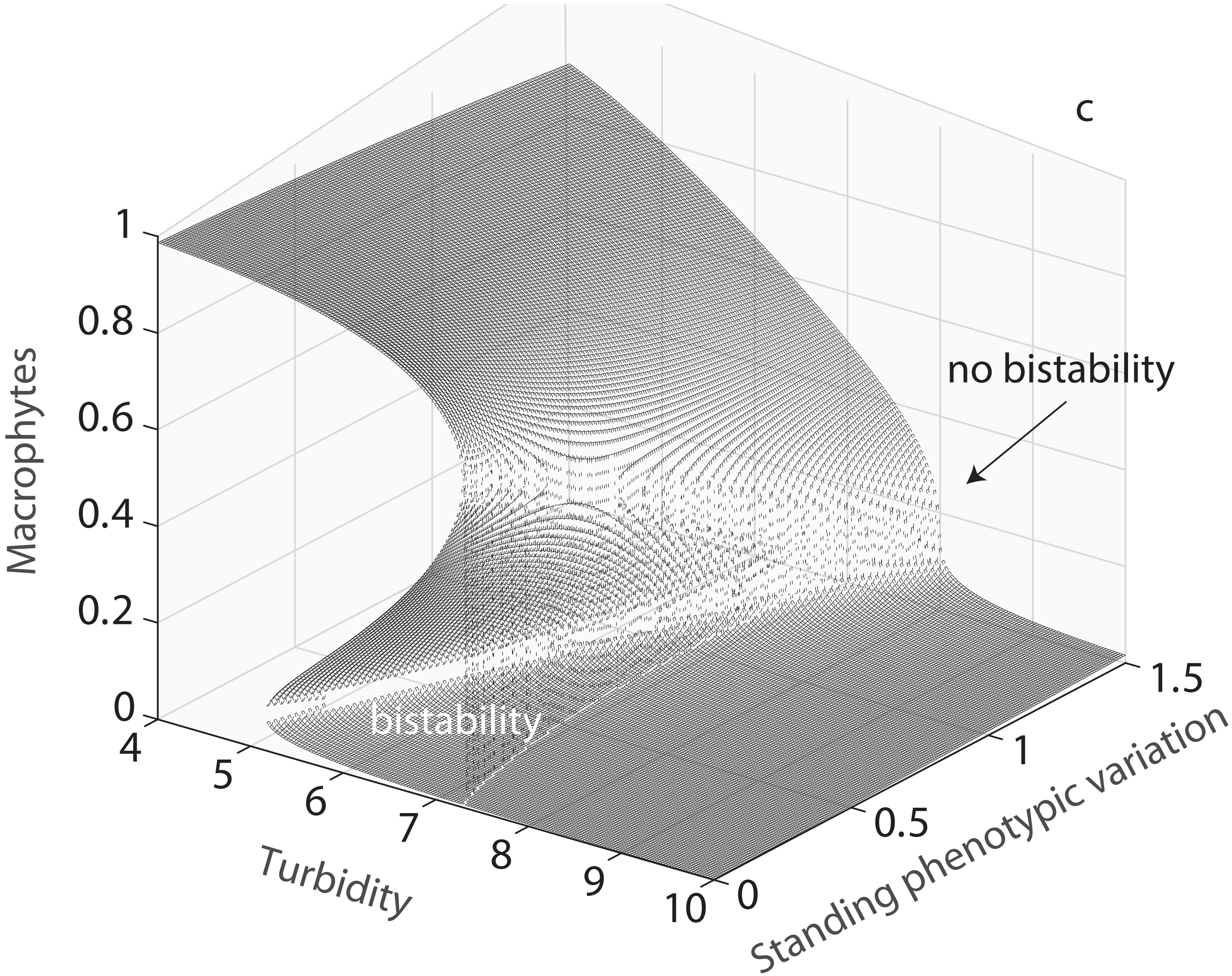



trait variation

$$M' = \int_{-z}^{z} \frac{h_T(z)^4}{h_T(z)^4 + T^4} p(z)dz$$

Dakos et al Nat Ecol & Evol 2019

# trait variation – loss of bistability



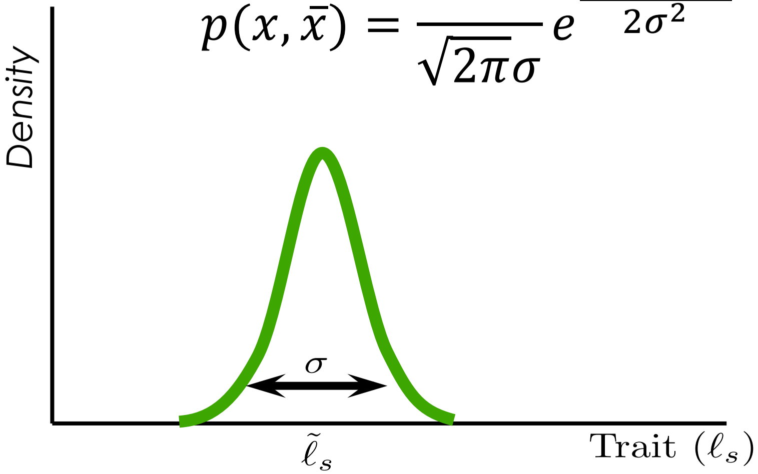

trait variation

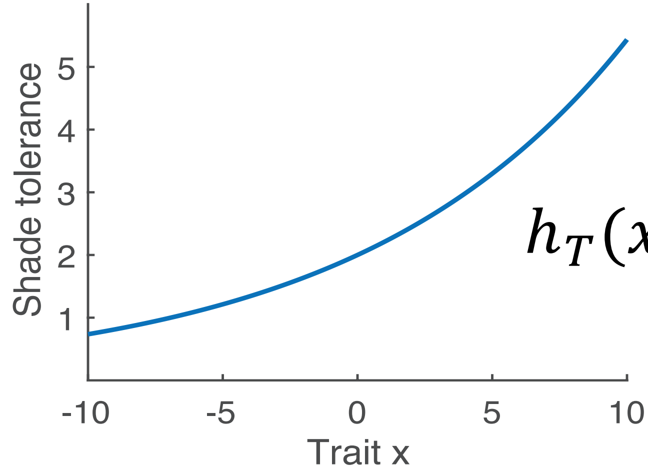
Dakos et al Nat Ecol & Evol 2019

# eco-evolutionary dynamics in a shallow lake


trait evolution

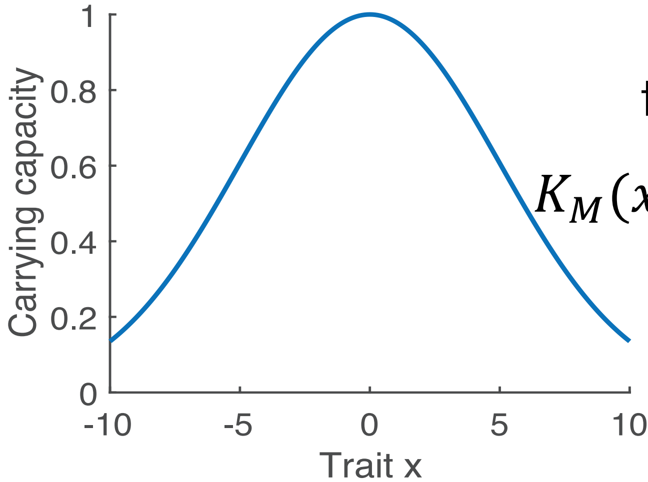
$$p(x, \bar{x}) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\bar{x})^2}{2\sigma^2}}$$




response

$$h_T(x) = h_{T0} e^{\lambda x}$$

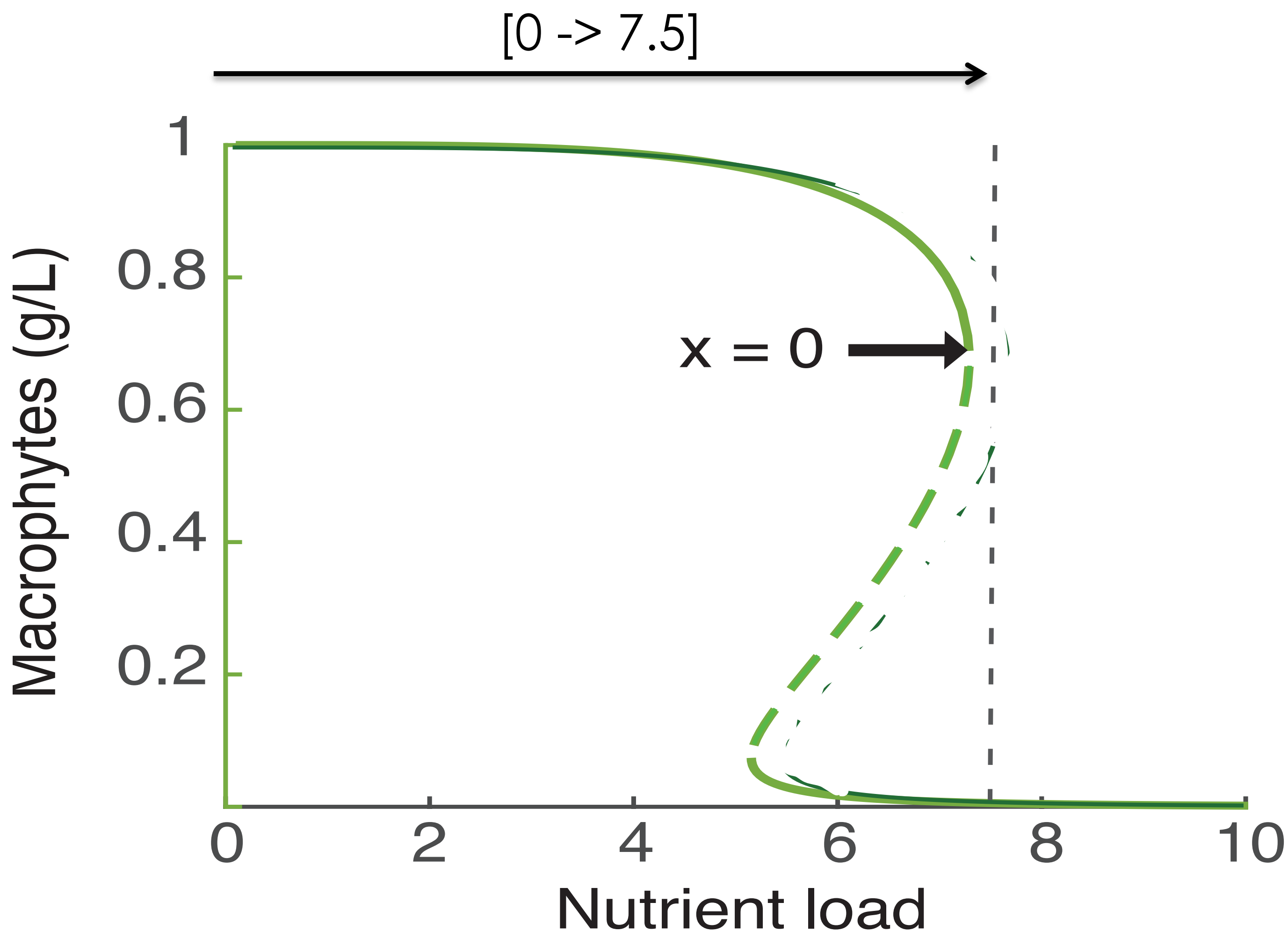



trade-off

$$K_M(x) = K e^{\frac{-(x-\theta)^2}{2\tau^2}}$$

Chaparro et al (in prep)


# macrophyte response to a strong increase in nutrient loading




Chaparro et al (in prep)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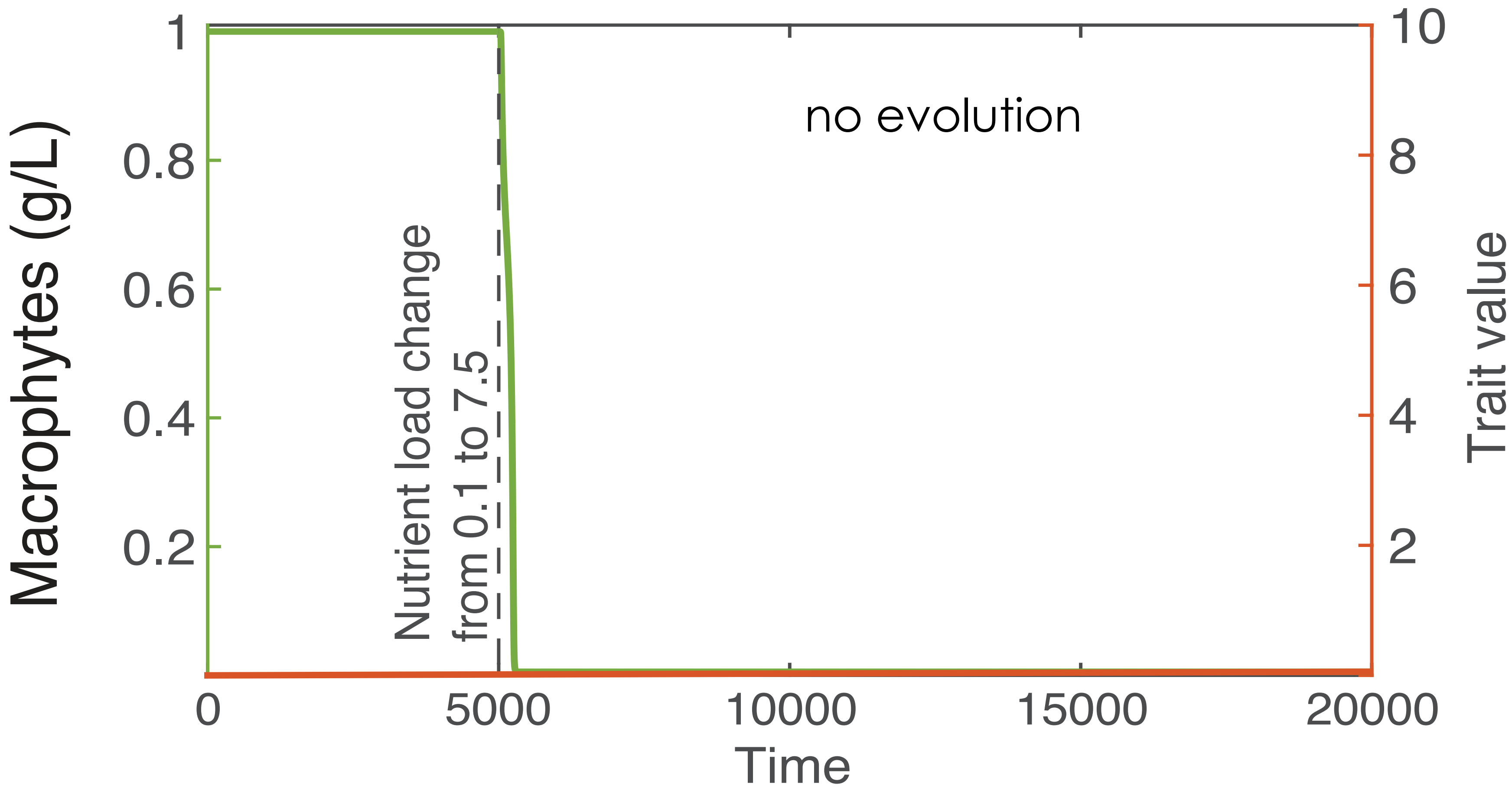
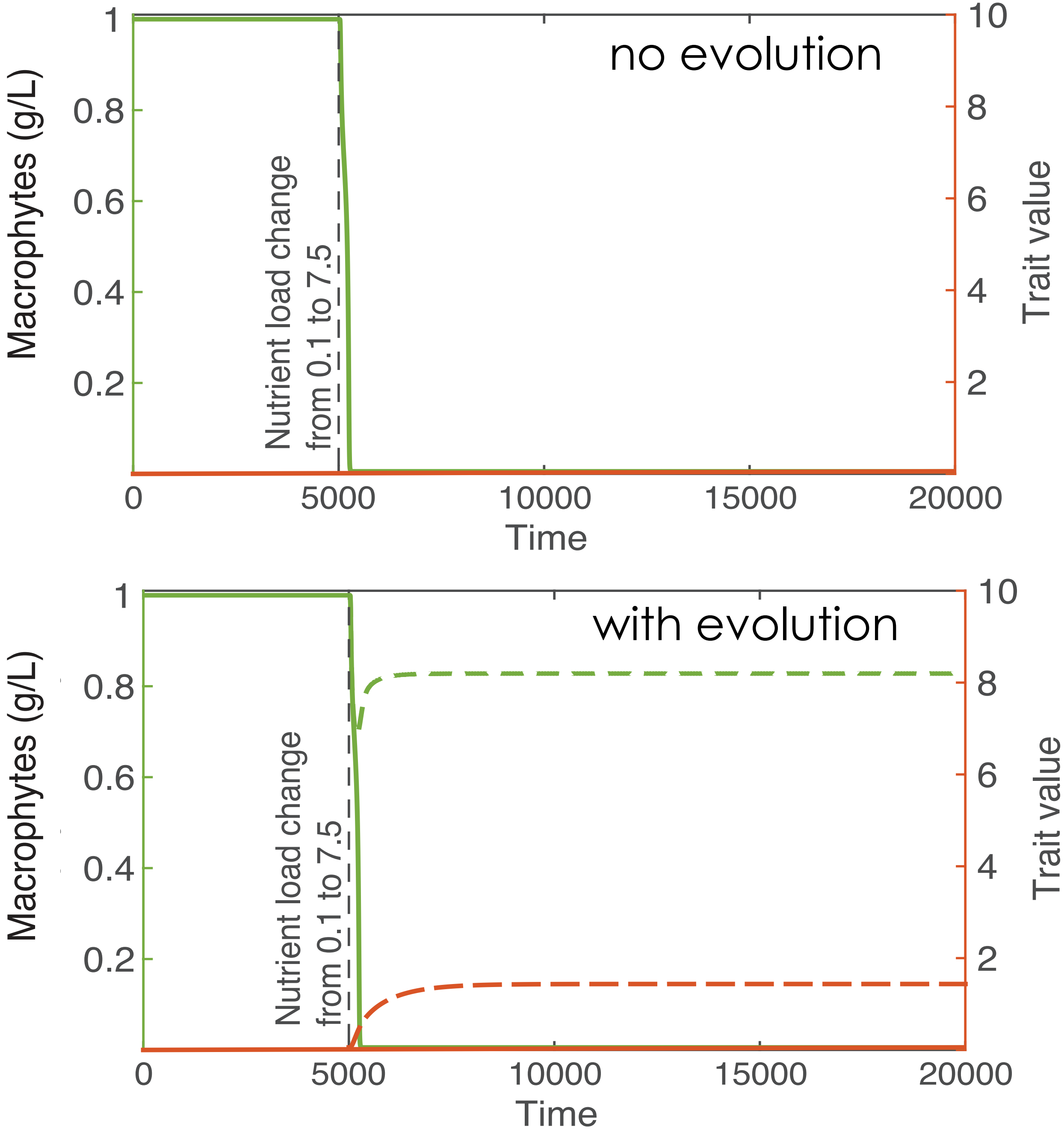



Chaparro et al (in prep)


# evolution delays ecosystem collapse ("rescue" like effect)




Chaparro et al (in prep)

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Stage M2 2020:

1. Ecological consequences of rapid evolution in ecosystems with tipping points
with Nicolas Loeulle (iEES), (financed by FRB)

2. Early warning signs of the sudden origin of species
with Patrik Nosil (Cefe), Montpellier

# Quantifying resilience: tipping points and evolution(?)

www.vasilisdakos.info
iEES UPMC, Paris

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Blake Matthews

**EERI team**

**Long-term collaborators**
Sonia Kéfi
Marten Scheffer
Egbert van Nes
Stephen Carpenter

Early Warning Signals Toolbox

early-warning-signals.org
github.com/earlywarningtoolbox