Preparing for Surprise under Global Change:

Resilience, Tipping Points, Early-Warning Signals

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IHP, 5 Oct 2023

Climate emergency: world 'may have crossed tipping points'

Warning of 'existential threat to civilisation' as impacts lead to cascade of unstoppable events

Guardian
Nov 2019

Amazon near tipping point of switching from rainforest to savannah – study

Climate crisis and logging is leading to shift from canopy rainforest to open grassland

Guardian
Oct 2020

Could biodiversity destruction lead to a global tipping point?

Guardian
Jan 2018

World is approaching coronavirus tipping point, say experts

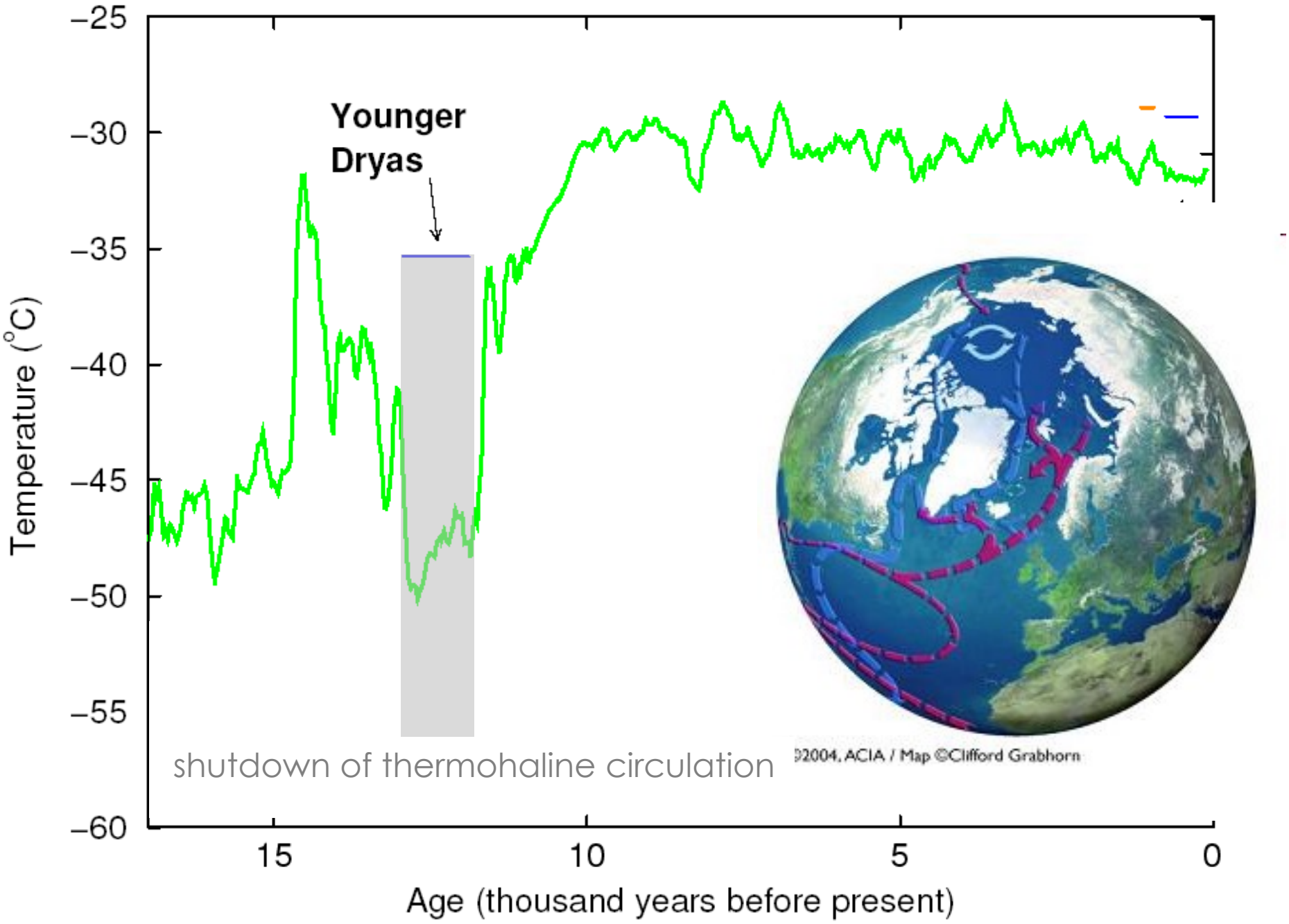
78,000 cases confirmed, as Italy and Iran scramble to contain major outbreaks

- **Follow the latest coronavirus news and updates - live**

Guardian
Feb 2020

what is a tipping point?

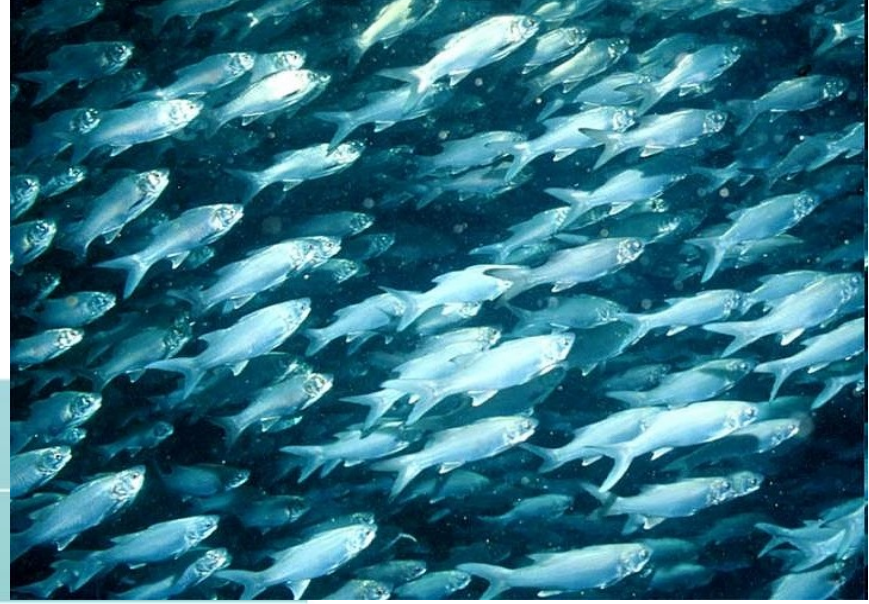
climate systems can change abruptly

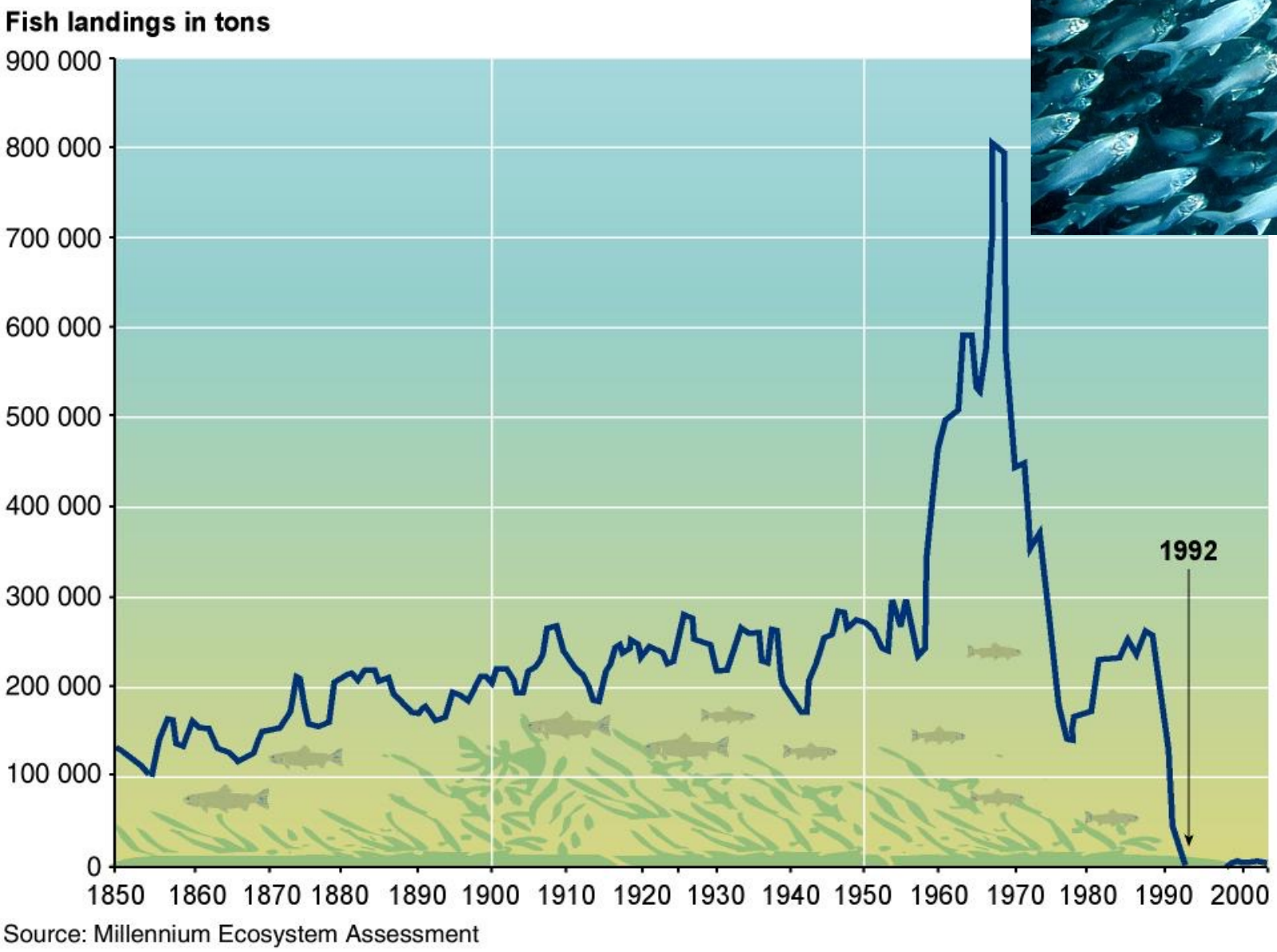


biomes may shift to a desert state

deMenocal et al (2000), *Science*

populations collapse





Source: Millennium Ecosystem Assessment


coral reefs shift to an alternative macroalgae state


shalow lakes shift from a clear to a turbid state
due to eutrophication

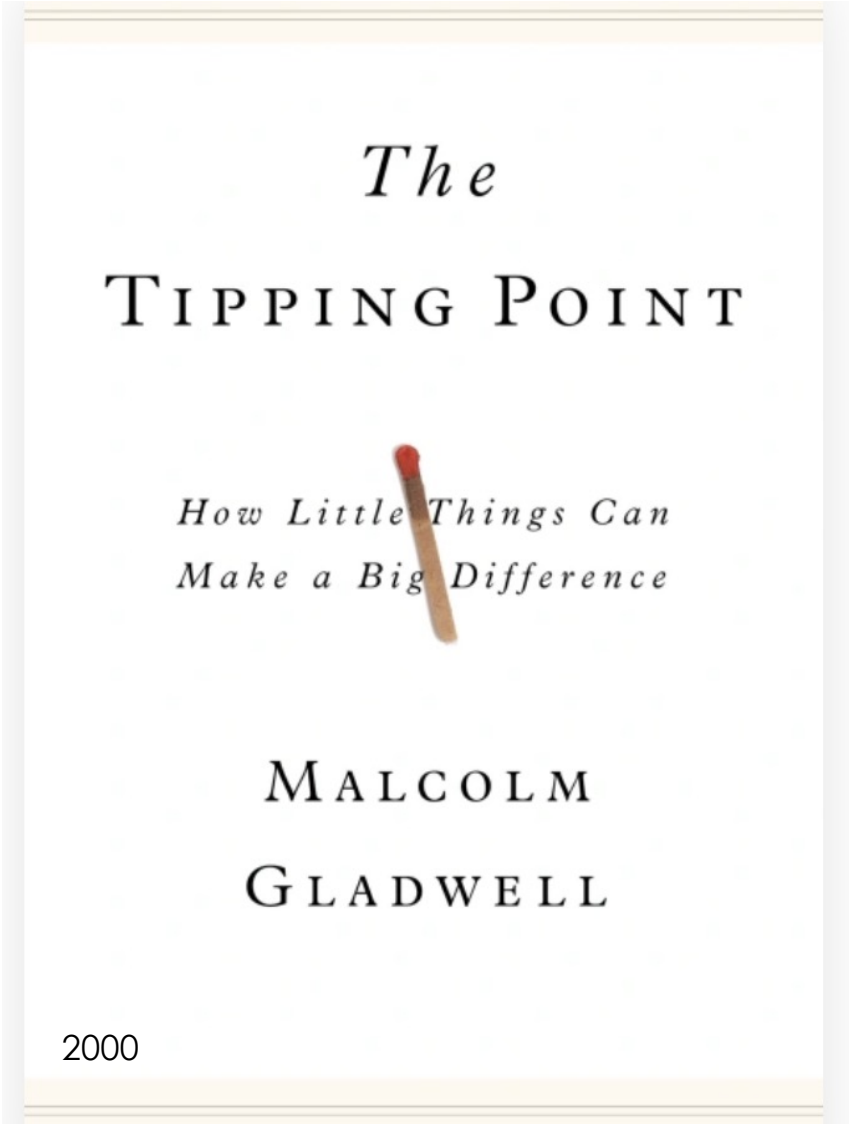
understanding and anticipating
ecological tipping point responses to stress

Outline

1. Basics of tipping point detection and quantification of resilience

2. An empirical assessment of tipping point detection and resilience

what is a tipping point?



Change:

- **Abrupt (relative to the a driver and system time-scale)**

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- **Unexpected (triggered by small perturbations)**

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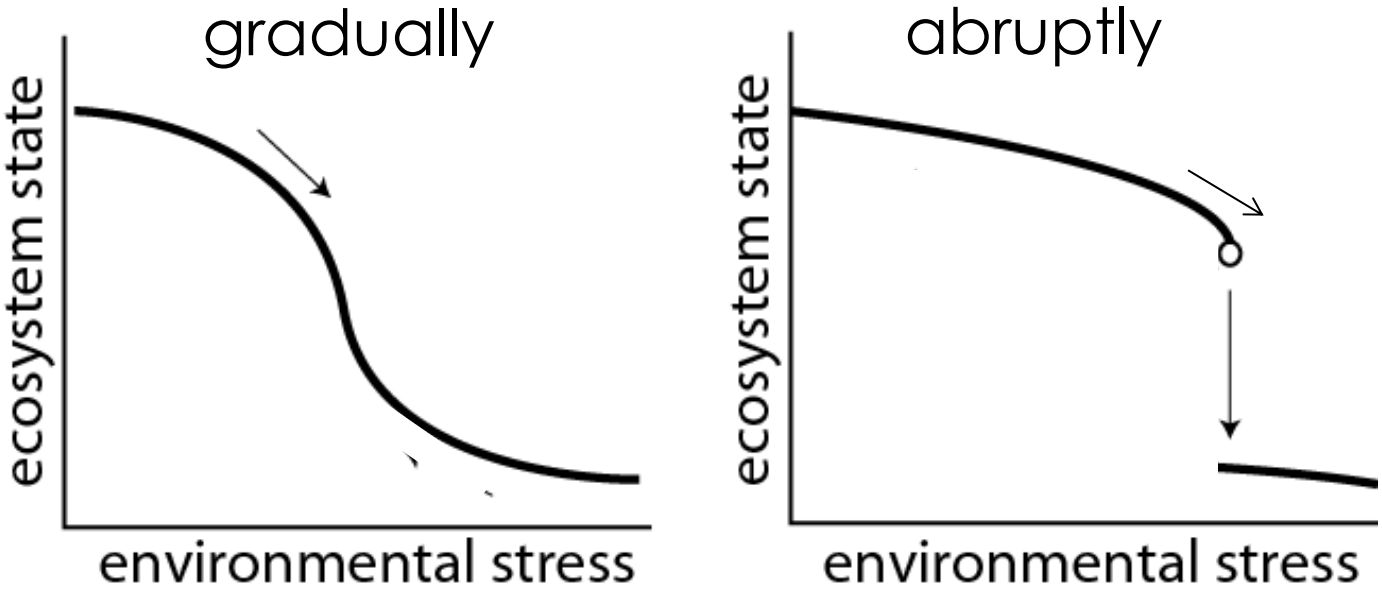
***Tipping point*:**

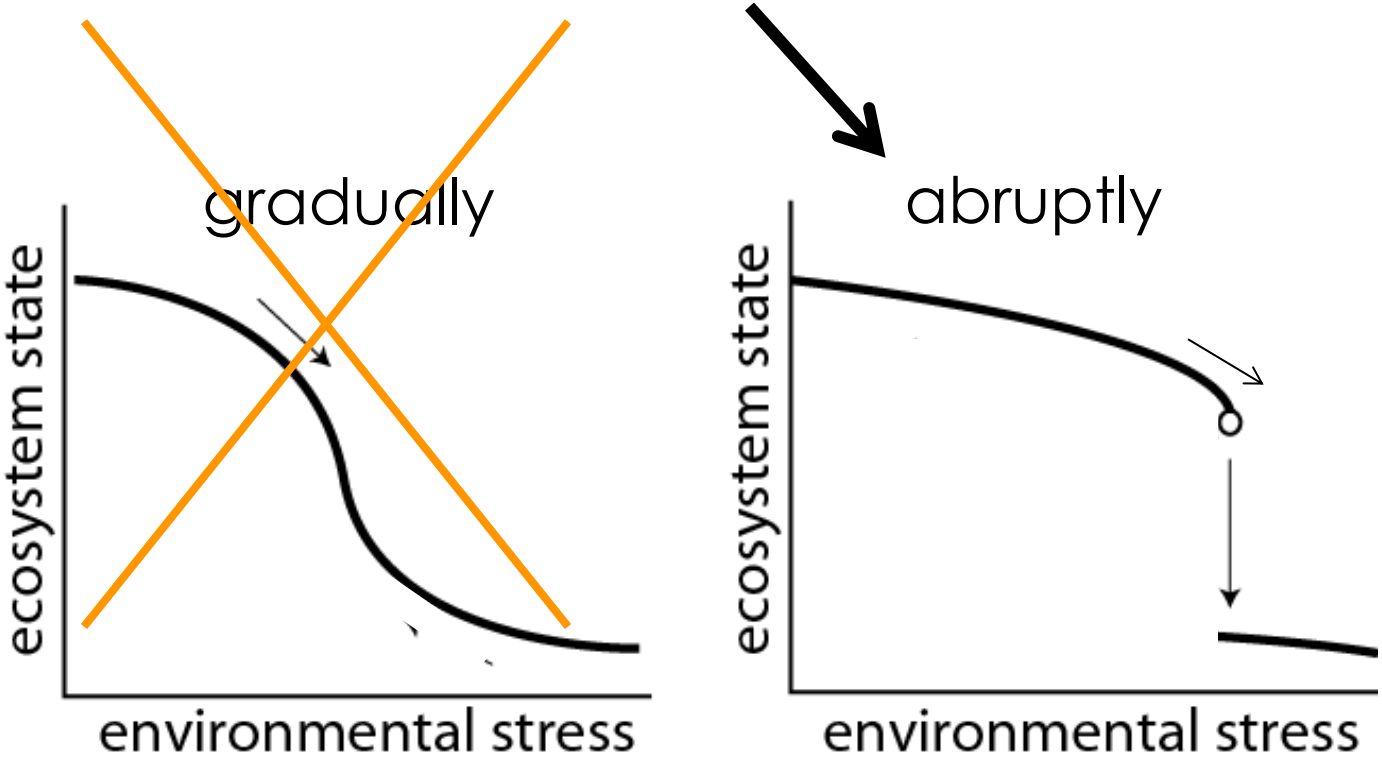
a situation where accelerating change caused by a positive feedback drives the system to a new state

(van Nes et al TREE 2016)

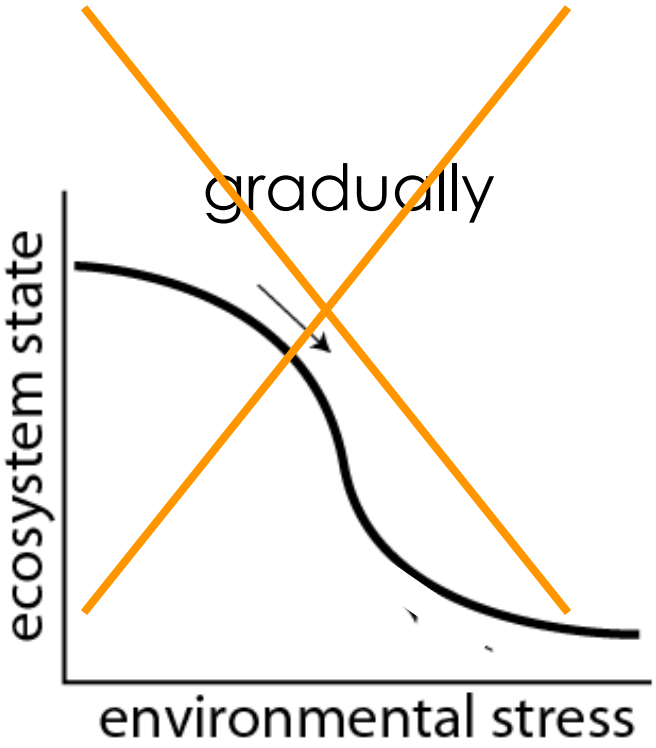
systems responses to environmental stress

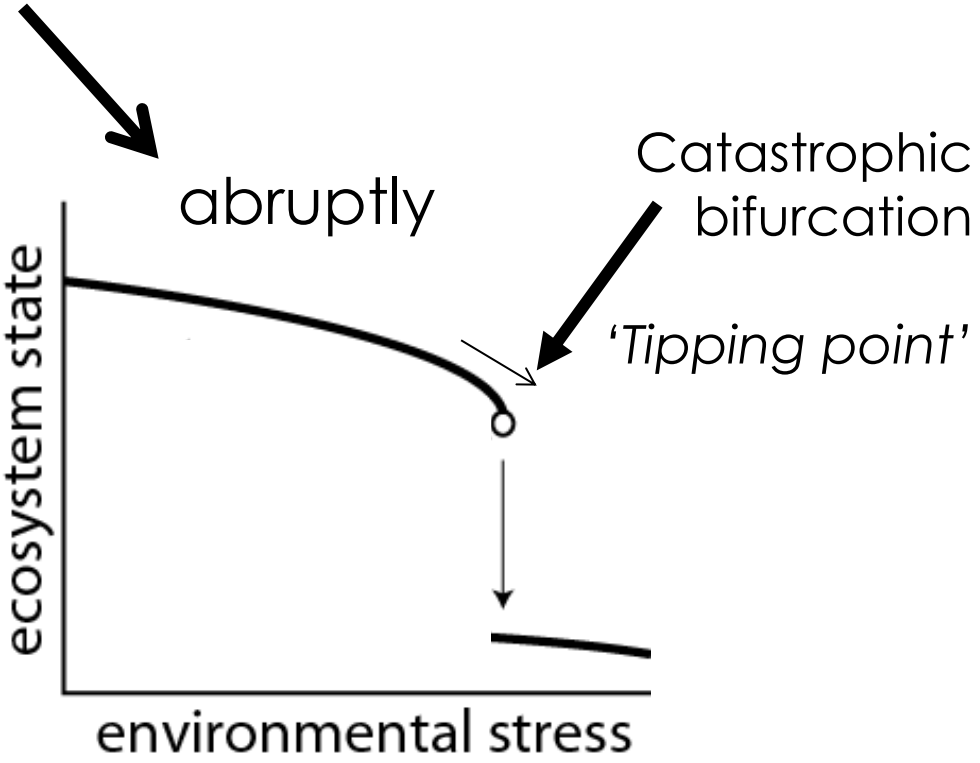


systems responses to environmental stress

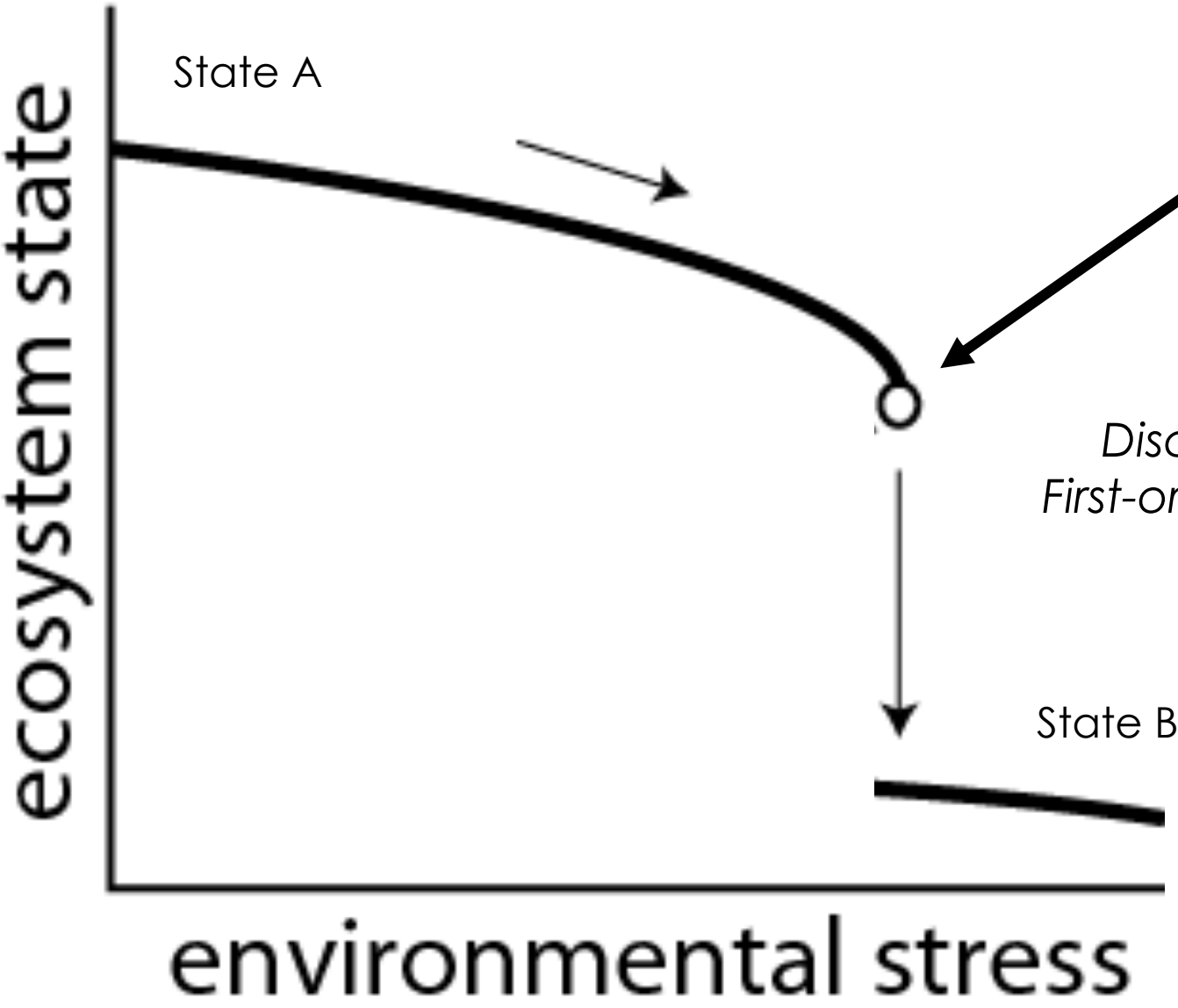


systems responses to environmental stress





tipping points between alternative stable states

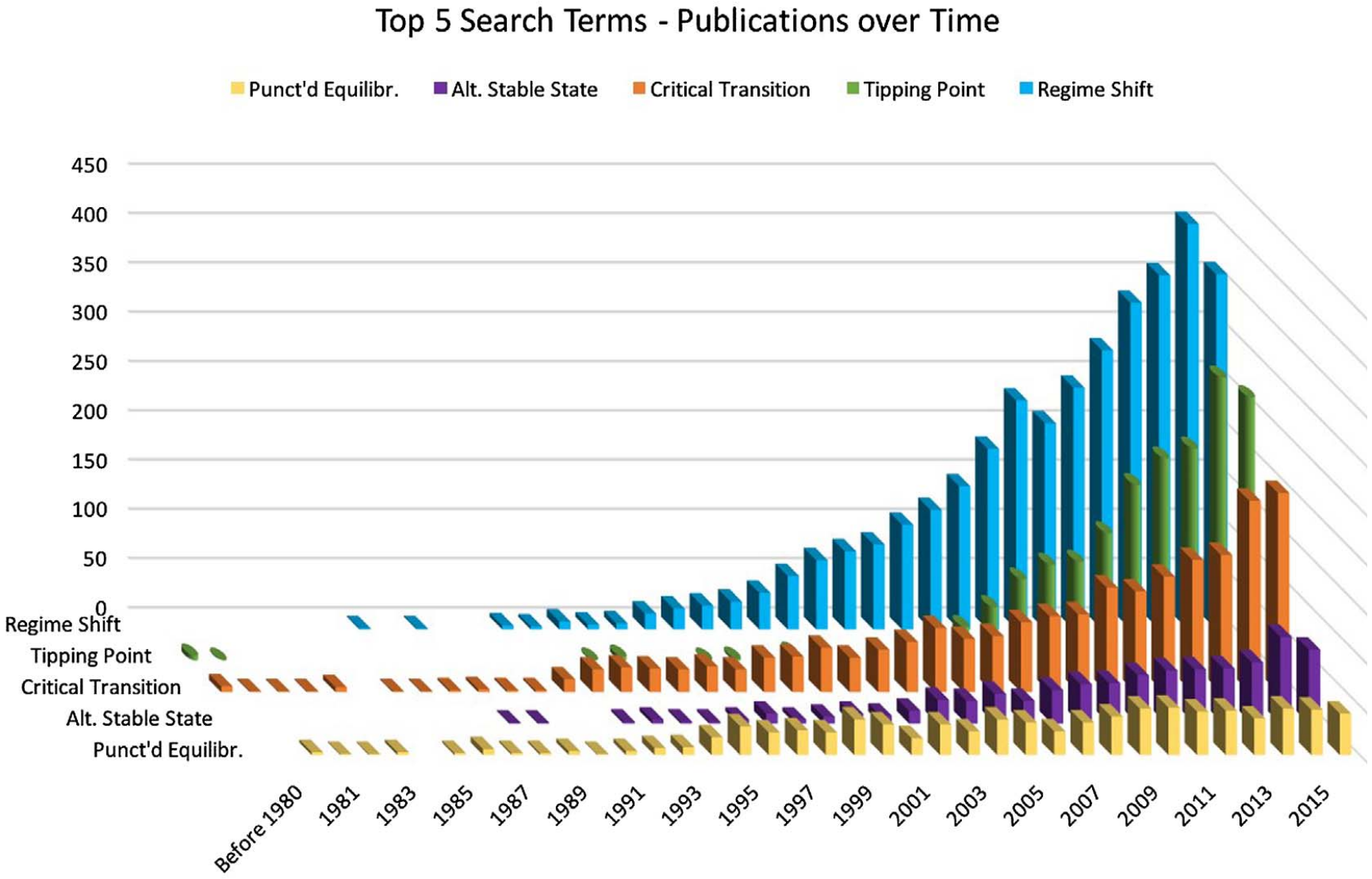


Catastrophic bifurcation

'Tipping point'

Catastrophic shift
Critical transition
Discontinuous transition
First-order phase transition

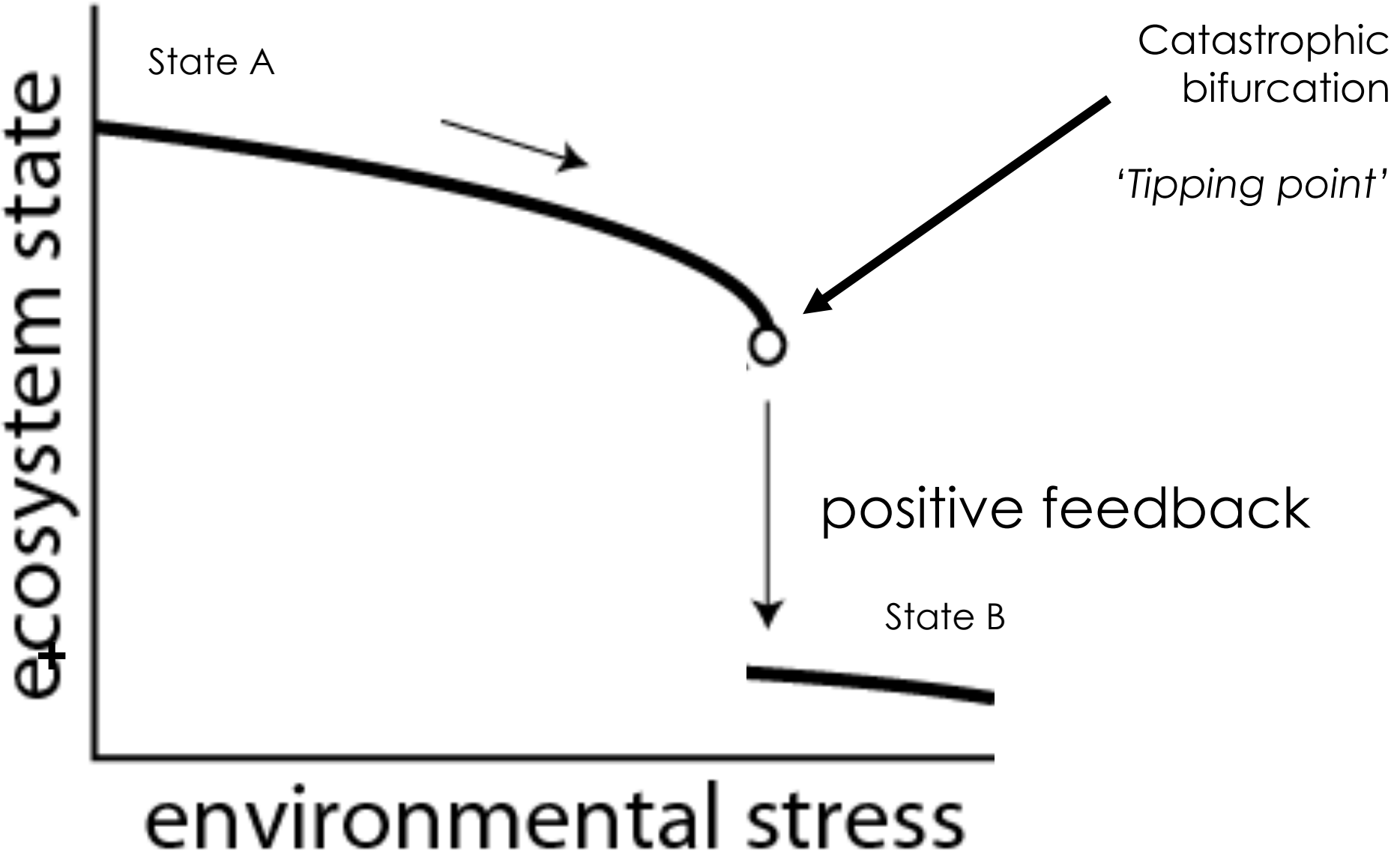
Regime shift
Abrupt change



Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review

Milkoreit et al 2016 Env Res Let

tipping points between alternative stable states



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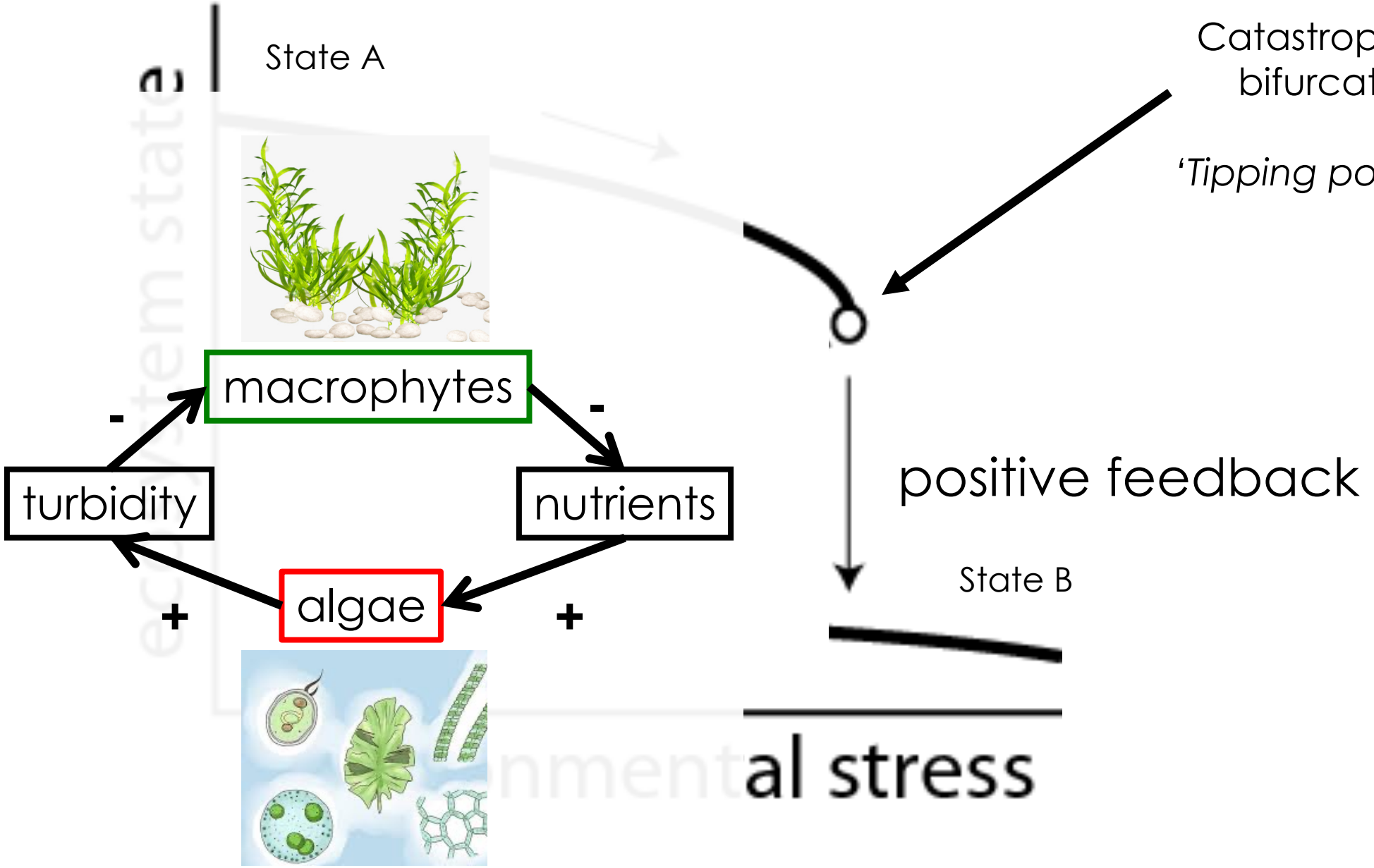

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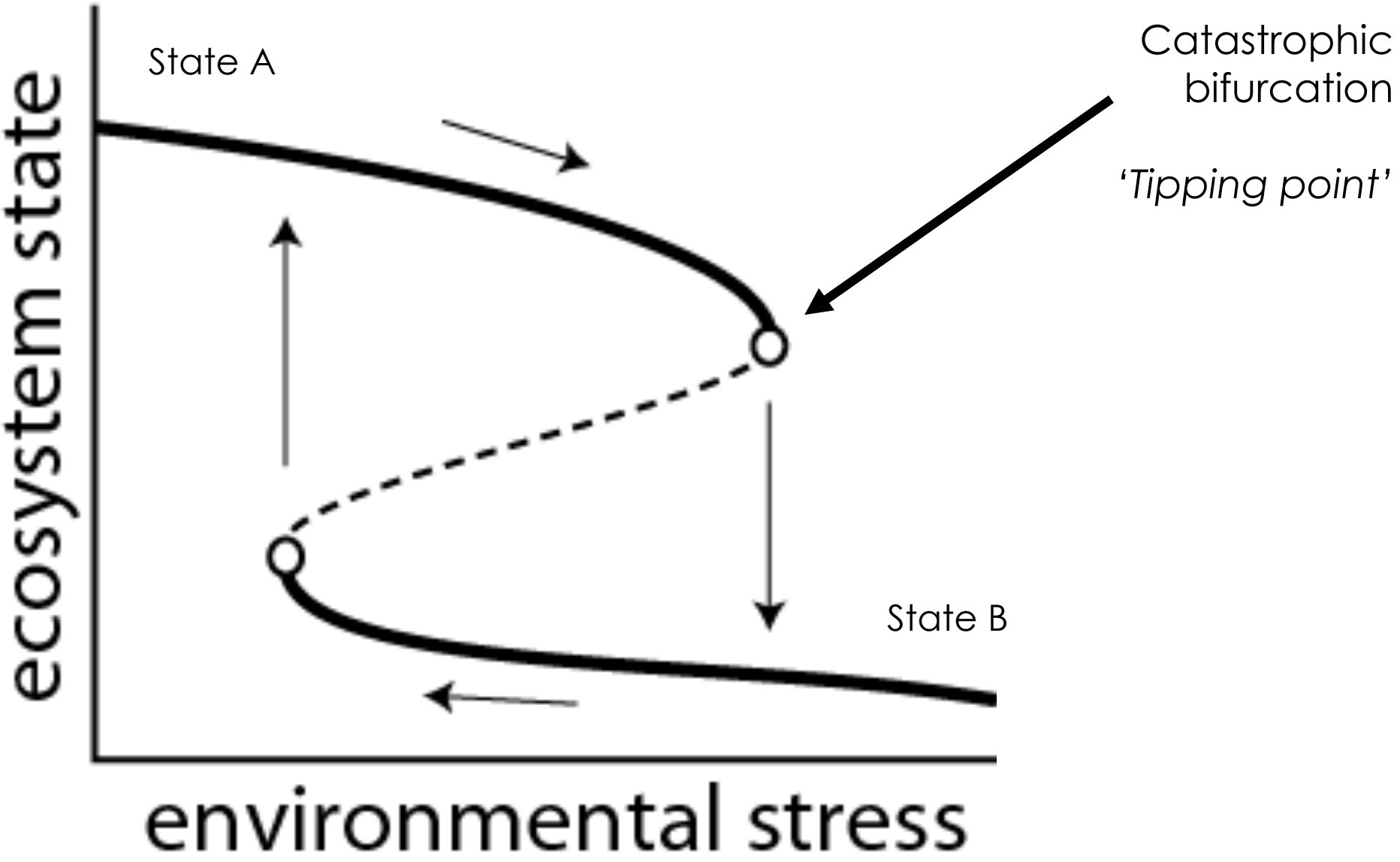

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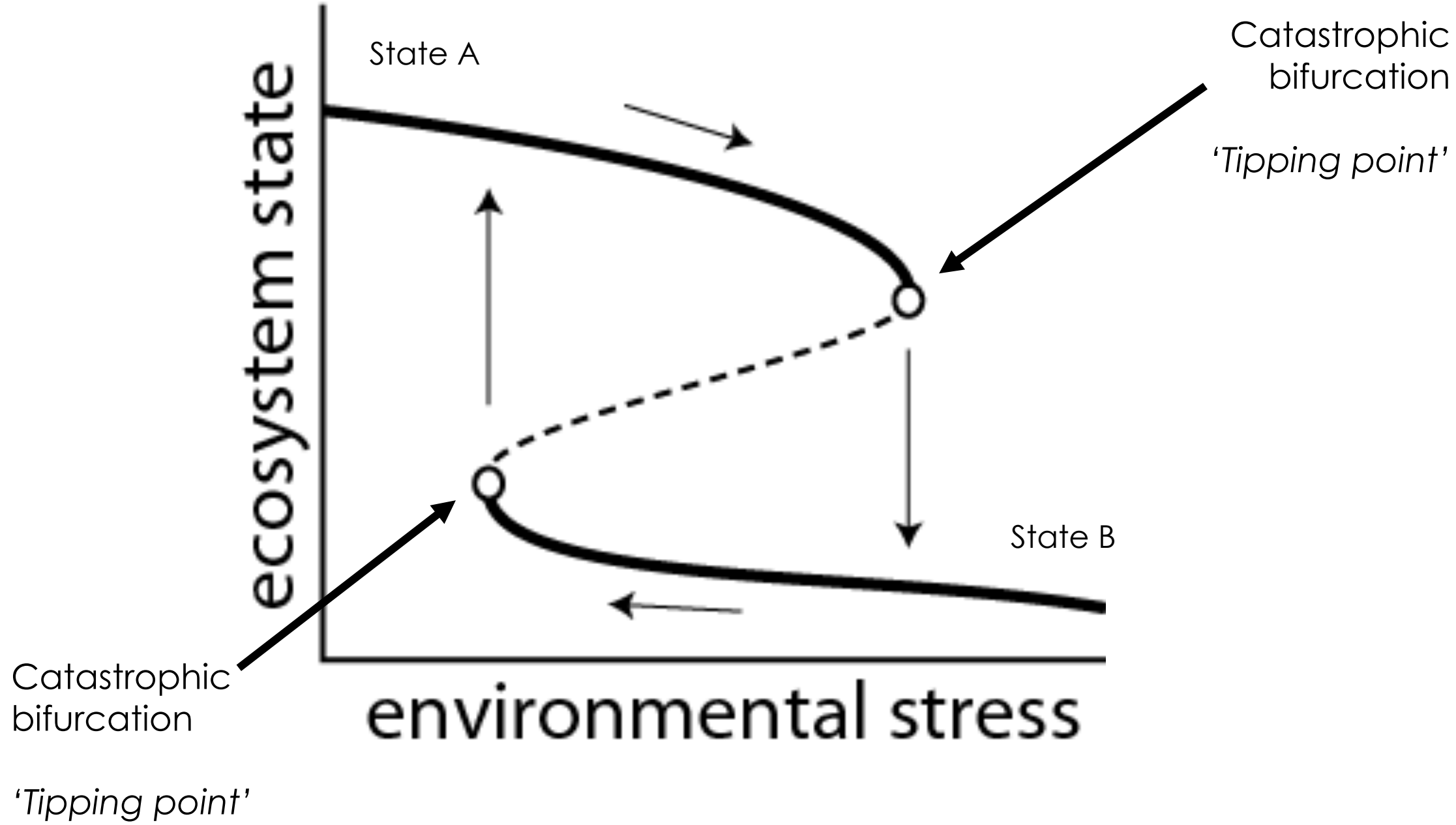

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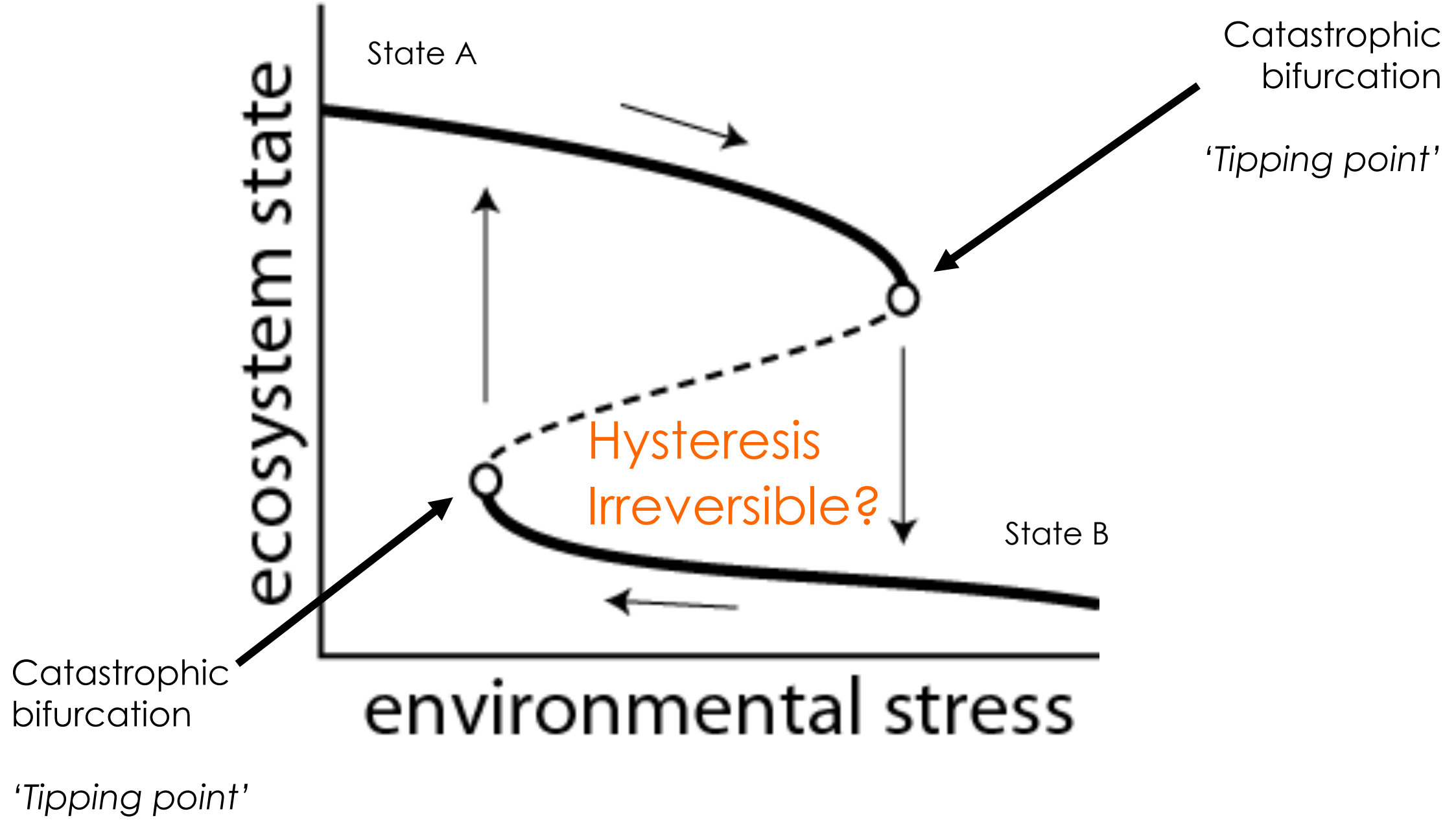

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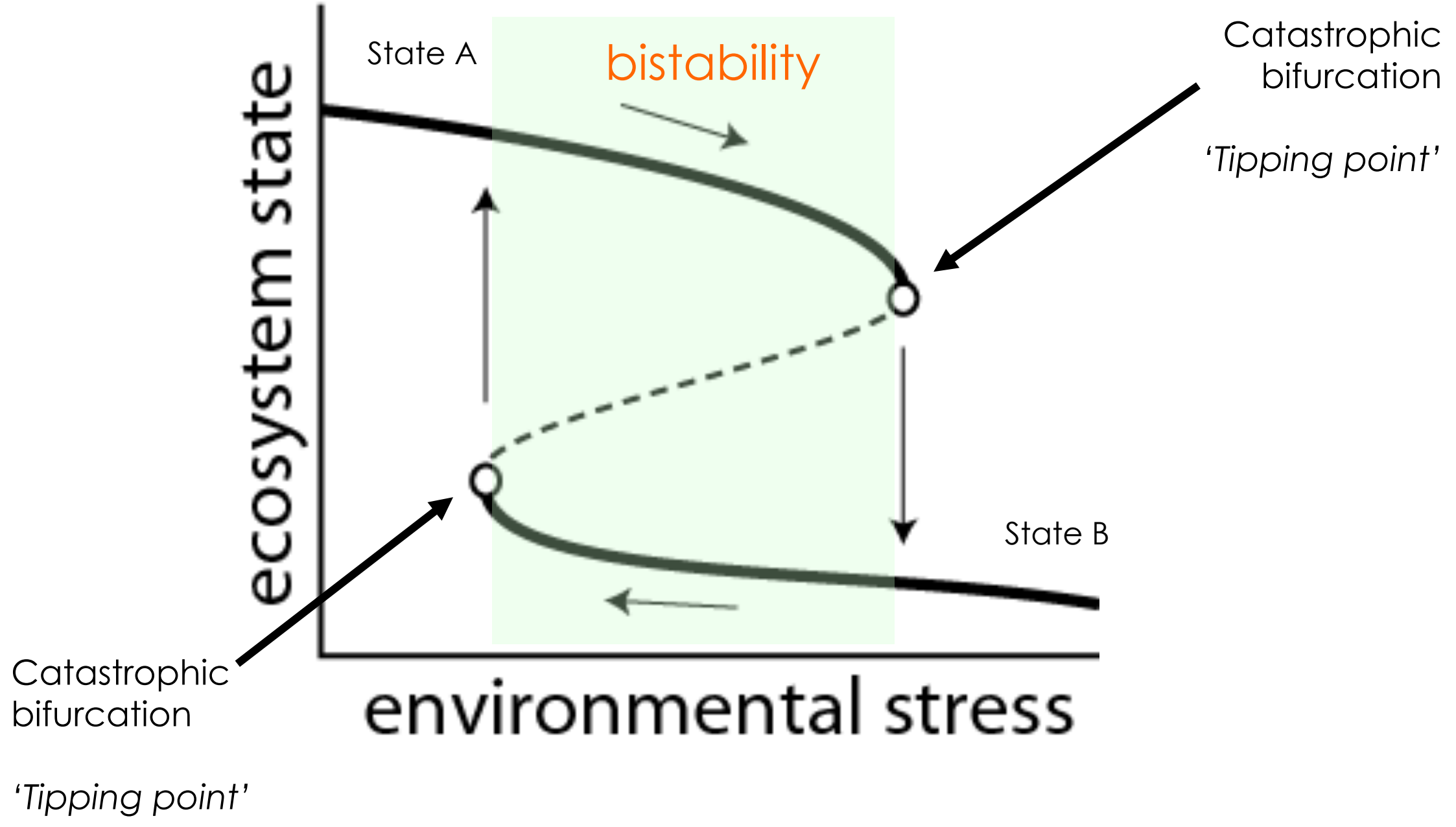

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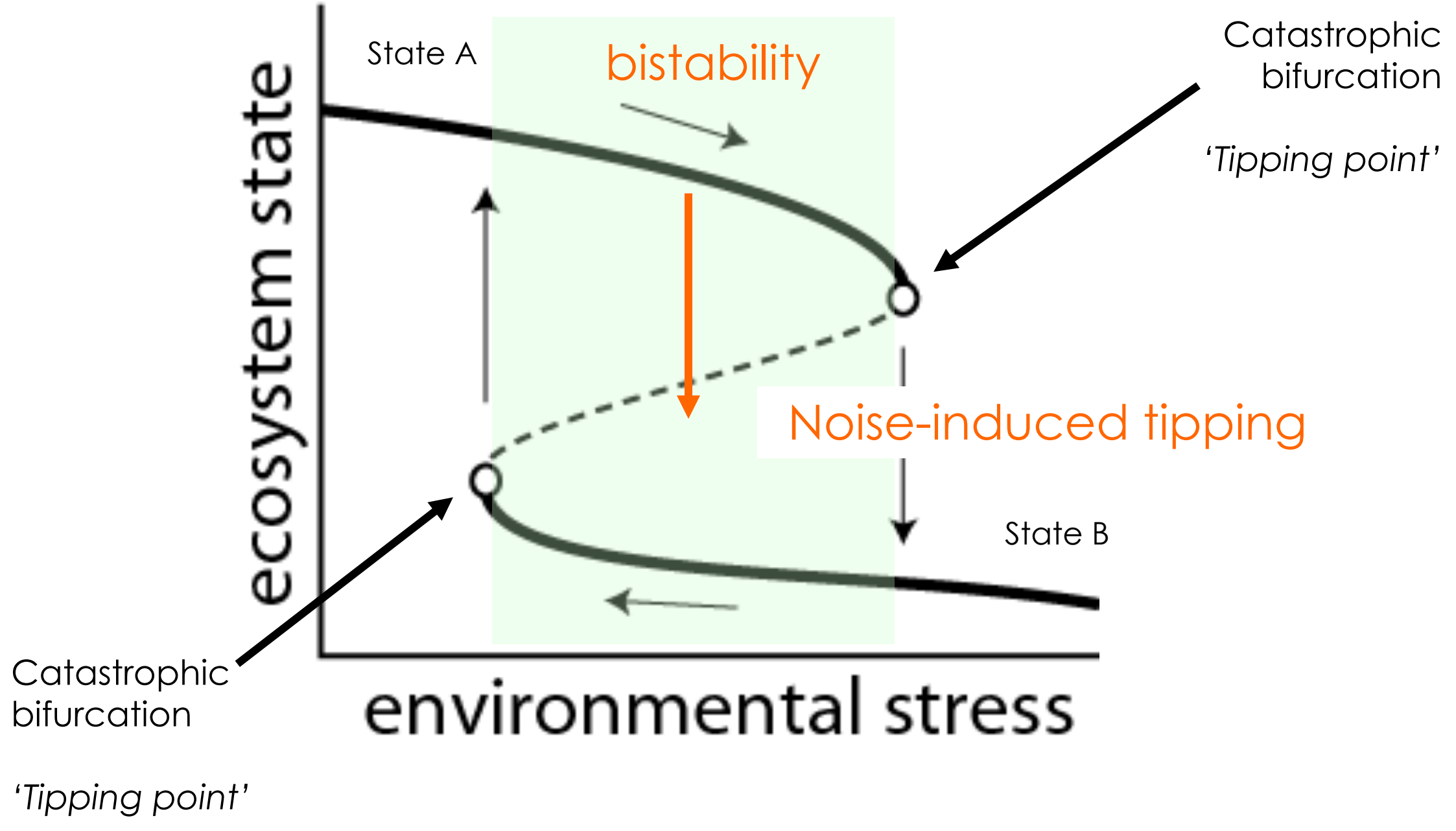

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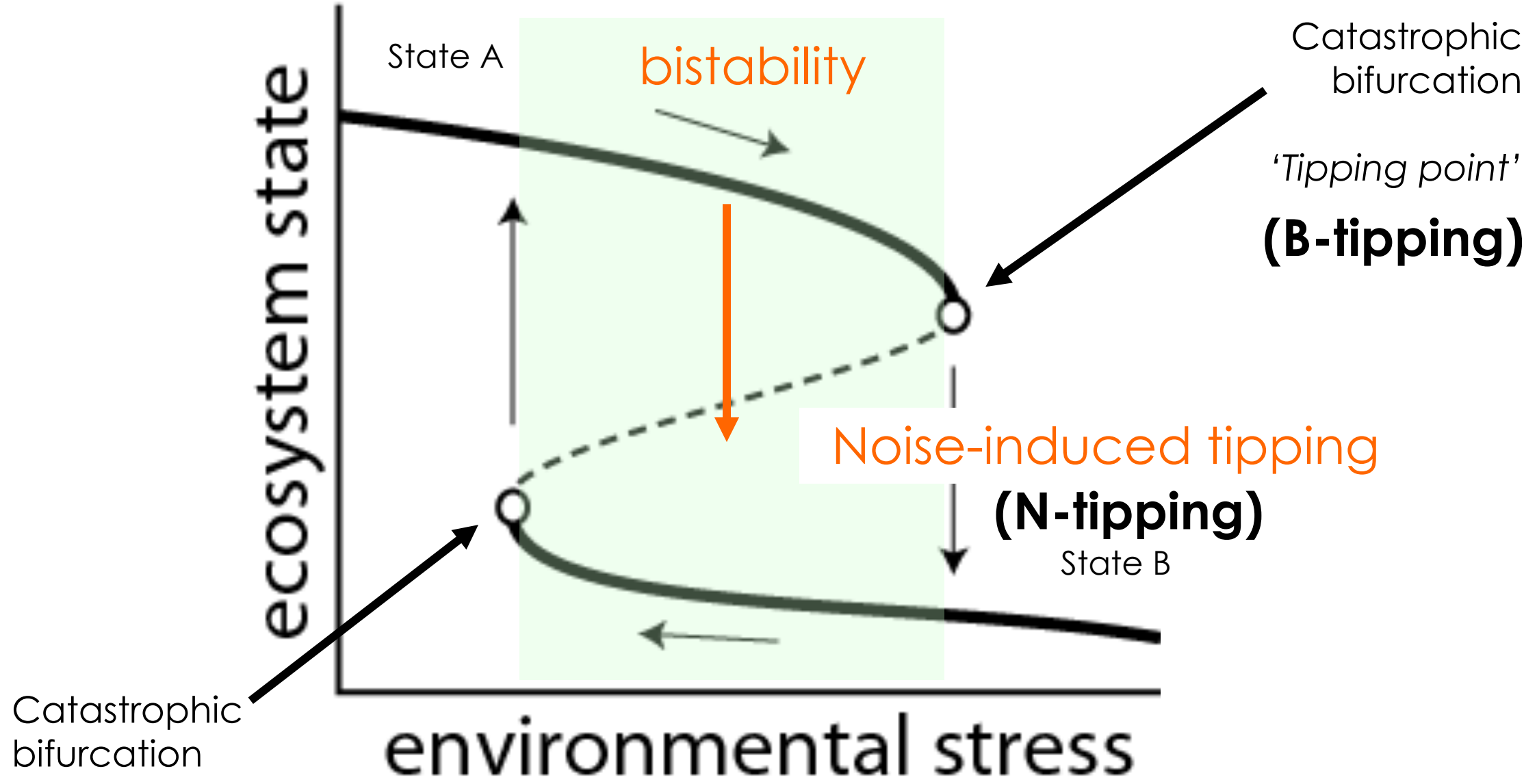
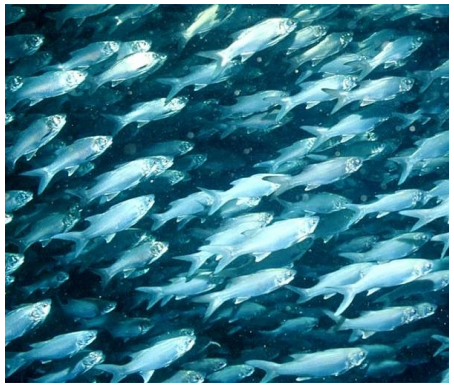
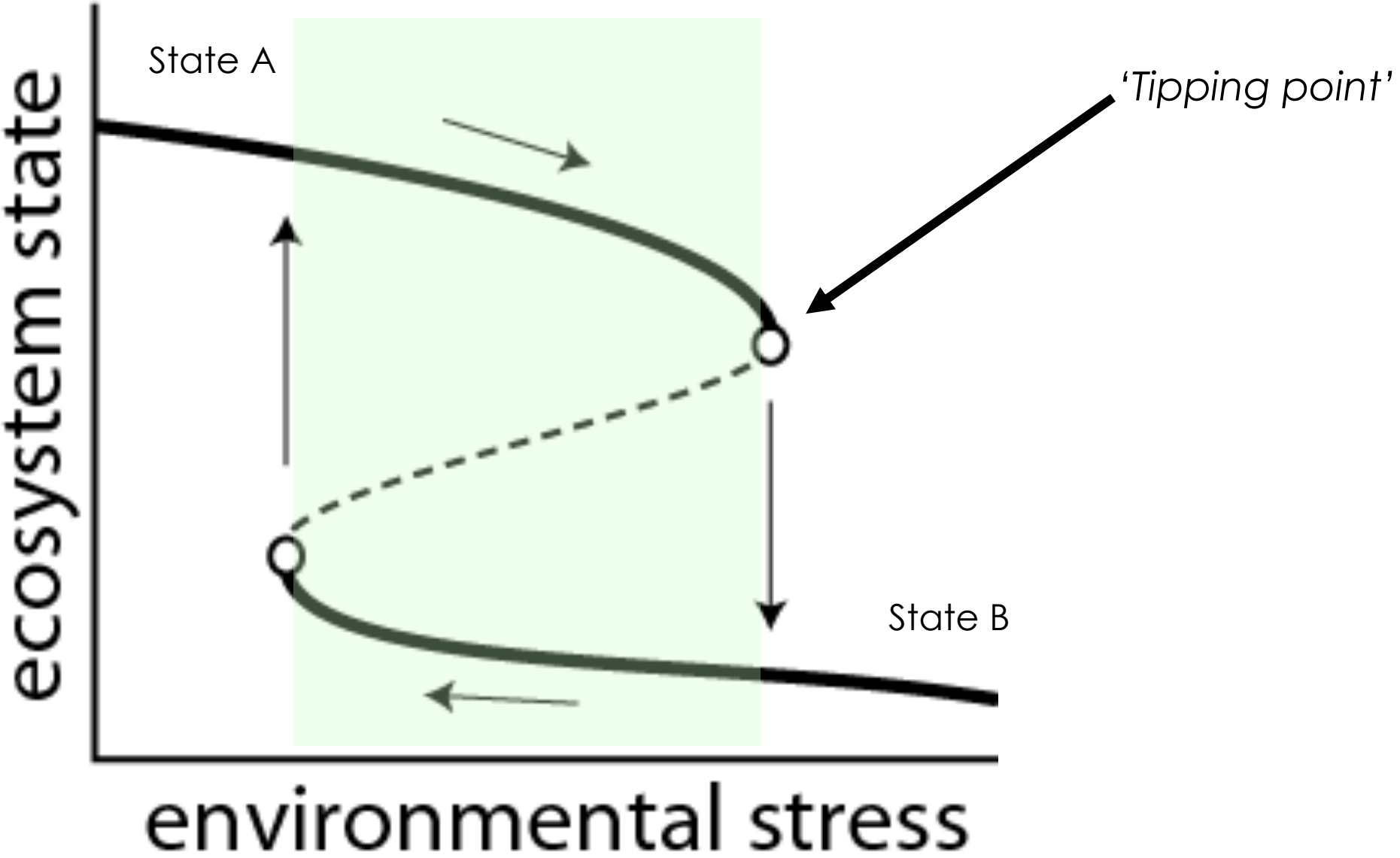
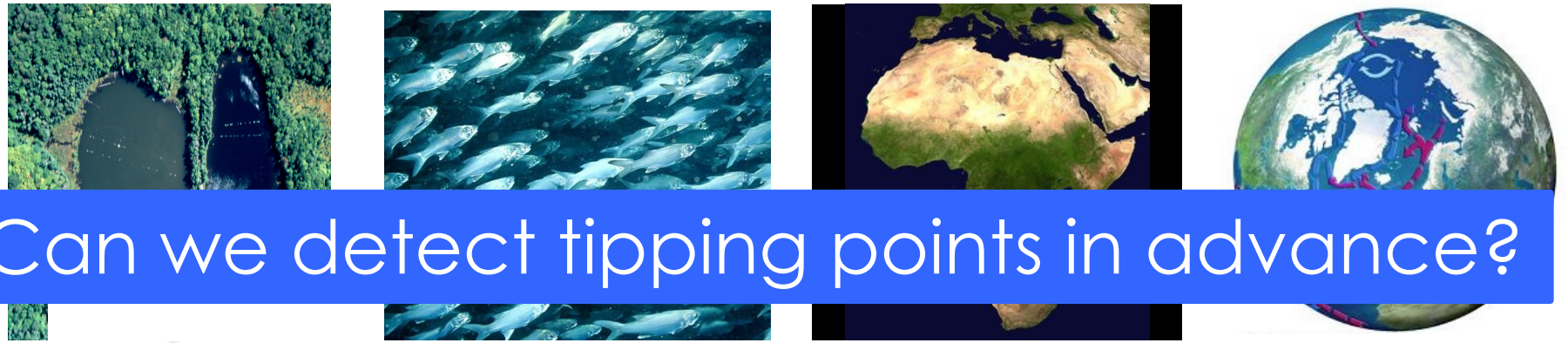


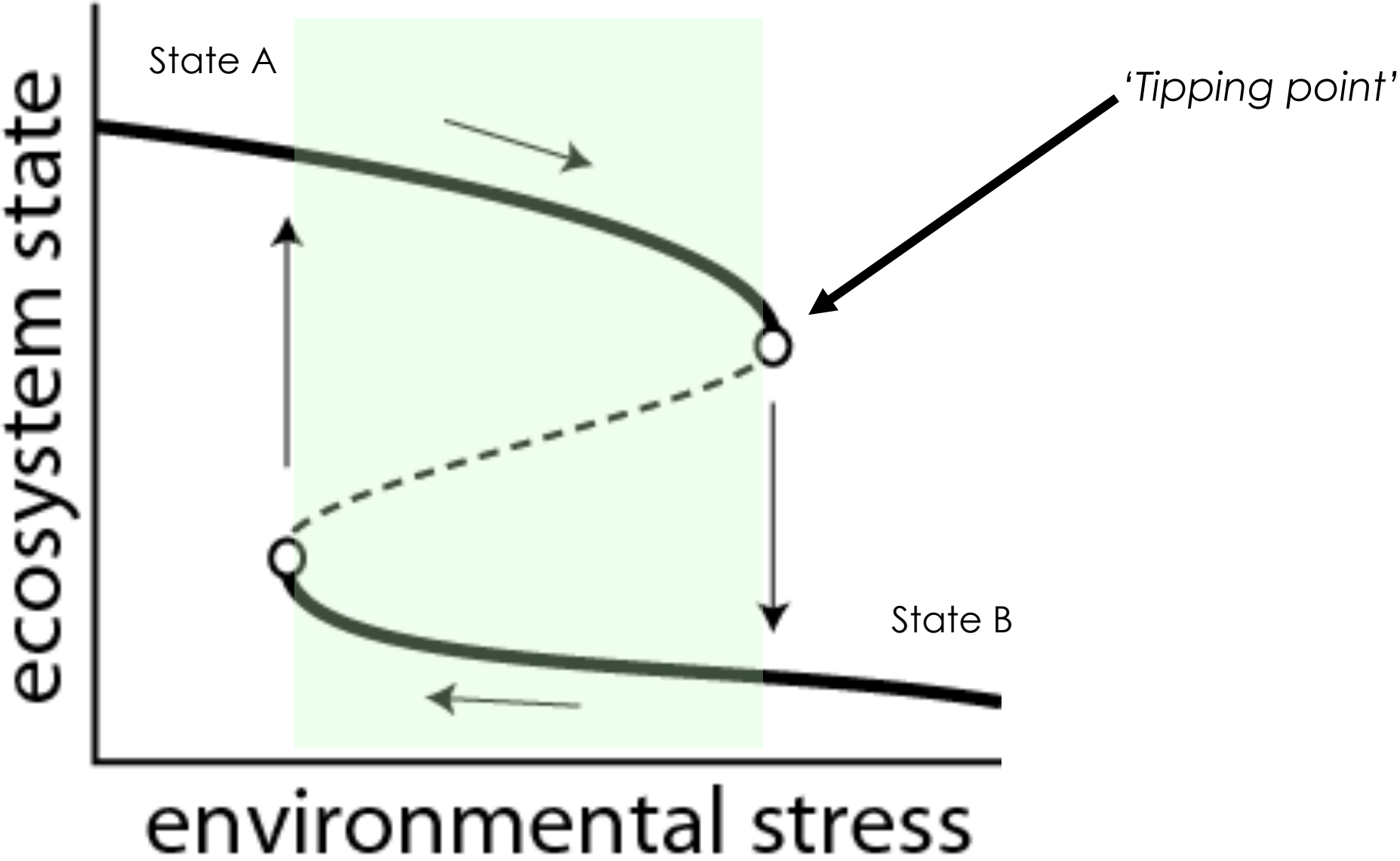
Ashwin et al 2012, Phil Trans R Soc A

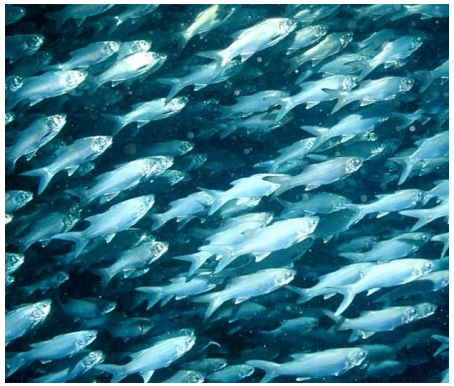




State A
'Tipping point'
ecosystem state
State B
environmental stress



Can we detect tipping points in advance?



State A

'Tipping point'

resilience

State B

ecosystem state

environmental stress

Resilience (ecological):

the magnitude of disturbance a system can tolerate before shifting to an alternative state

(Holling 1973)

loss of (ecological) resilience ~ proximity (high-risk) to tipping point

TOPICAL REVIEW

Ecological resilience: what to measure and how

Vasilis Dakos* and Sonia Kéfi

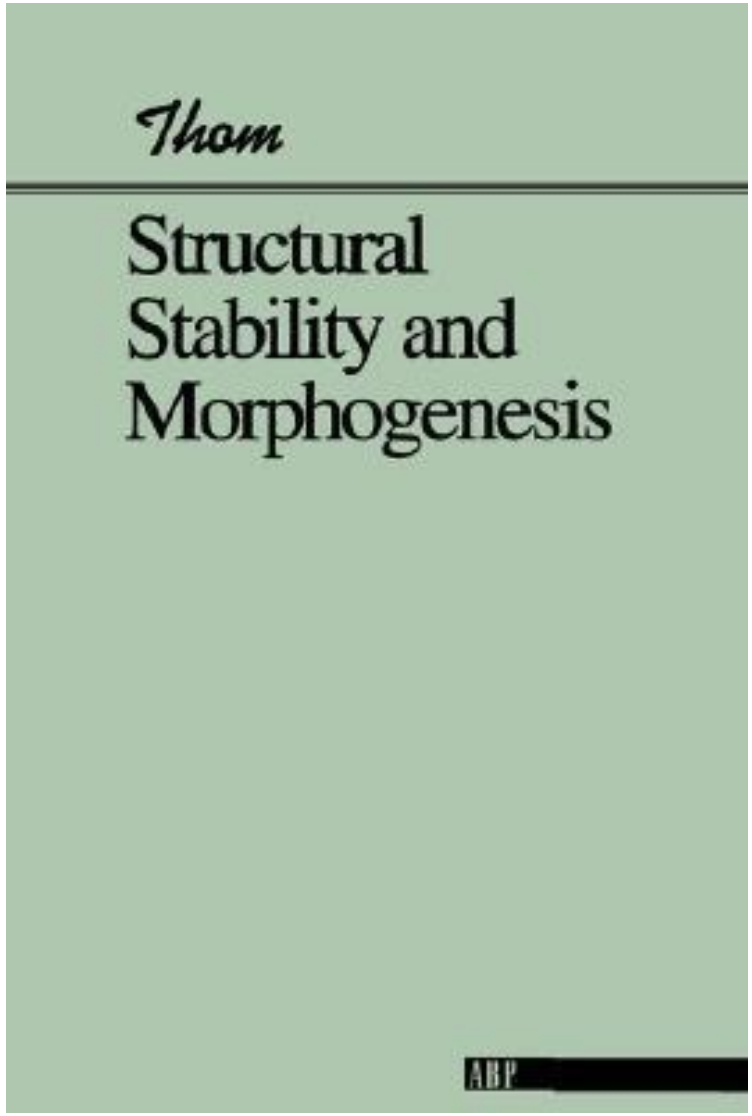
but hard to measure ecological resilience

Dakos & Kefi 2022, Env Res Lett

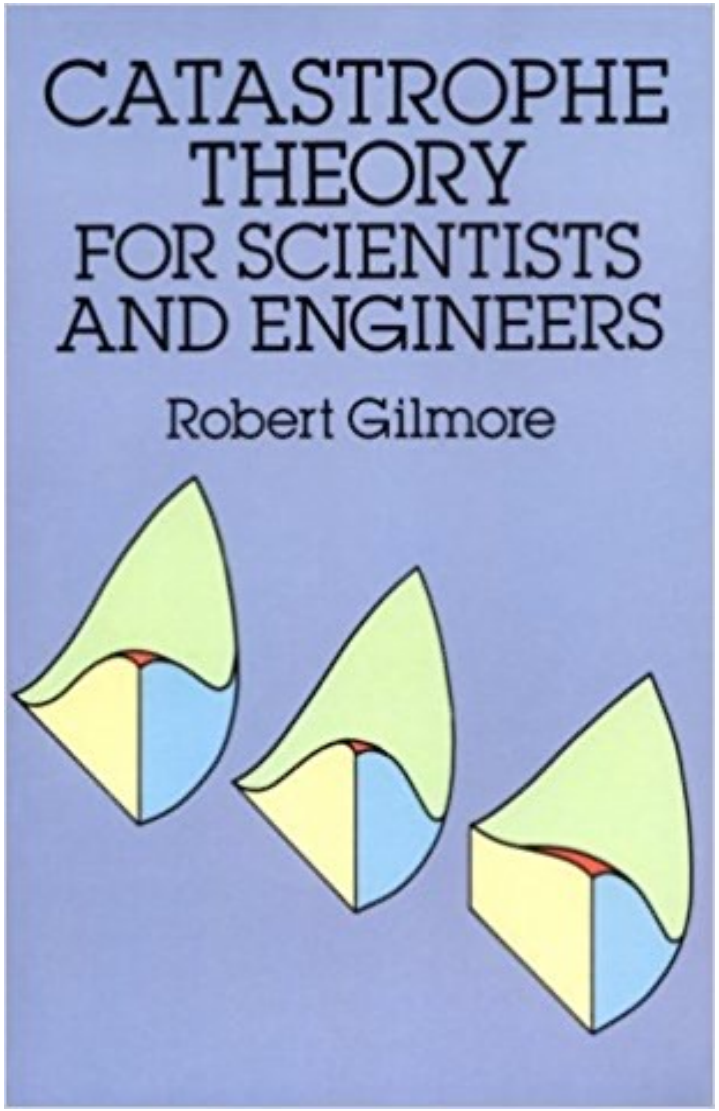
systems prior to tipping points slow down

Wissel 1984 Oecologia; Strogatz 1994

catastrophe theory and catastrophe flags

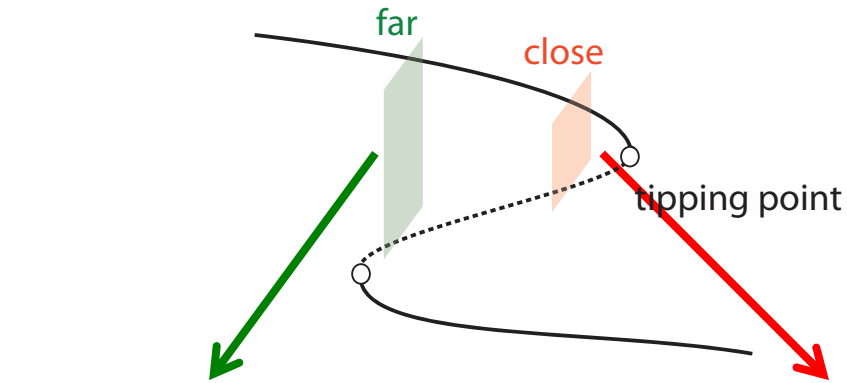


Thom 1976



Gilmore 1981

tipping point indicators



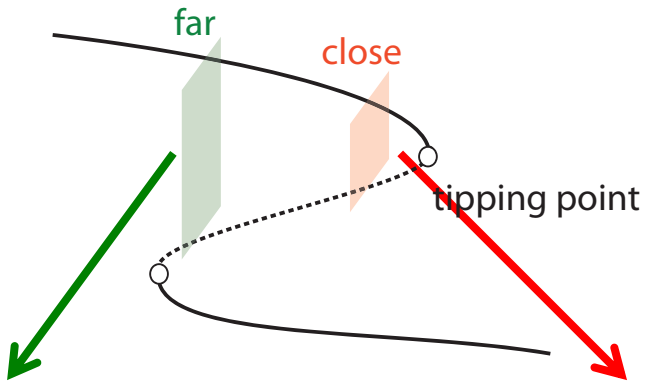
far from tipping

close to tipping

Critical Slowing Down (CSD)

Resilience Indicators (or Early Warnings)

tipping point indicators



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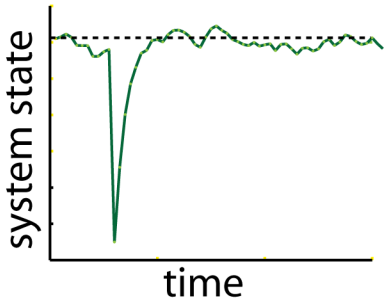
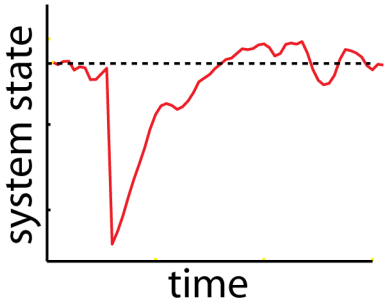


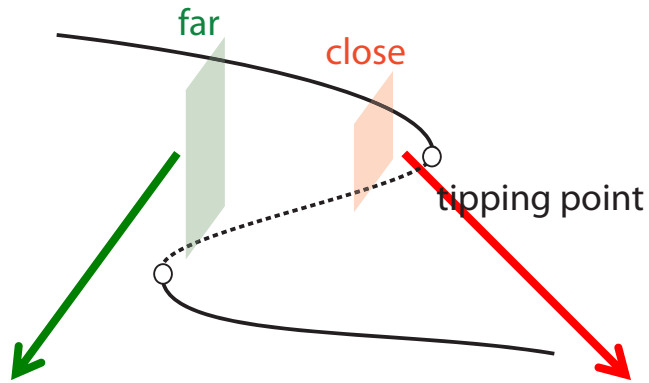
close to tipping



Resilience Indicators (or Early Warnings)

recovery time increases

tipping point indicators



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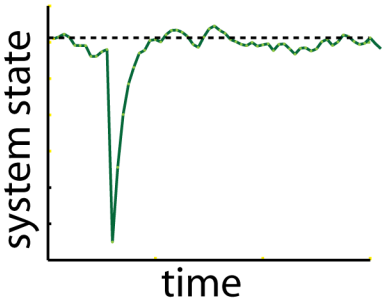
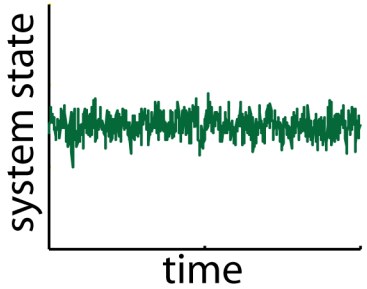
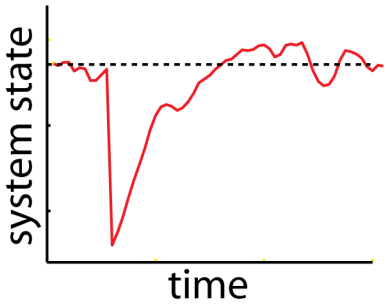
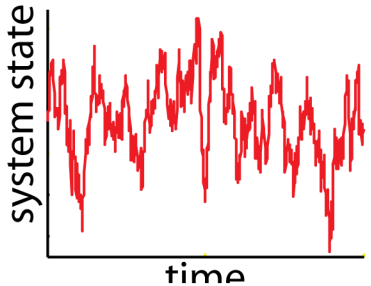




close to tipping



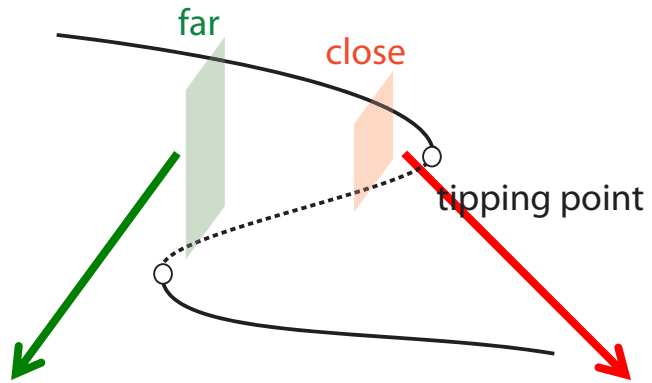


Resilience Indicators (or Early Warnings)

recovery time increases

variance increases

tipping point indicators

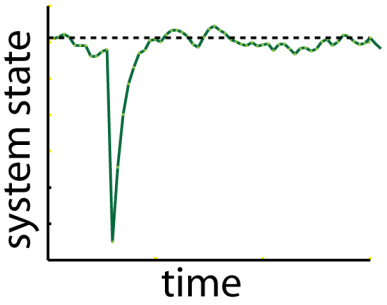


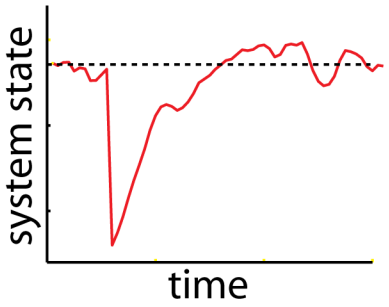
Critical Slowing Down (CSD)

far from tipping

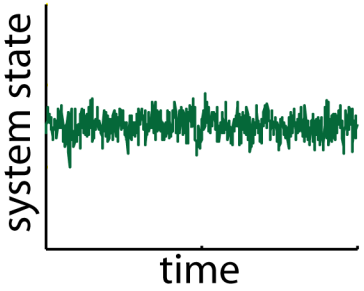
close to tipping

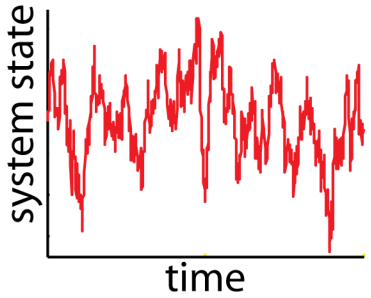
Resilience Indicators (or Early Warnings)



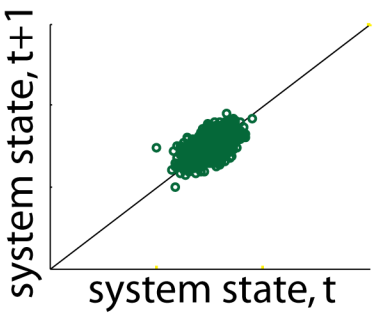


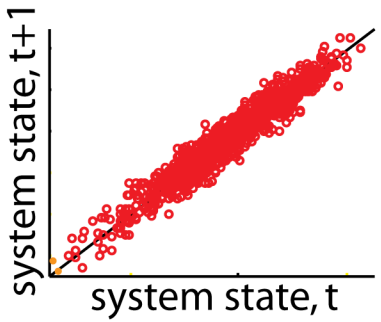
recovery time increases





variance increases





autocorrelation rises

Vol 461|3 September 2009|doi:10.1038/nature08227 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], Hermann Held[6], Egbert H. van Nes[1], Max Rietkerk[7] & George Sugihara[8]

Early-warning signals (for tipping point detection)

changes in statistical signatures in time or space that infer loss of resilience and proximity to tipping point responses

slowing down in a living system

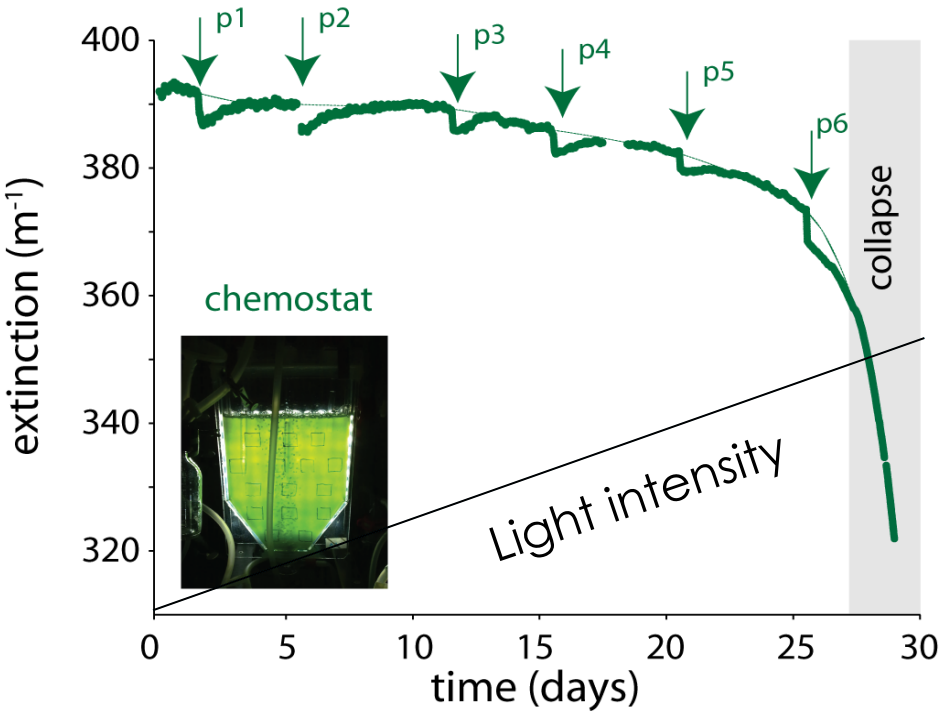
phytoplankton collapse due to photoinhibition

Veraart et al 2012, Nature

slowing down in a living system

phytoplankton collapse due to photoinhibition

removal of 10% of standing stock through dilution



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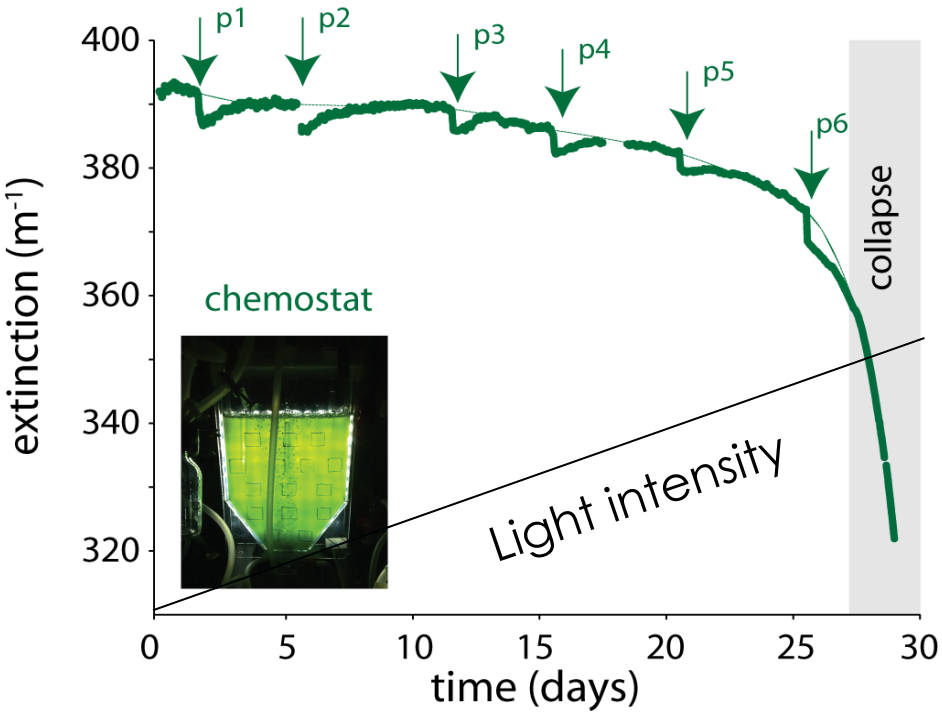
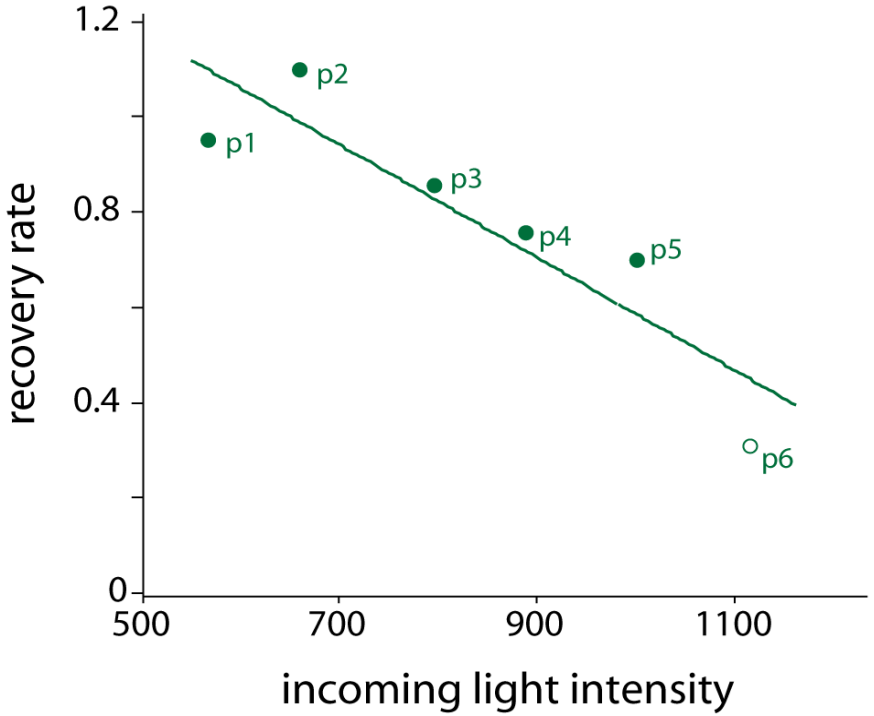
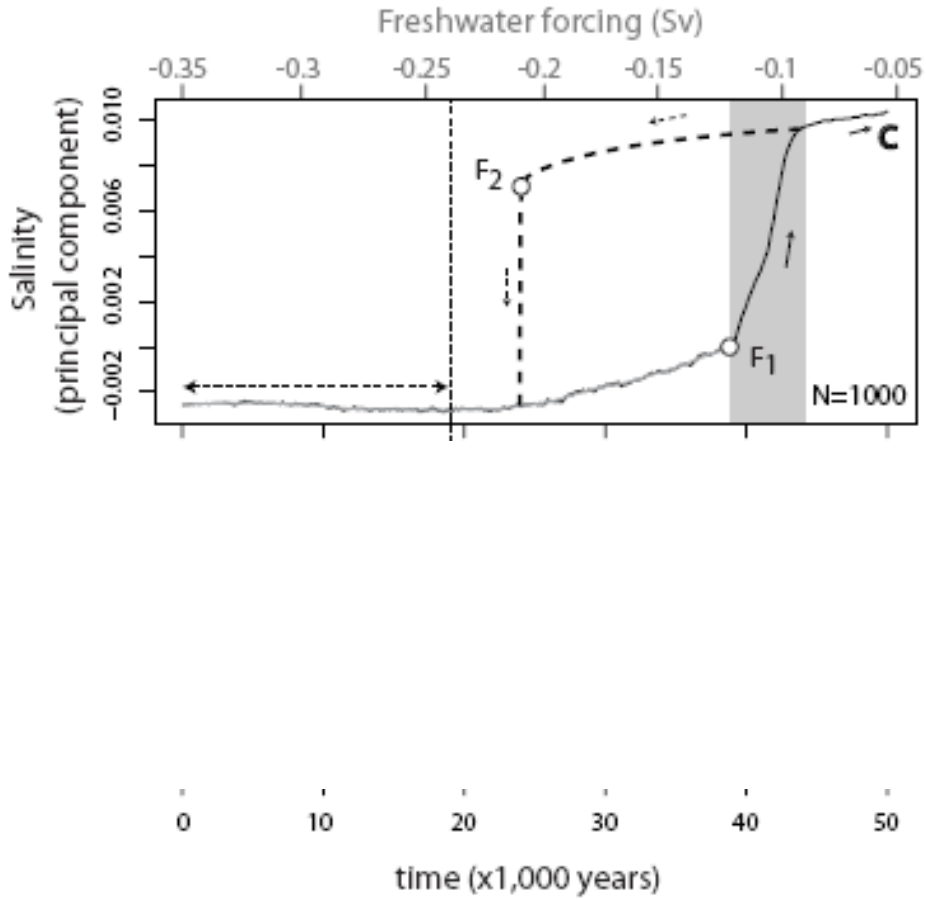




Veraart et al 2012, Nature

slowing down before past climate shifts

Shutdown of thermohaline circulation (CLIMBER2 EIC)



Model data

Dakos et al 2008, PNAS

slowing down before past climate shifts

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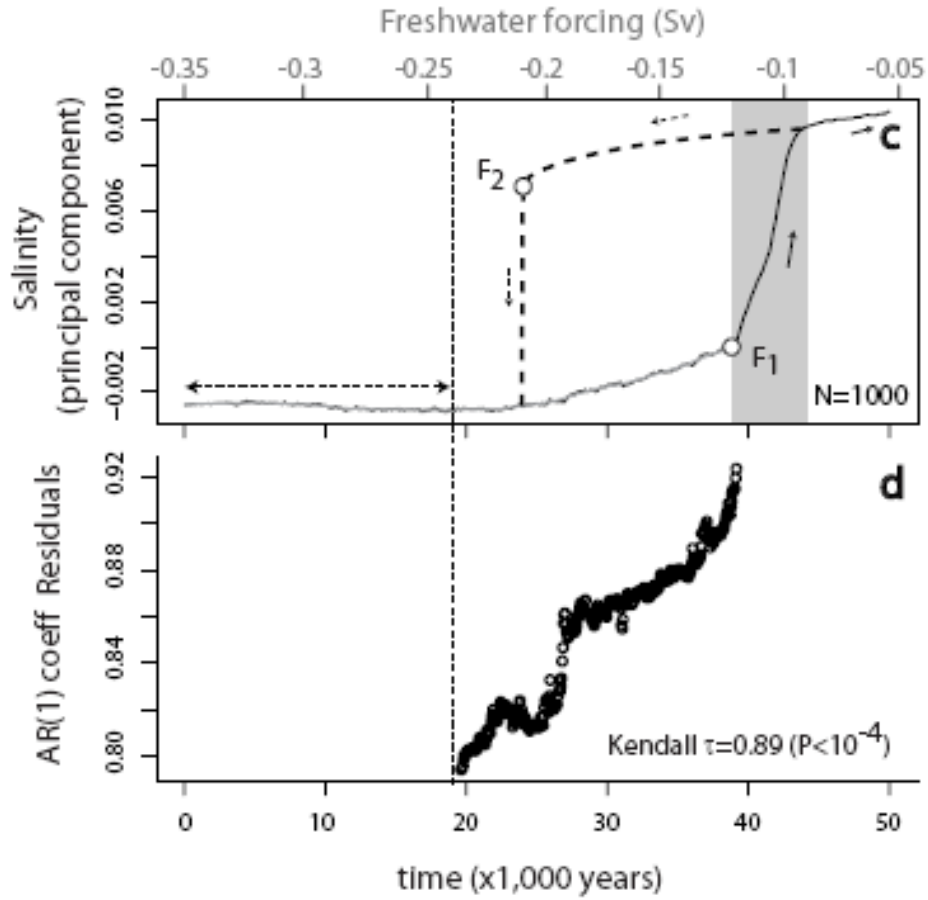

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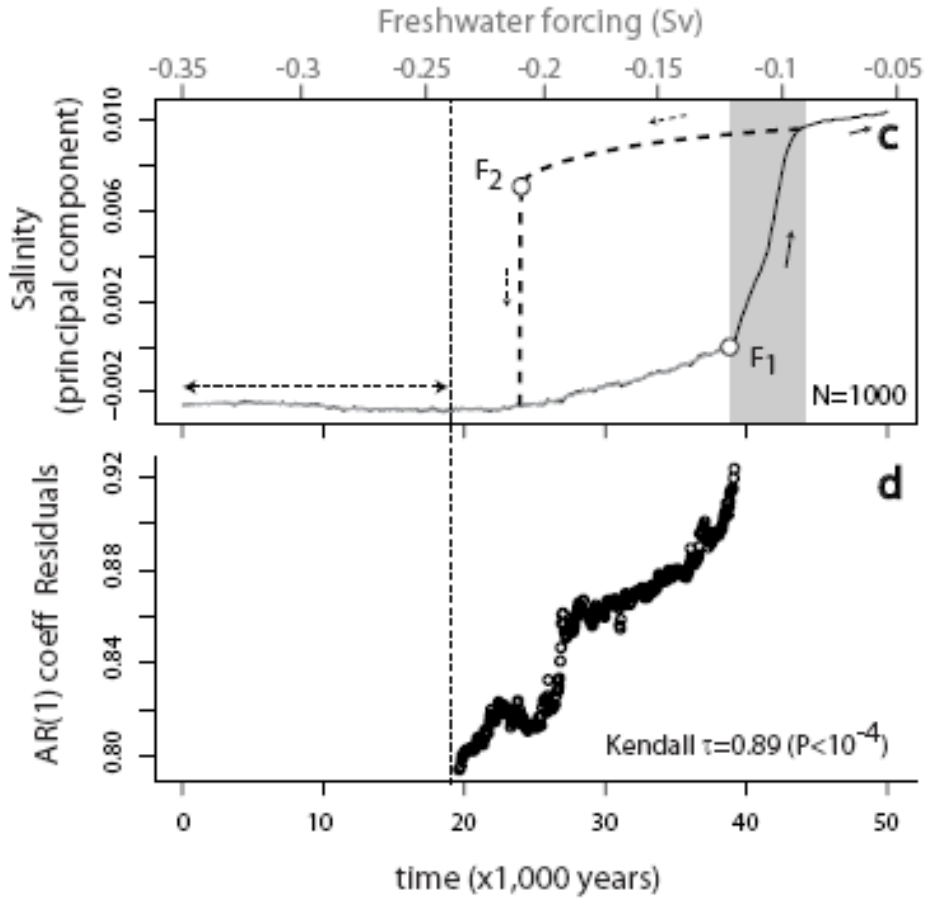
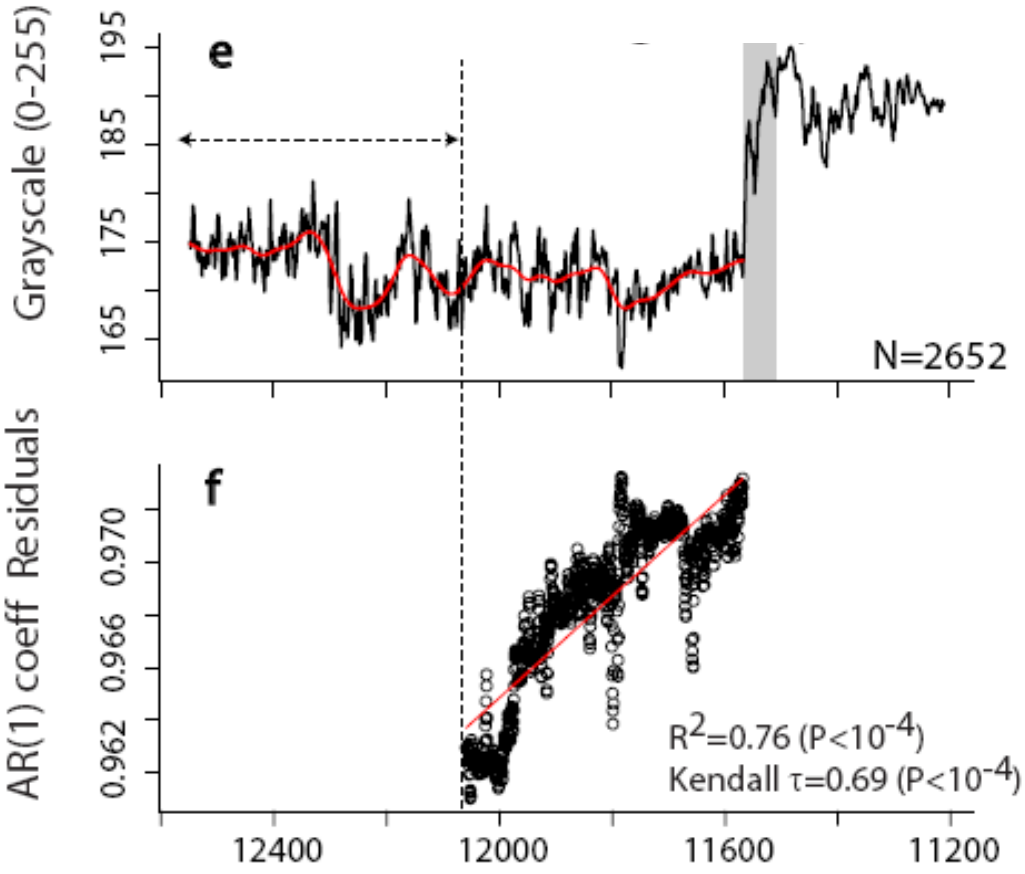


Model data

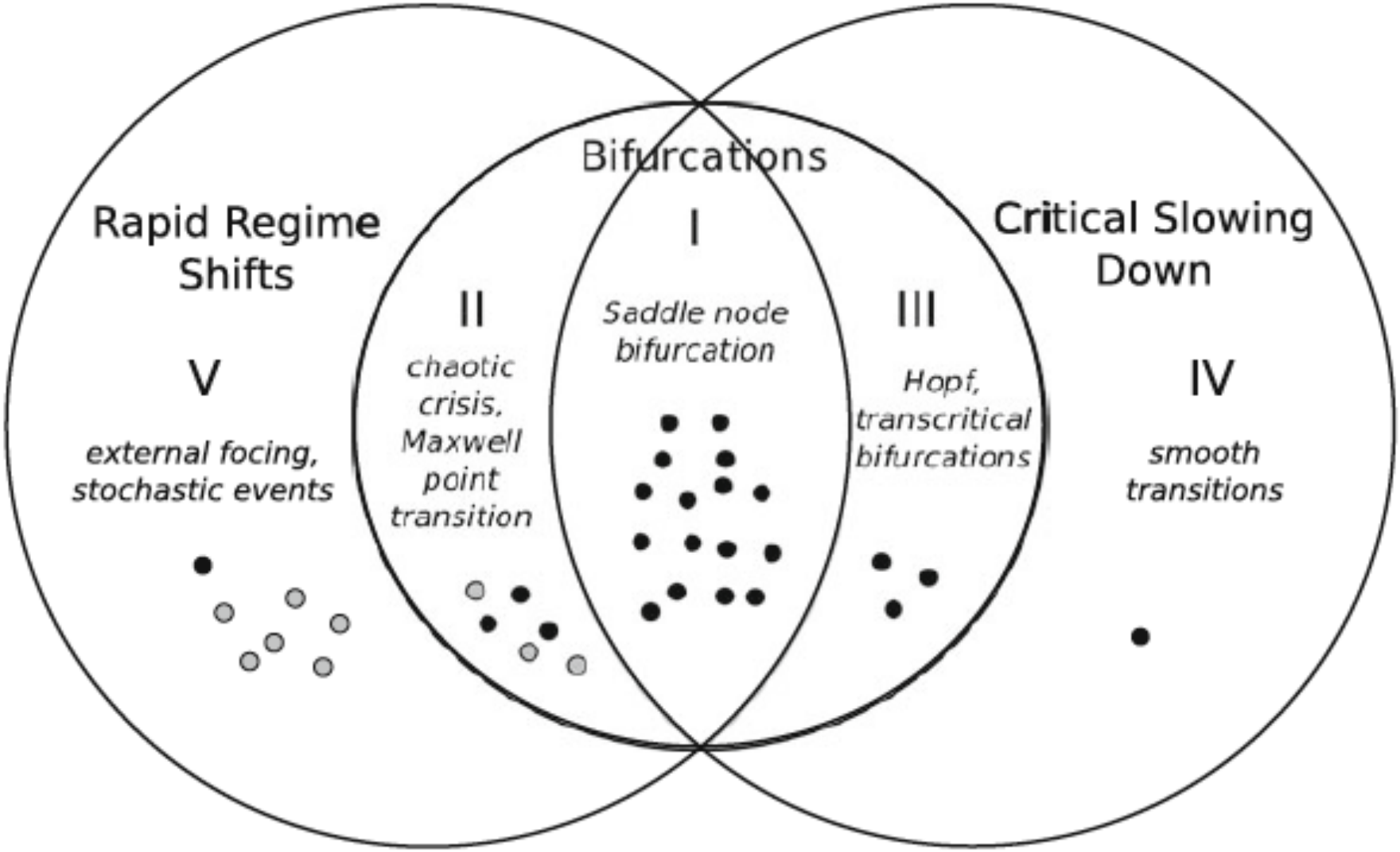
end of Younger Dryas



Paleo-climate data

Dakos et al 2008, PNAS

theoretical challenge - too generic?

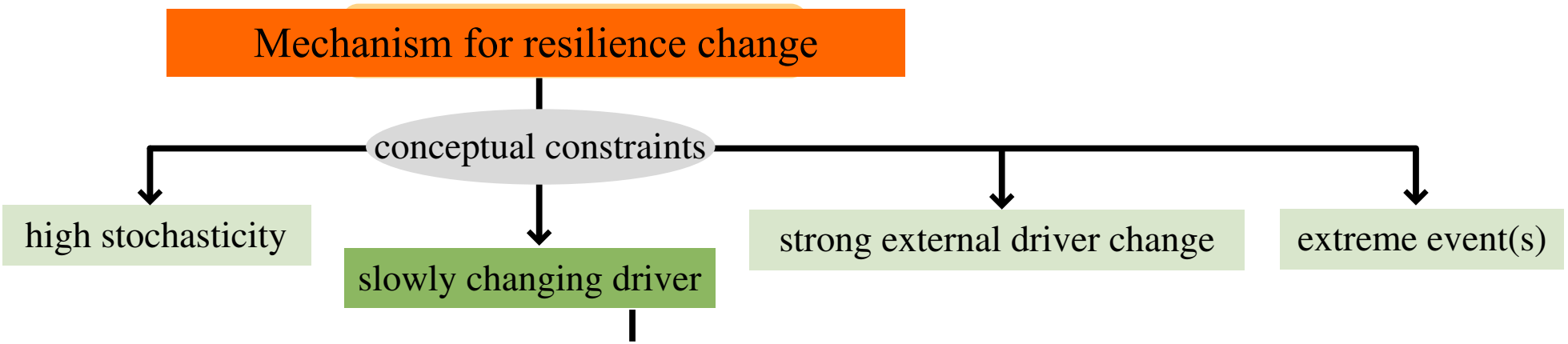


There can be tipping points without EWS

There can be EWS without tipping points

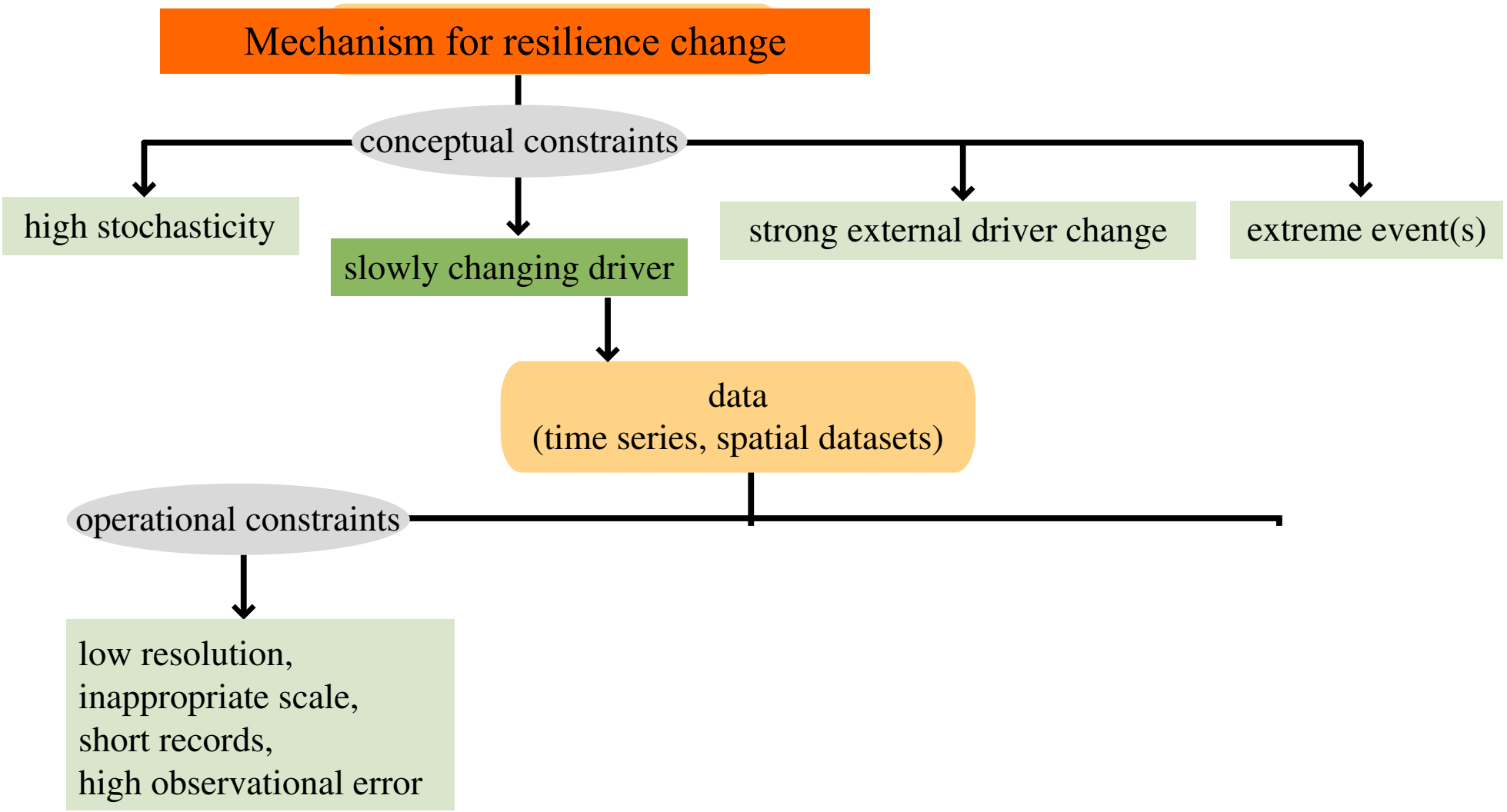
Boettiger et al. 2013

Constraints and Challenges



Dakos et al 2015, Phil Trans B Roy Soc

Constraints and Challenges



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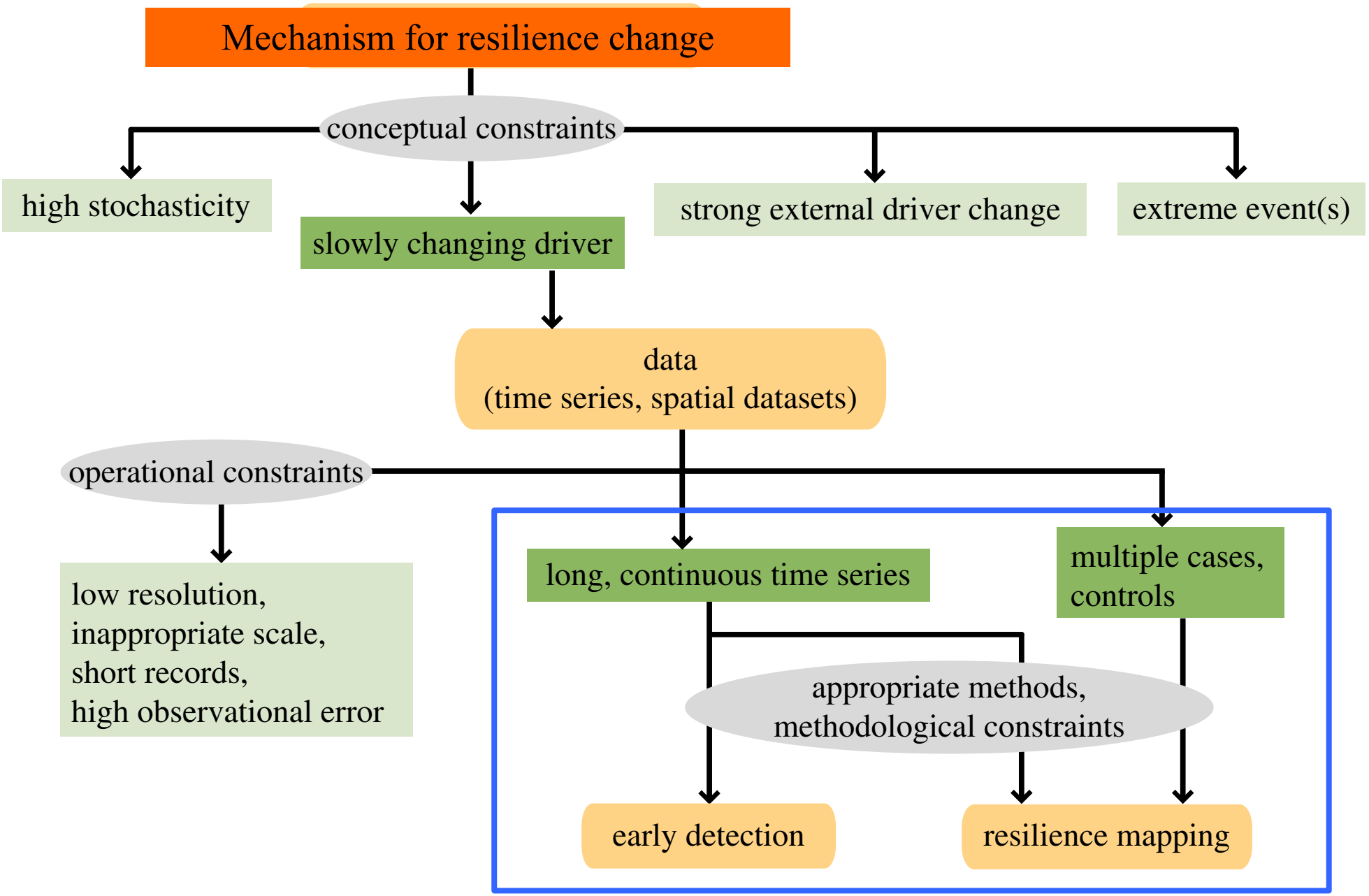
Constraints and Challenges



Dakos et al 2015, Phil Trans B Roy Soc

methods for tipping point detection – mostly on temporal data (less spatial)

	CSD-based (~ B-tipping)	non-CSD-based (~ B-tipping/ N-tipping)
pattern-based	variance (temporal/spatial) autocorrelation (temporal/spatial) return rate/time (temporal) detrended fluctuation analysis (temporal) spectral reddening (temporal) variance-covariance eigenvalue (temporal) dynamic eigenvalue (temporal) Machine-Learning approach (temporal) recovery length (spatial) speed of traveling waves (spatial) repair time (spatial) Discrete Fourier transform (spatial)	skewness (temporal/spatial) conditional heteroscedasticity (temporal/spatial) potential analysis (temporal) kurtosis (temporal) quickest detection method (temporal) Fisher information (temporal) mean exit time-Fokker-Planck (temporal) nonlinearity (temporal) trait statistical changes (temporal) Machine-Learning approach (temporal) average flux (temporal) Turing patterns (spatial) patch size distributions (spatial) Kolmogorov complexity (spatial) network–properties (spatial/temporal)
process-based	generalised models (temporal) time-varying AR(p) models (temporal) probabilistic time-varying AR(p) (temporal)	drift-diffusion-jump models (temporal) threshold AR(p) models (temporal) likelihood ratio (temporal)

Dakos et al (2023) EGUsphere

methods for tipping point detection – mostly on temporal data (less spatial)

early-warning-signals.org

Name	Software	Description	Reference
earlywarnings	R package	One of the earliest R packages to calculate model and metric based early-warnings	(Dakos et al., 2012) github.com/earlywarningtoolbox
earlywarning	R package format	Fits a normal form model with and without a saddle-node bifurcation based on a likelihood approach	(Boettiger and Hastings, 2012b) github.com/cboettig/earlywarning
Generic_ews	Matlab	Matlab translation from the early-warning signals toolbox in R	git.wur.nl/sparcs/generic_ews-for-matlab/-/tree/master
spatialwarnings	R package	Estimates spatial warning signals based on spatial statistics and spatial pattern formation	(Génin et al., 2018)
ewstools	Python package	Python translation of the earlywarnings toolbox, with the addition of deep learning classifiers	(Bury, 2023)
EWSmethods	R package	toolbox inspired by *earlywarnings*, that omits model-based EWS, but includes multivariate indicators	(O'Brien et al., n.d.)

Dakos et al (2023) EGUsphere

Outline

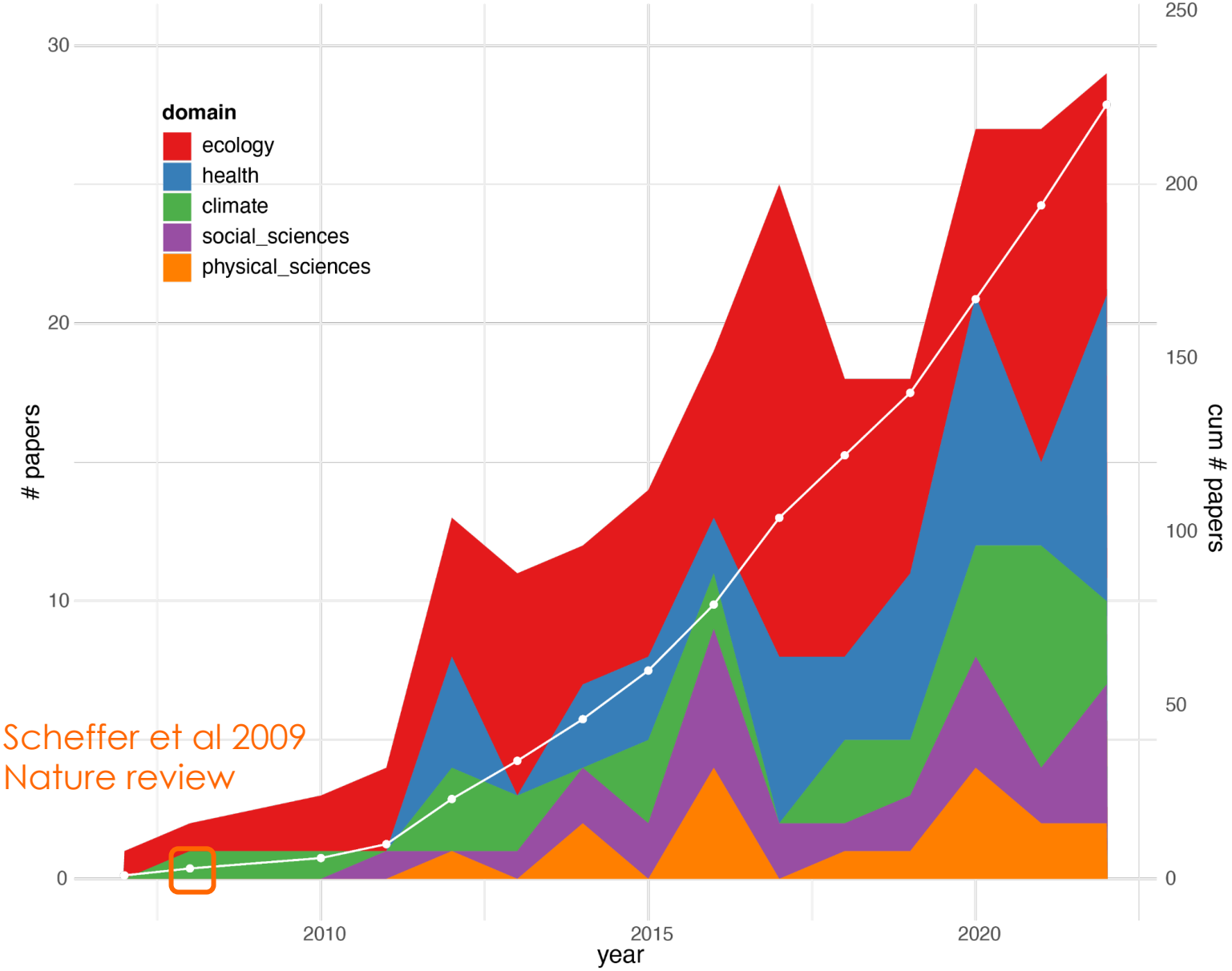
1. Basics of tipping point detection and quantification of resilience

2. **An empirical assessment of tipping point detection and resilience**

Systematic review of empirical use of early-warnings

Dakos et al (2023) EGUsphere

A growing list of empirical studies (229!) …



Scheffer et al 2009
Nature review

Ecology (104)
(desertification, lake eutrophication, population collapse, community shifts)

Climate (33)
(paleoclimatic shifts, current climate systems)

Physical sciences (18)
(power grid, material science)

Health (53)
(cardiac instability, depression, geriatrics, disease epidemics, gut microbiome)

Social sciences (31)
(social unrest, finance)

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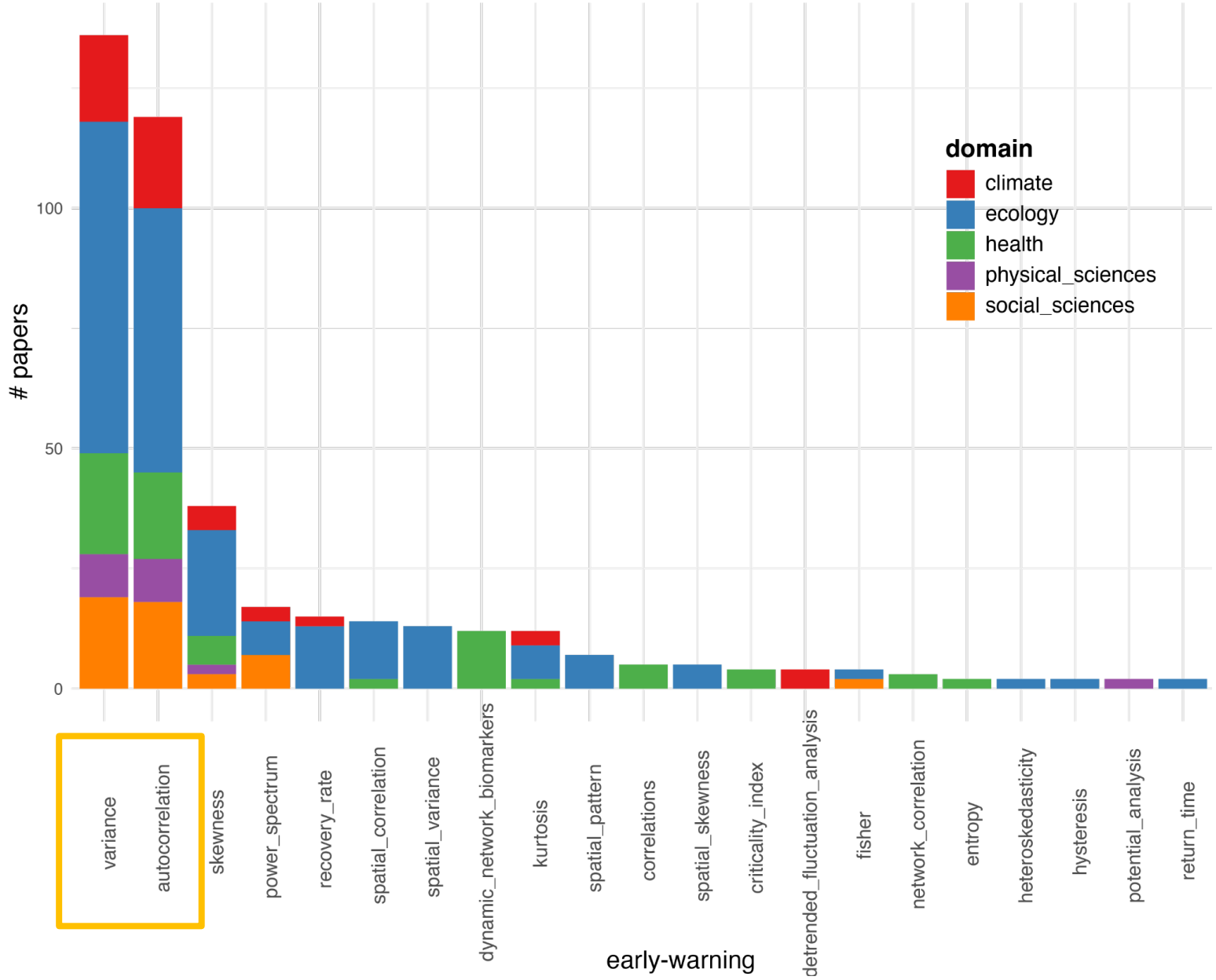
Multitude of early-warnings: 65 signals but only 21 used in more than 1 paper



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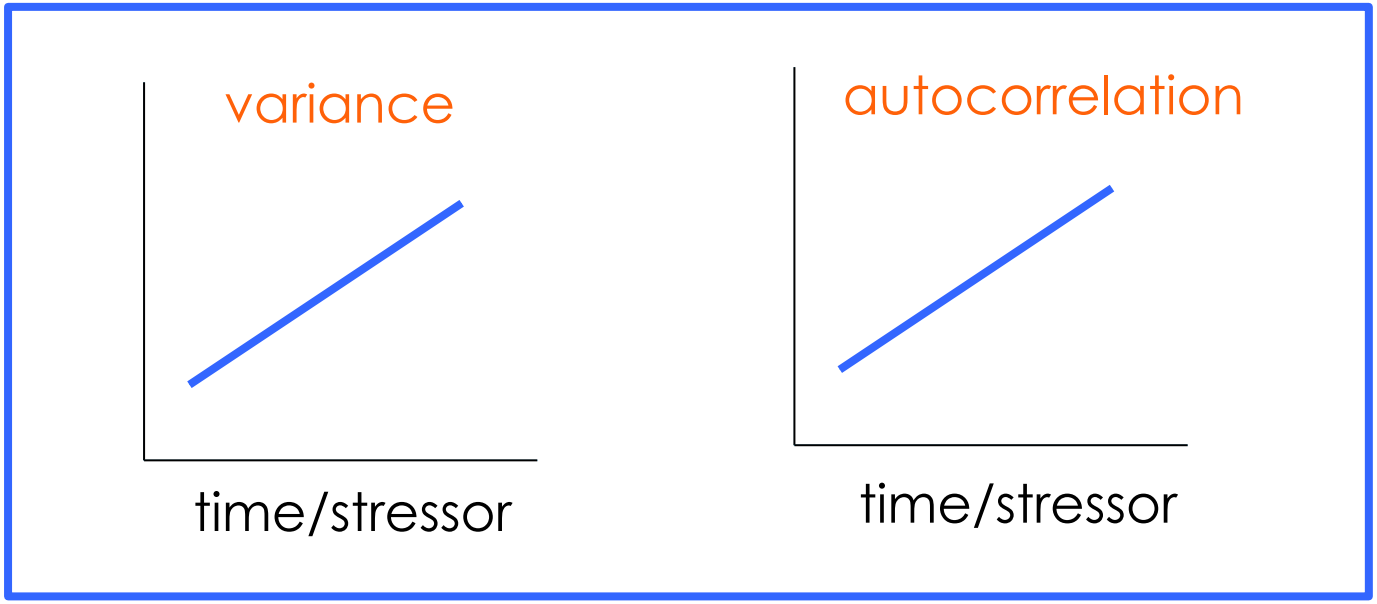
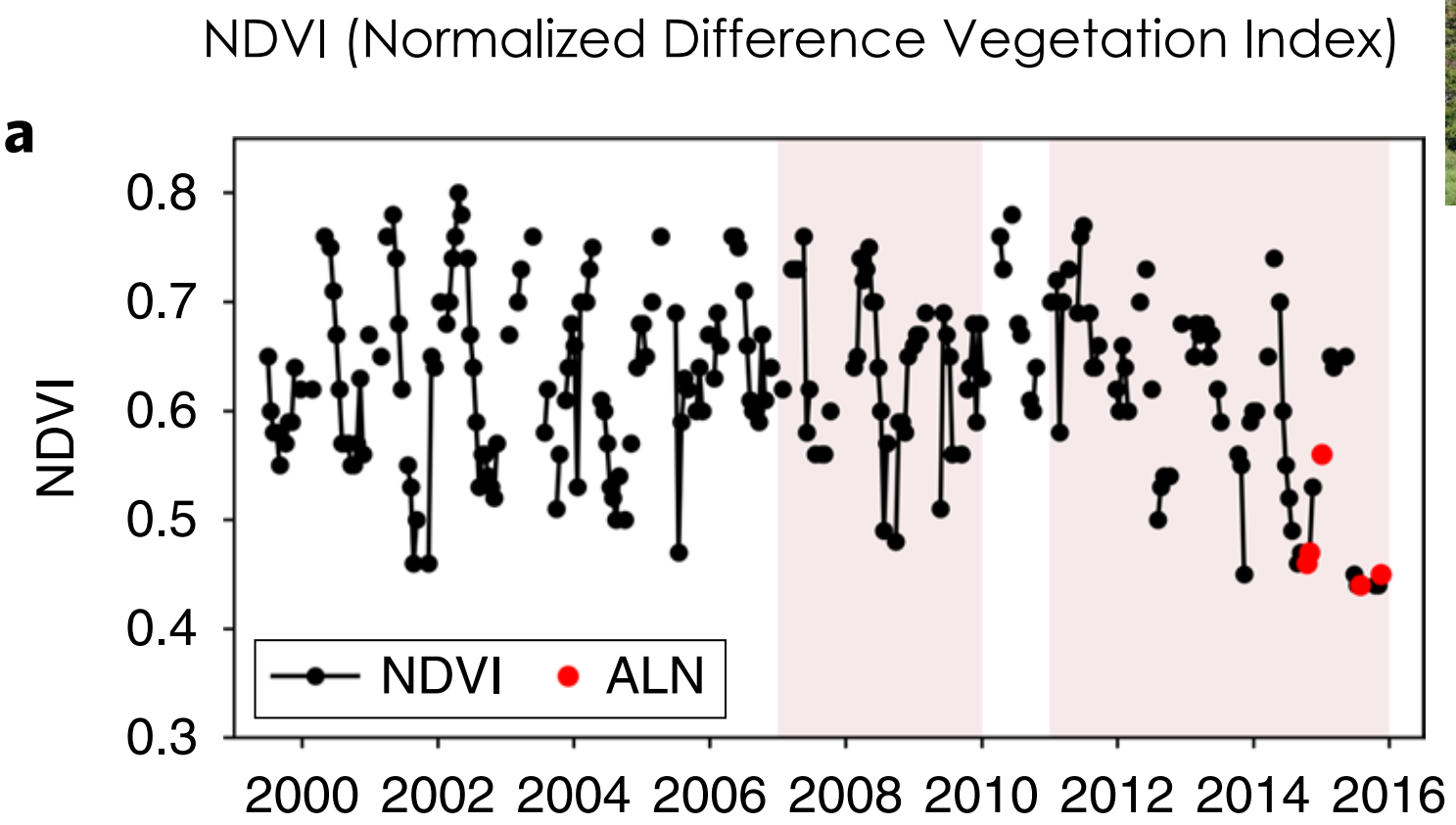
application: monitoring, mapping, ranking



- **monitor** changes in resilience within a system (early-warnings)
- **map+rank** resilience across systems/sites/species (identify hotspots of resilience loss)

monitoring tree mortality risk

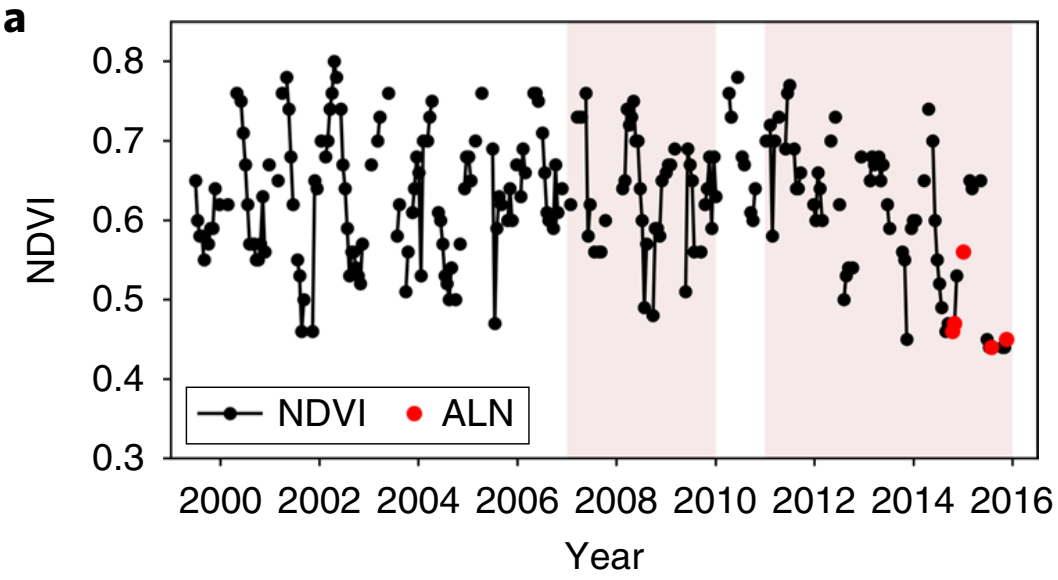
monitoring tree mortality risk

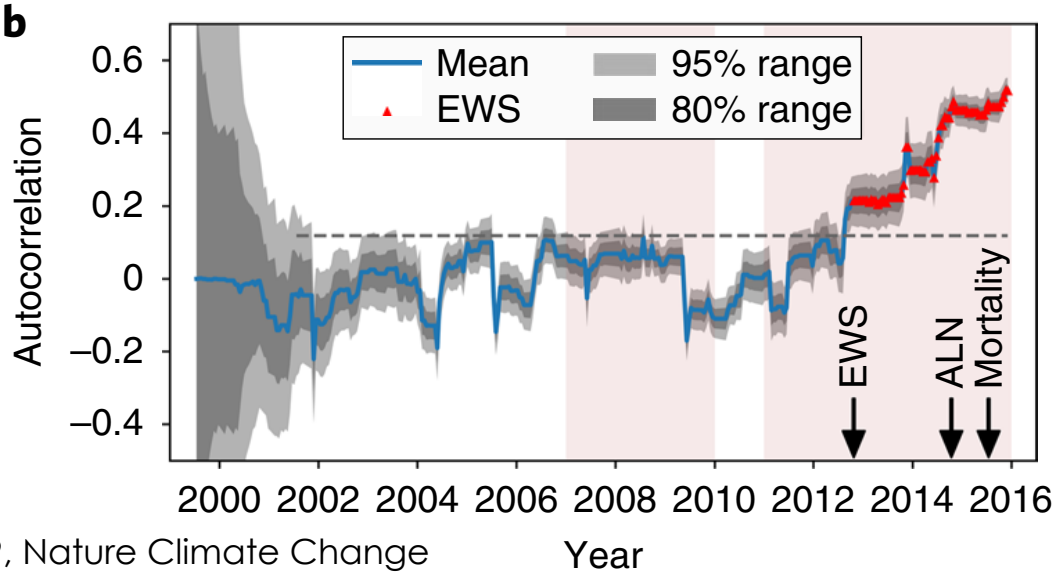


Liu, et al 2019, Nature Climate Change

monitoring tree mortality risk

NDVI (Normalized Difference Vegetation Index)





Liu, et al 2019, Nature Climate Change

mapping and ranking forest resilience at global scales

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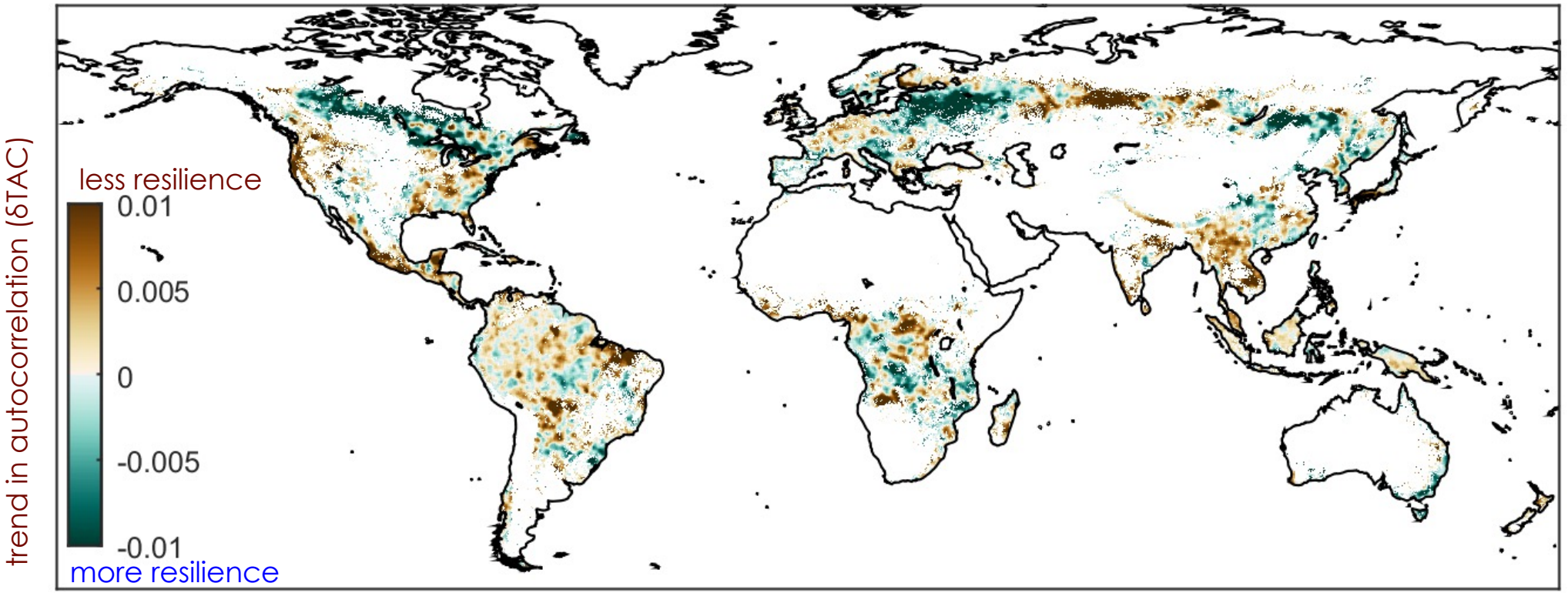
NDVI from global forest ecosystems



higher autocorrelation (δTAC) = less resilience ~ higher risk of tipping response

Forzieri, Dakos et al Nature (2022)

mapping – projected changes in climate variability as proxy for hotspots of climate instability

Relative changes in variability of monthly temperature between historical record (~1900) and model projections until 2100

based on output from 37 models from CMIP5

Bathiany, et al 2018, Science Advances

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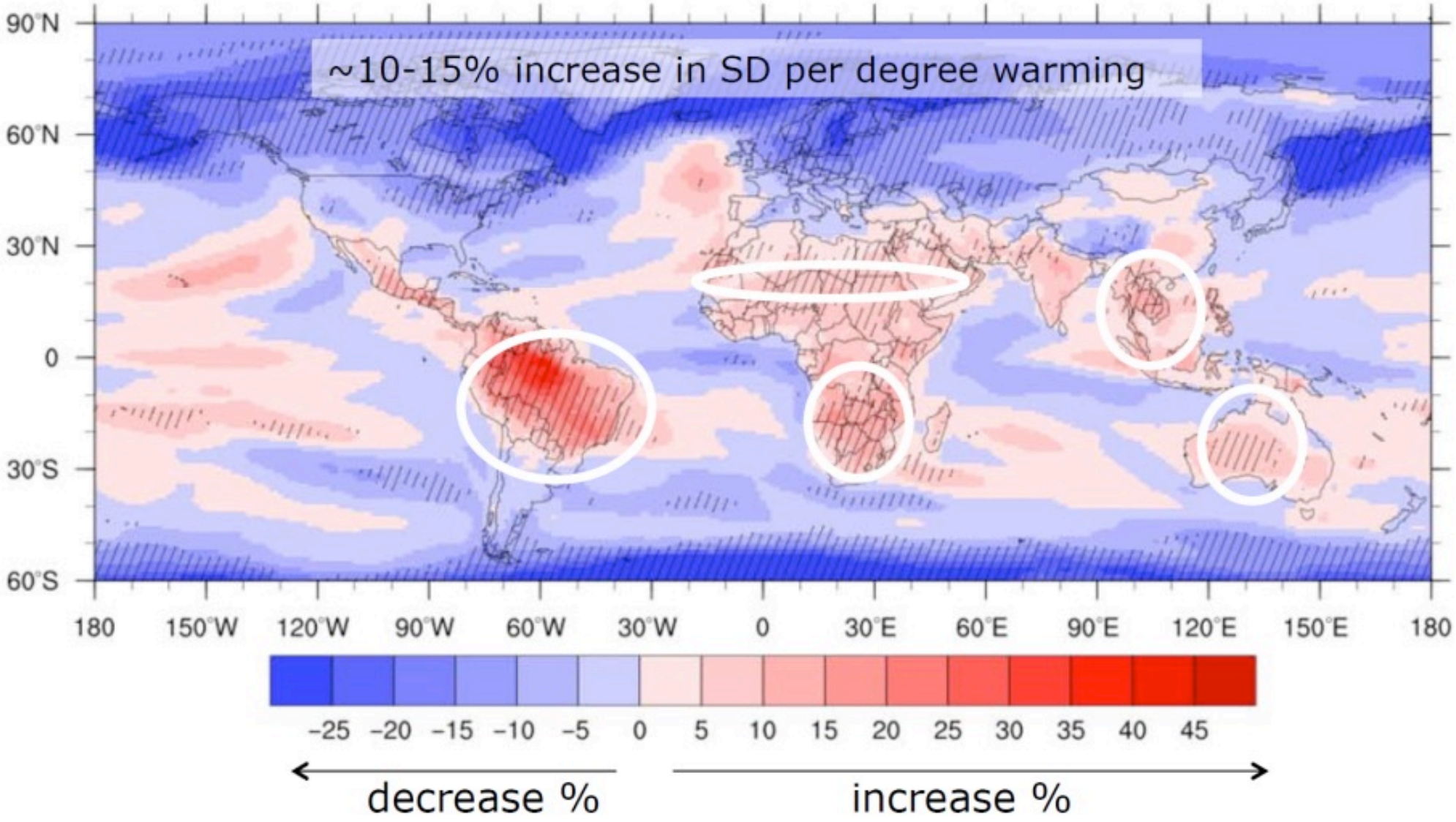

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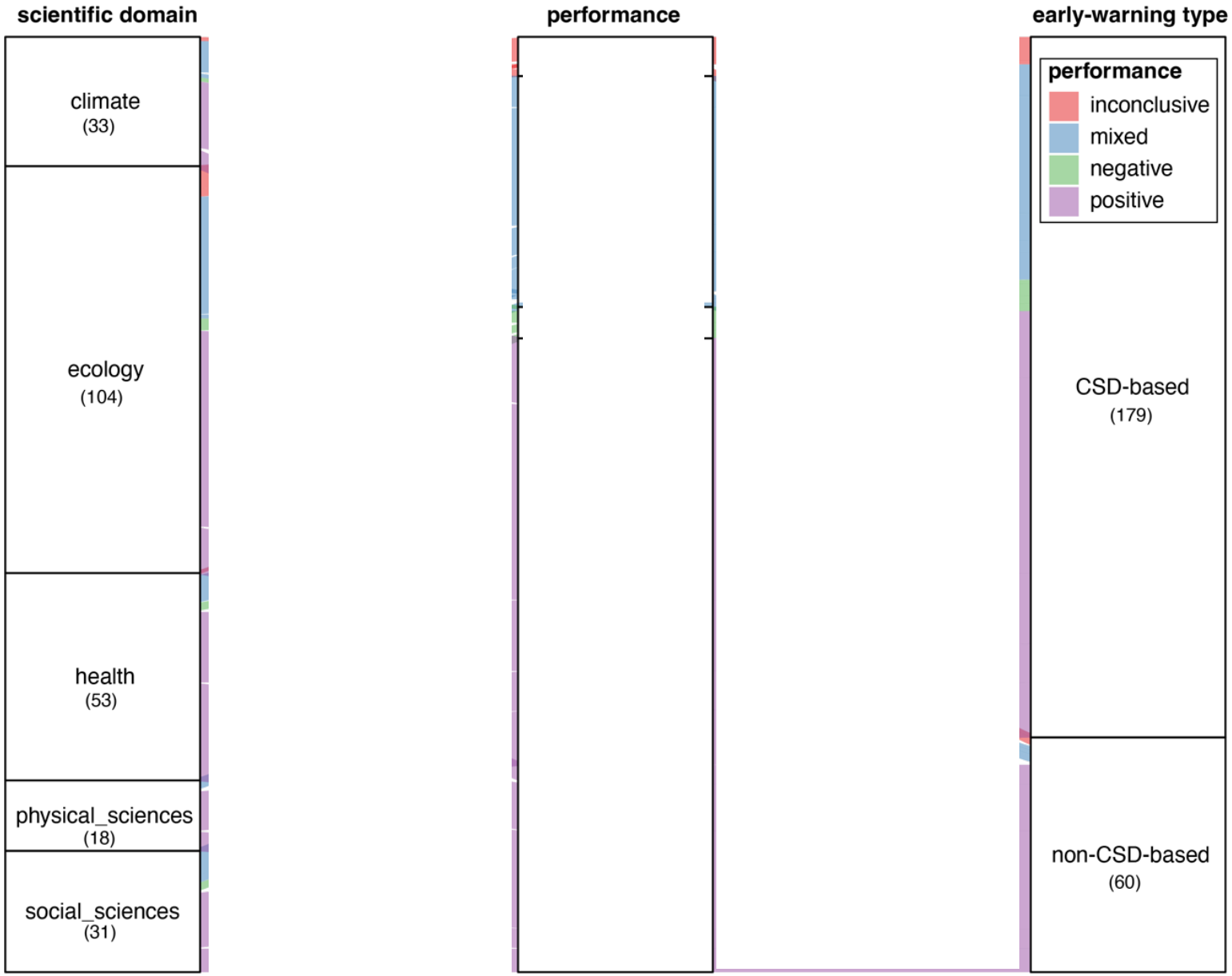
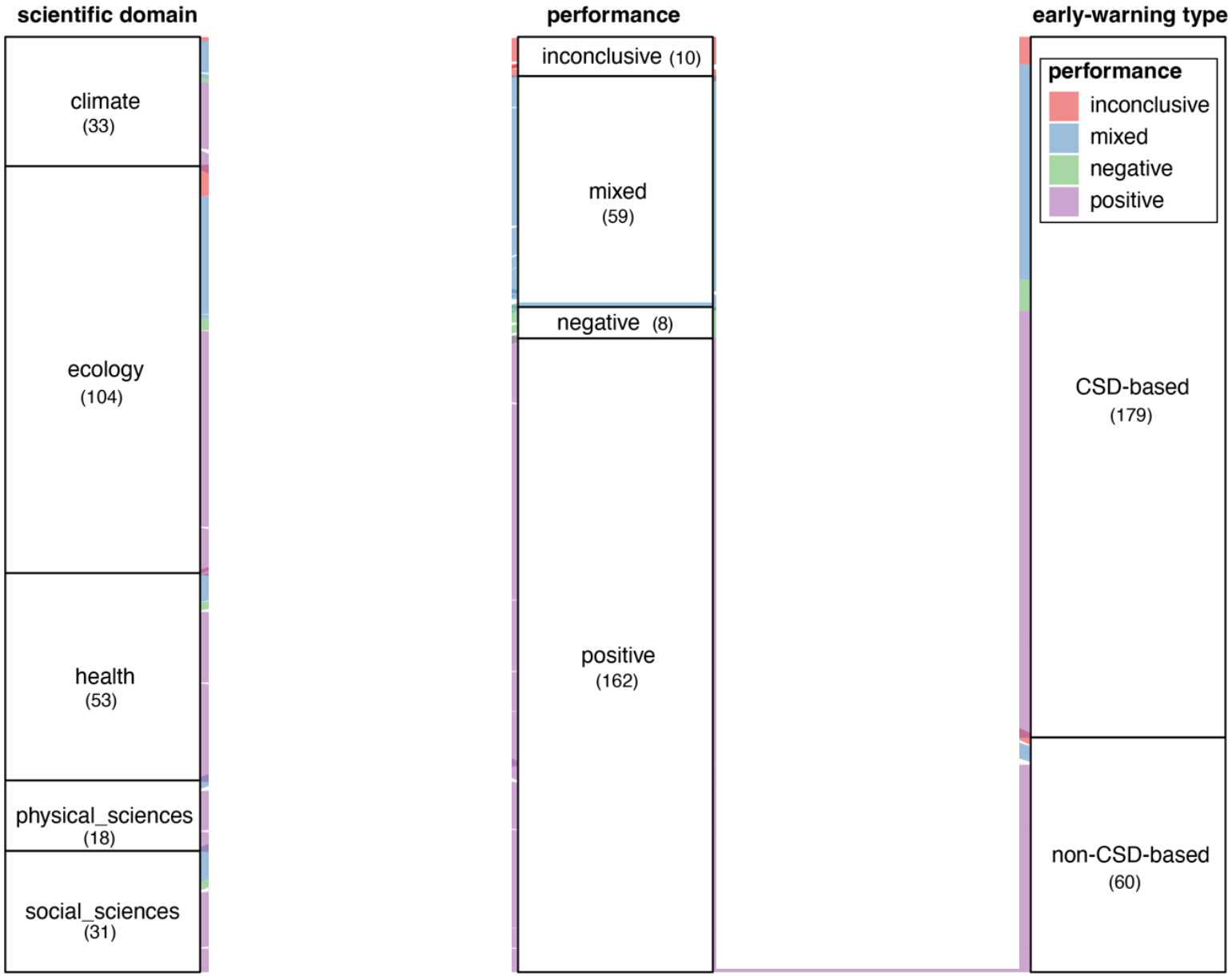
empirical performance of early-warnings?



Dakos et al (2023) EGUsphere

empirical performance of early-warnings: 68% positive



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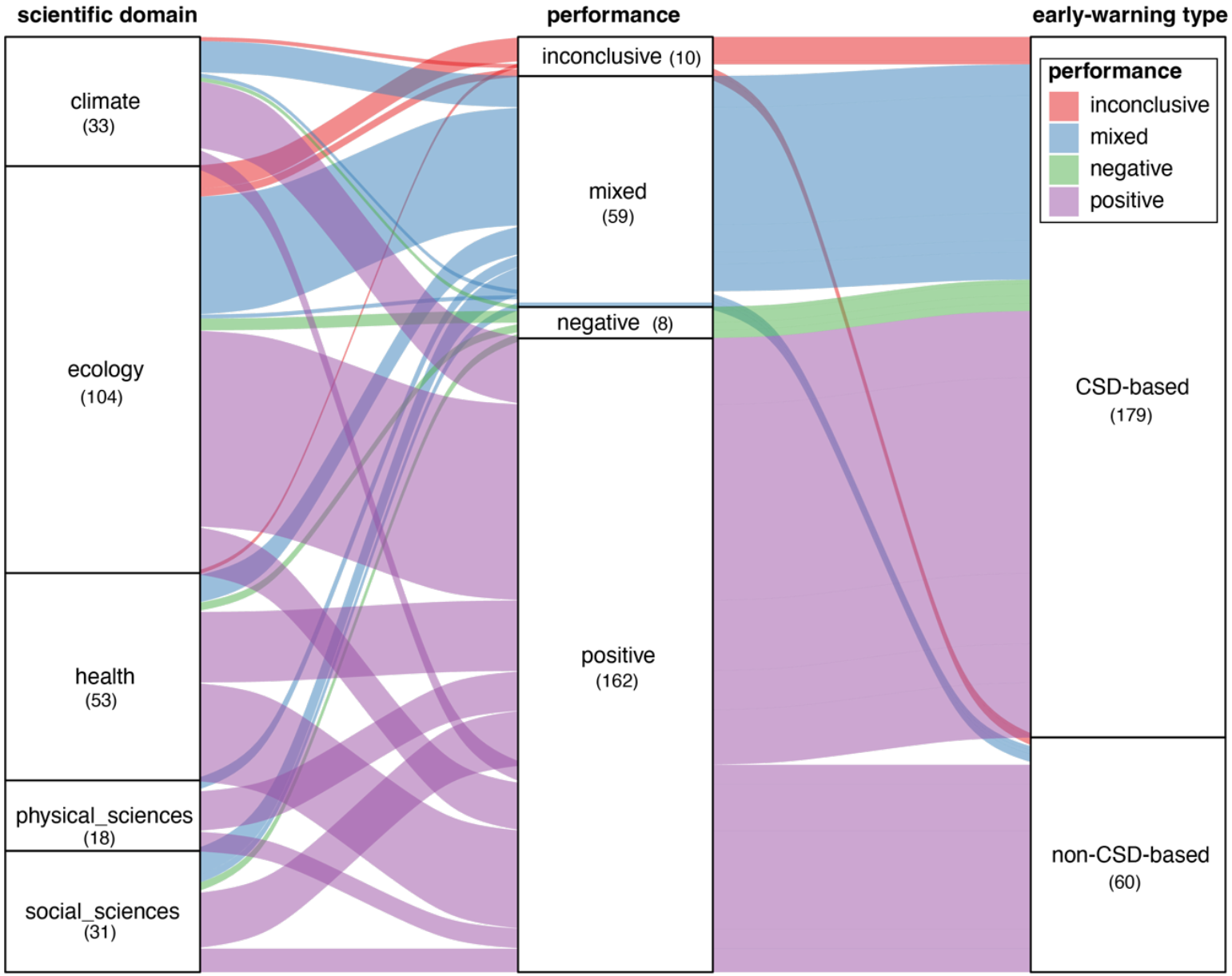

Dakos et al (2023) EGUsphere

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challenge: assumption of tipping point
-Mechanisms (positive feedbacks)
-Bistability
-Irreversibility

Thank you

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early-warning-signals.org

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