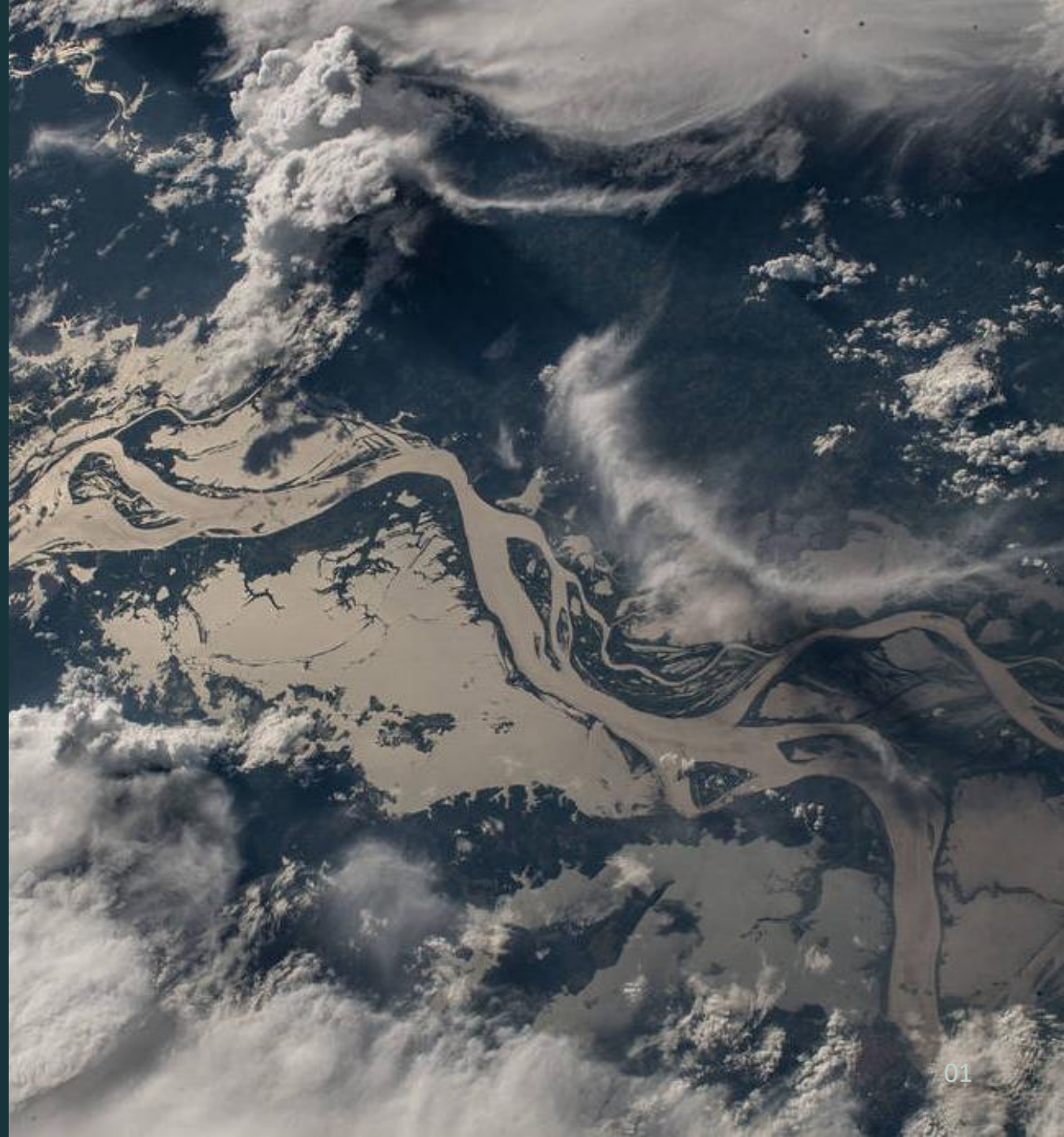
Ecosystems in transition

Baselines, resilience and tipping points



Baseline, reference and target answer different questions

BASELINE

What was observed at the starting point?

REFERENCE

What condition is expected under a specified context and pressure level?

TARGET

What future outcome do we choose to pursue?

The first is a record. The second is an ecological comparison. The third requires an explicit objective and timeframe.

A measured baseline may already represent a degraded ecosystem.

Stoddard et al. (2006); Gann et al. (2019)

What if each generation remembers a smaller fish?

1957



1980s



2007

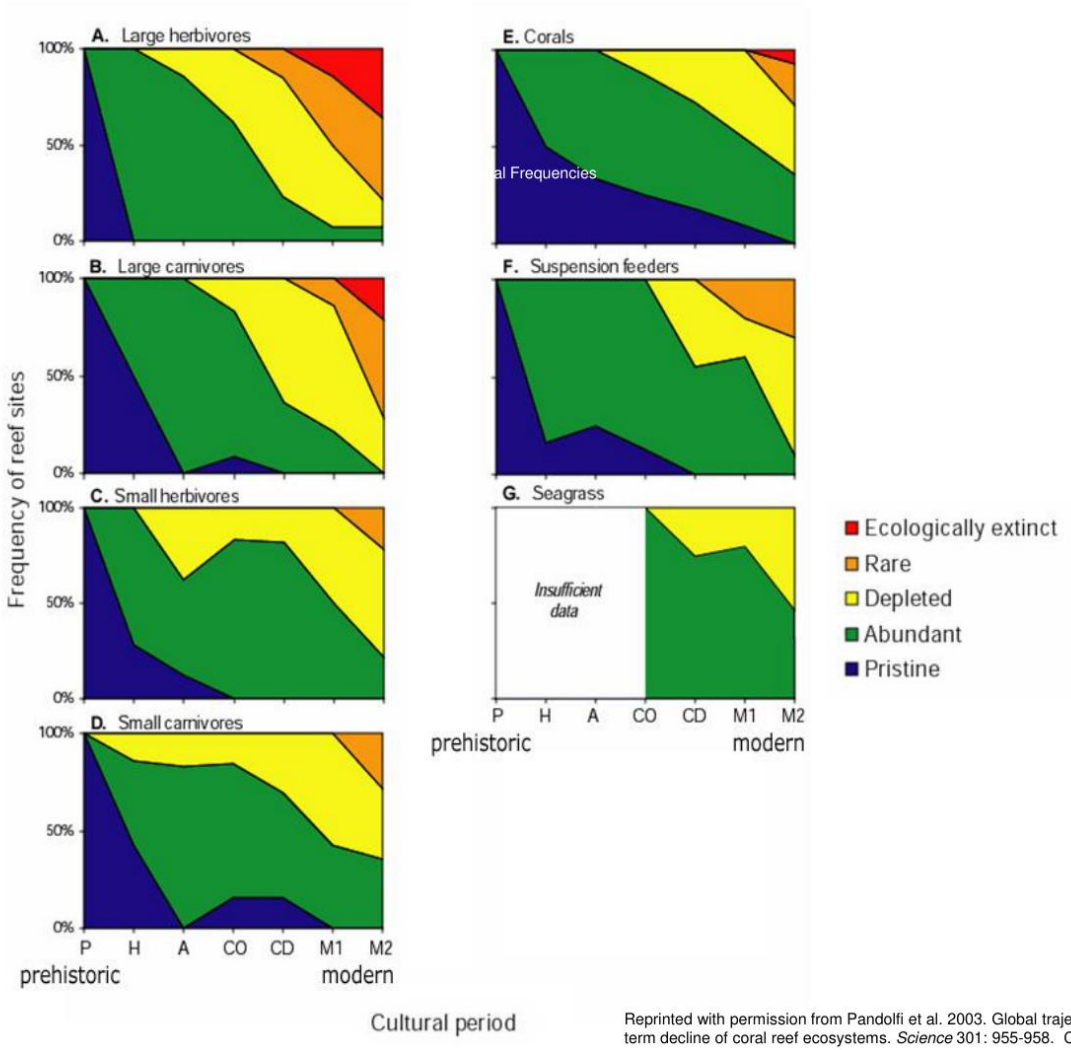


Estimated mean mass of trophy fish: 19.9 kg → 2.3 kg (1956–1960 vs 2007)

Historical archives extend the comparison beyond living memory.

McClenachan (2009), Fig. 1; Pauly (1995)

Historical change affected whole reef communities



Reprinted with permission from Pandolfi et al. 2003. Global trajectories of the long-term decline of coral reef ecosystems. *Science* 301: 955-958. Copyright 2003 AAAS.

14 reef systems

Different functional groups.
Different histories of loss.

Historical categories
are not equally spaced
calendar years.

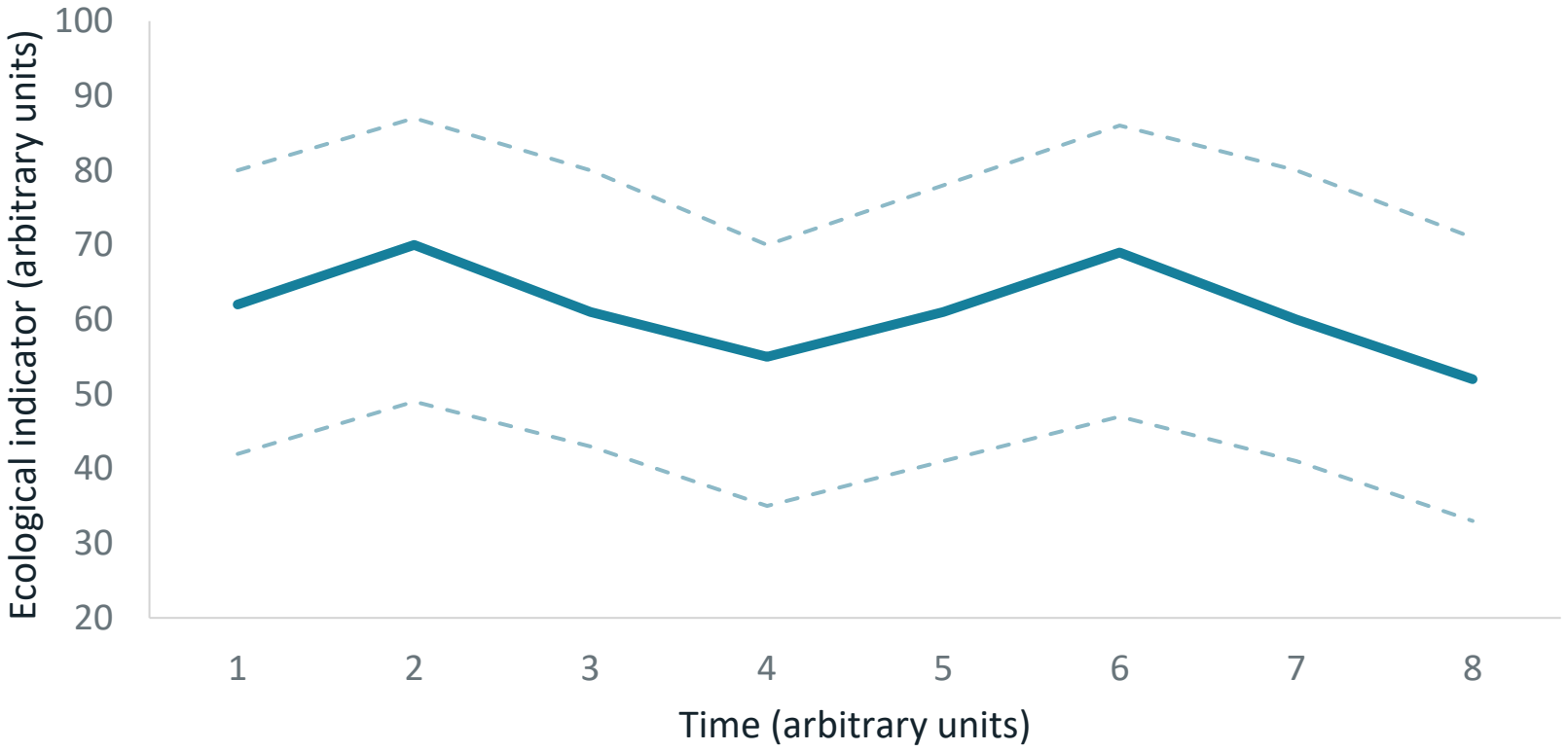
Pandolfi et al. (2003), Science. Figure via Jeremy Jackson, Hot Science–Cool Talks, UT Austin (2006), p. 44.

Reconstruct a reference from independent evidence

Evidence	What it adds	What limits it
Monitoring	Measured change and natural variation	May begin after degradation
Sediment / pollen archives	A longer time window	Dating and proxy uncertainty
Records and local knowledge	Past distributions, uses and disturbances	Uneven coverage and context
Matched comparison sites	Contemporary ecological expectations	Environmental differences

A reference is an evidence-based expectation with uncertainty.

Reference conditions vary



Season and flow

Disturbance history

Spatial context

Degradation needs a specified property and a justified reference.

Synthetic teaching example. Dashed lines are reference bounds, not statistical confidence intervals.

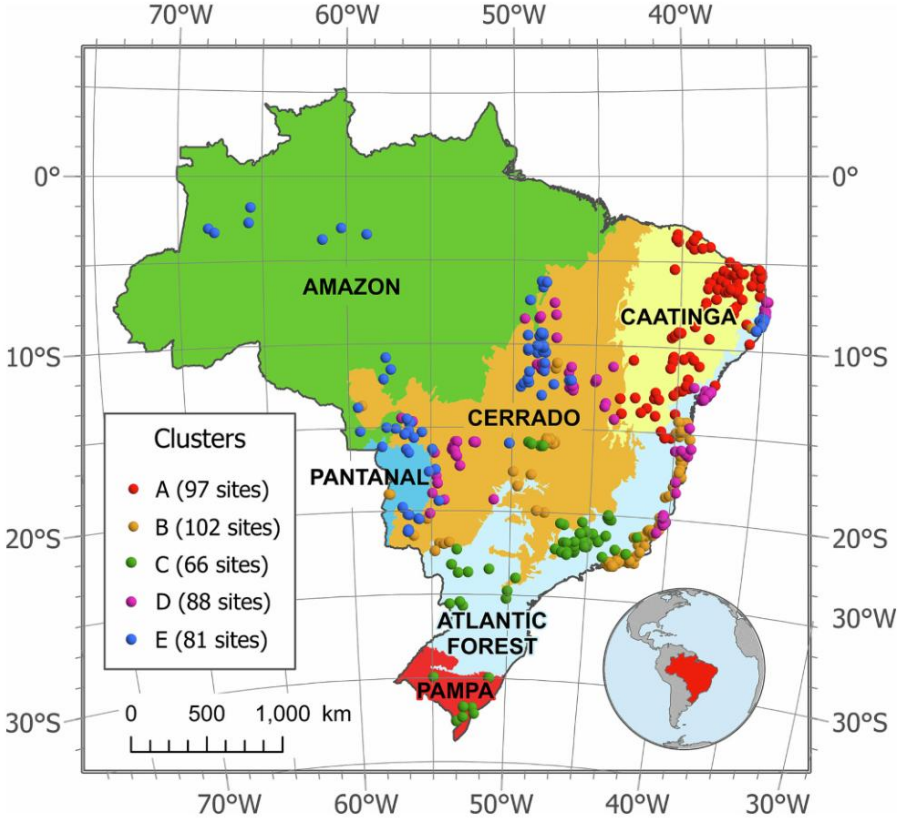
A defensible reference uses several kinds of evidence

Evidence	What it can establish	What needs checking
Contemporary sites	Conditions under low current pressure	Are “least disturbed” sites still degraded?
Historical records	Earlier states and ranges of variation	Selection, dating and changing methods
Models and gradients	Expected condition after accounting for drivers	Extrapolation and unmeasured pressures

Specify ecosystem type, spatial scale, season, pressure and uncertainty.

Stoddard et al. (2006); Jackson & Hobbs (2009)

Define nutrient references while informative sites remain



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non-nested Brazilian watersheds

THE SCIENTIFIC QUESTION

How much nutrient variation is natural, and how much is associated with land use?

Losing low-pressure sites also means losing evidence about expected conditions.

Tromboni et al. (2024), Science of the Total Environment, Fig. 2

From field measurements to a reference estimate

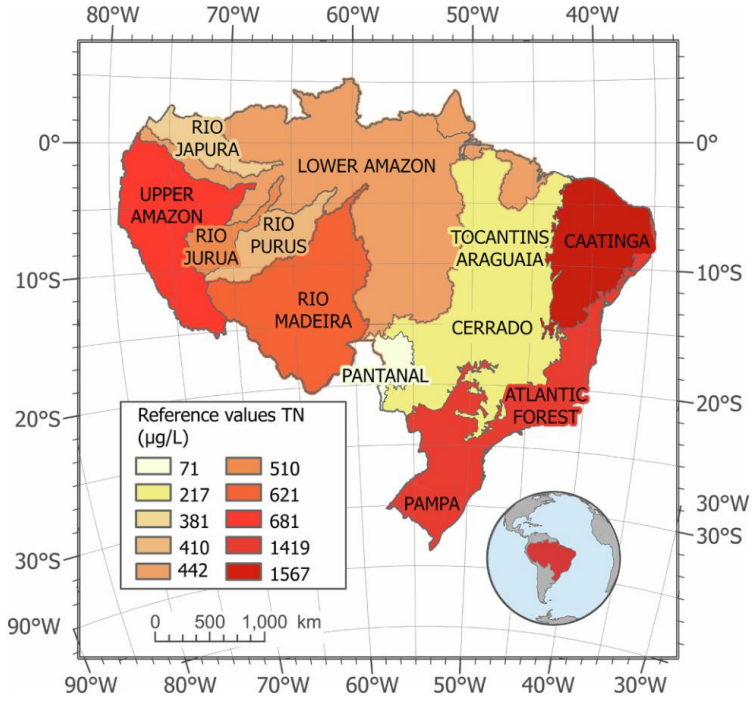
Step	Application to river nutrients
1 Define the comparison	TN or TP, river type, spatial scale and sampling period
2 Describe natural variation	Group TN by biome and TP by climate and soil
3 Estimate low-pressure conditions	Use land-use gradients or distributions of concentrations
4 Evaluate uncertainty	Check data support, residual pressure and seasonal variation

The reference is an estimate conditional on environmental context.

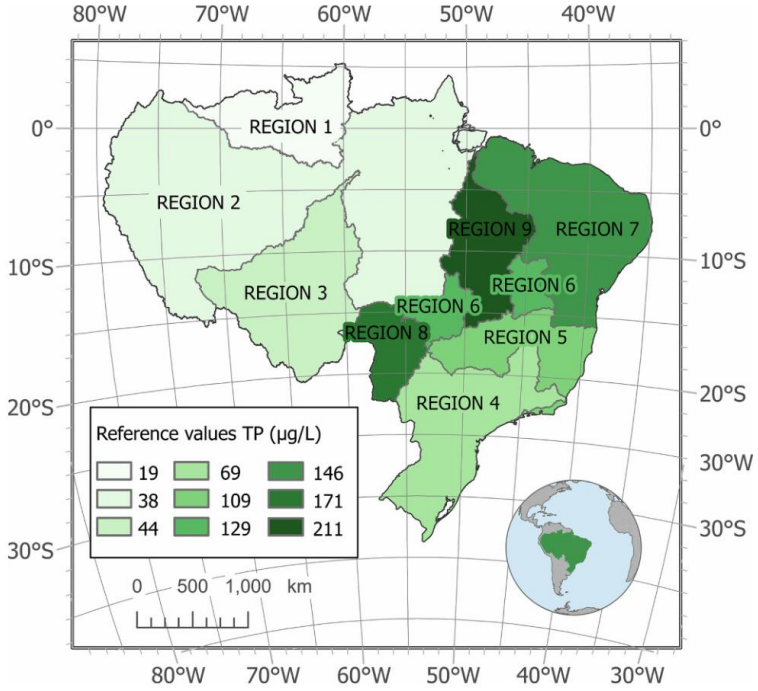
Tromboni et al. (2024); Stoddard et al. (2006)

Different nutrients require different reference models

TOTAL NITROGEN



TOTAL PHOSPHORUS



Read each scale separately. These are reference estimates, not maps of pollution.

Tromboni et al. (2024), Figs. 3–4 • Original legends retained

The same concentration can mean different departures

Total phosphorus	River A	River B
Observed concentration	40 µg/L	40 µg/L
Estimated reference	20 µg/L	100 µg/L
Observed / reference	2.0	0.4

Which river raises the stronger enrichment question?
What additional evidence would you request?

What disappears when a reference site disappears?

We can conserve the evidence of change.

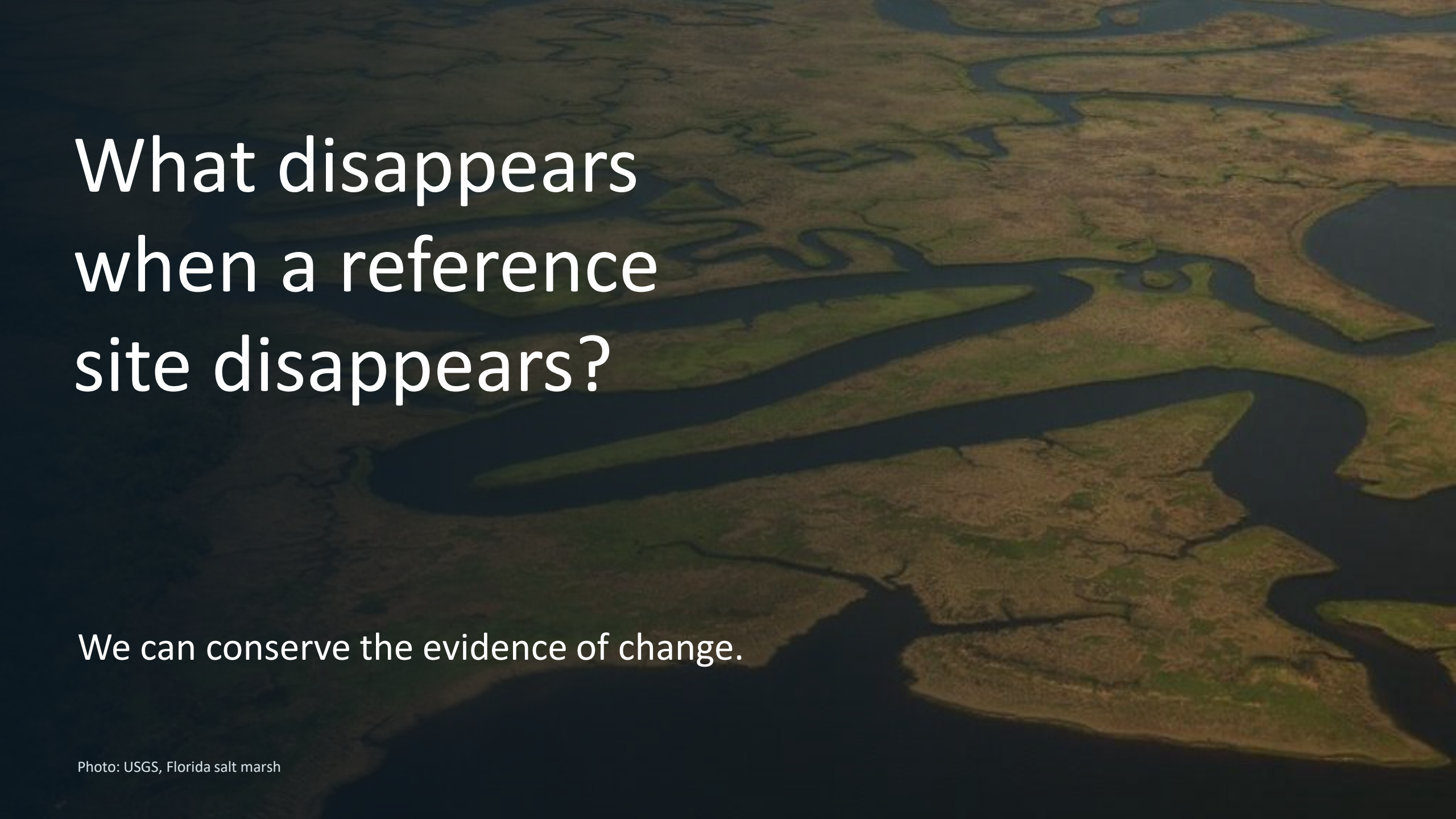


Photo: USGS, Florida salt marsh

What is resilience?

ECOLOGICAL RESILIENCE

The capacity of an ecosystem to absorb disturbance and reorganise while retaining its characteristic structure, functions and feedbacks.

ECOLOGICAL RESILIENCE

How much disturbance can it absorb while the same regime persists?

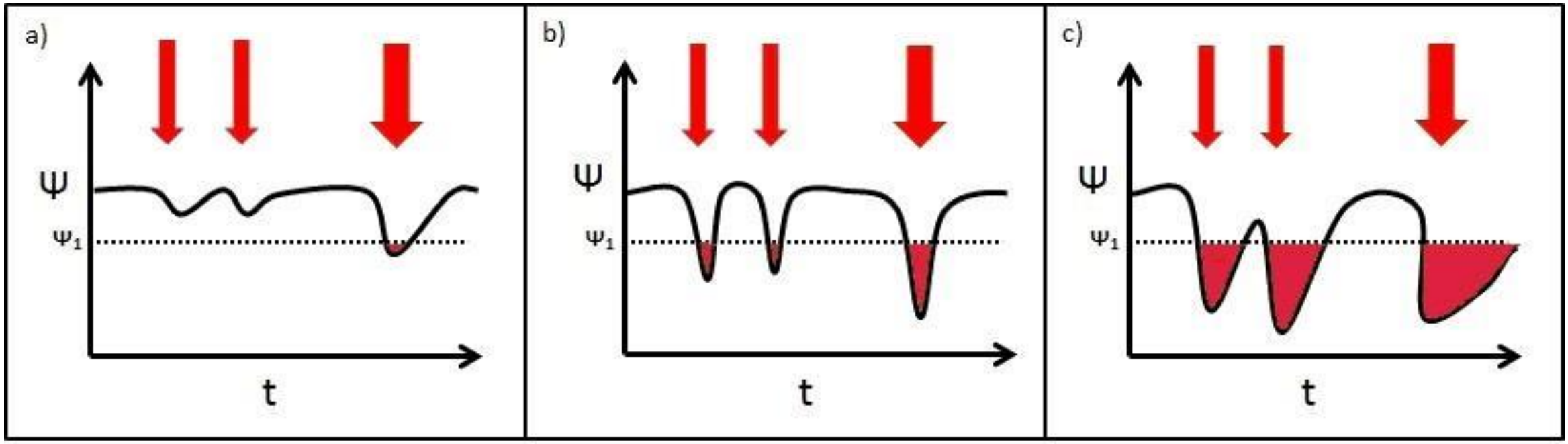
ENGINEERING RESILIENCE

How quickly does it return towards an equilibrium?

Regime persistence allows fluctuations while the defining feedbacks remain.

Holling (1973); Walker et al. (2004). Definition paraphrased for this lecture.

Resistance and recovery describe different responses



RESISTANCE = how much function changes

RECOVERY = how quickly function returns

The dotted line is a chosen minimum level of function, not an ecological tipping point.

Oliver et al. (2015), Fig. 1 • Published conceptual illustration

The same conditions can support different persistent states

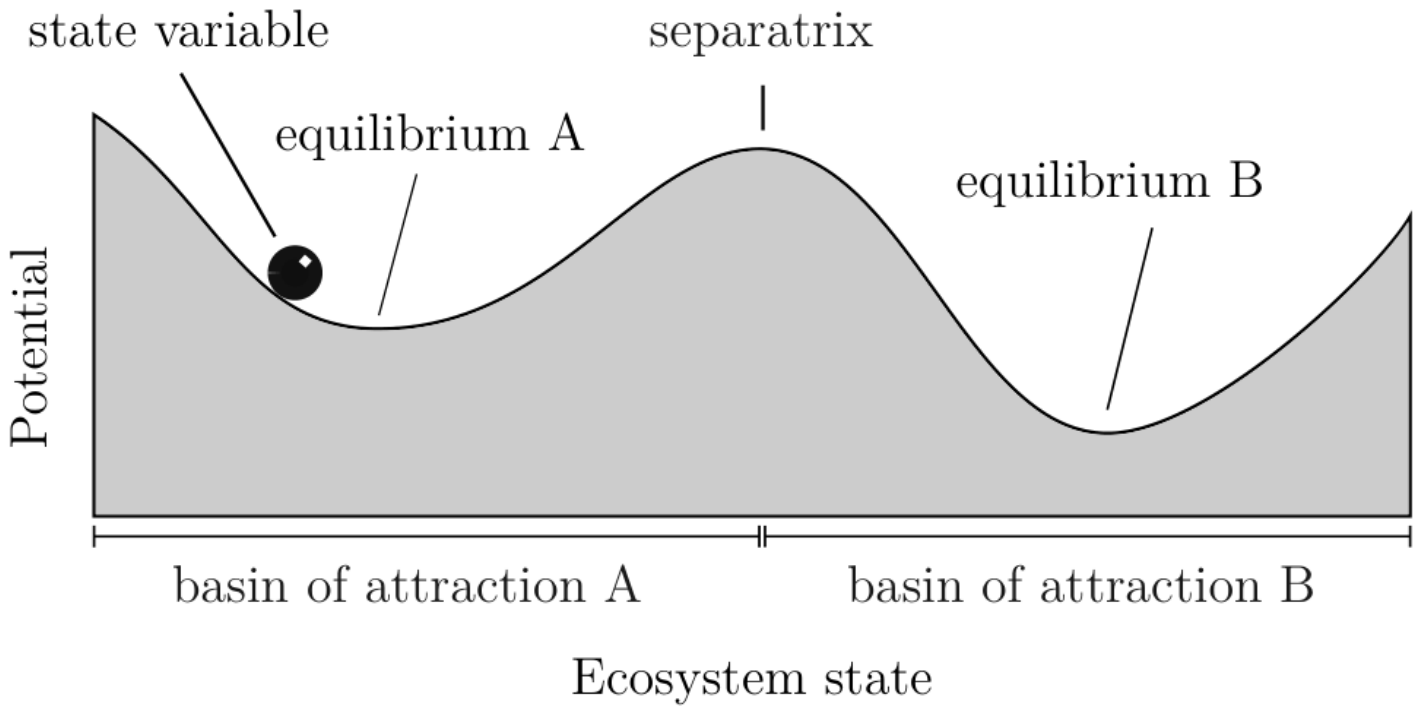


Figure 1: Ball-and-cup diagram

ECOLOGICAL RESILIENCE

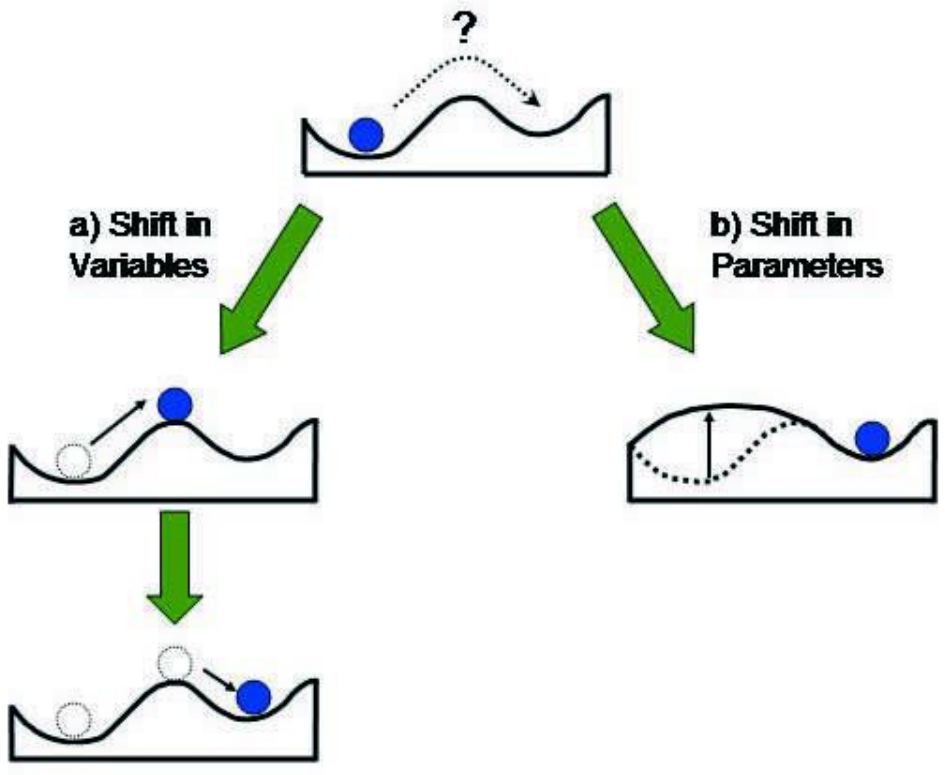
Capacity to absorb disturbance without shifting into a different regime.

The landscape is a conceptual model of dynamics—not physical topography.

Alternative states require persistence under comparable external conditions.

Stecher & Baumgärtner (2022), Fig. 1; Beisner et al. (2003)

Two routes to a change of state



A PULSE CHANGES THE STATE

A disturbance pushes the system across a basin boundary.

A DRIVER CHANGES STABILITY

Changing conditions reshape the basins of attraction.

Alternative stable states can persist under the same external conditions.

Beisner, Haydon & Cuddington (2003), Fig. 1

From ecosystem stability to early warning

01 When does a small change trigger a large shift?

02 How can we detect a loss of resilience?

03 What can the warning tell us about risk?

van Nes et al. (2016); Scheffer et al. (2009)

What is a tipping point?

A critical condition at which small changes can trigger a large shift in ecosystem state.

Reinforcing feedbacks can accelerate the transition.

Reversibility depends on the dynamics and on the conditions that remain accessible.



The critical feature is a large response to a small change near the threshold.

van Nes et al. (2016); Scheffer et al. (2001)

1. What is a tipping point?

Change:

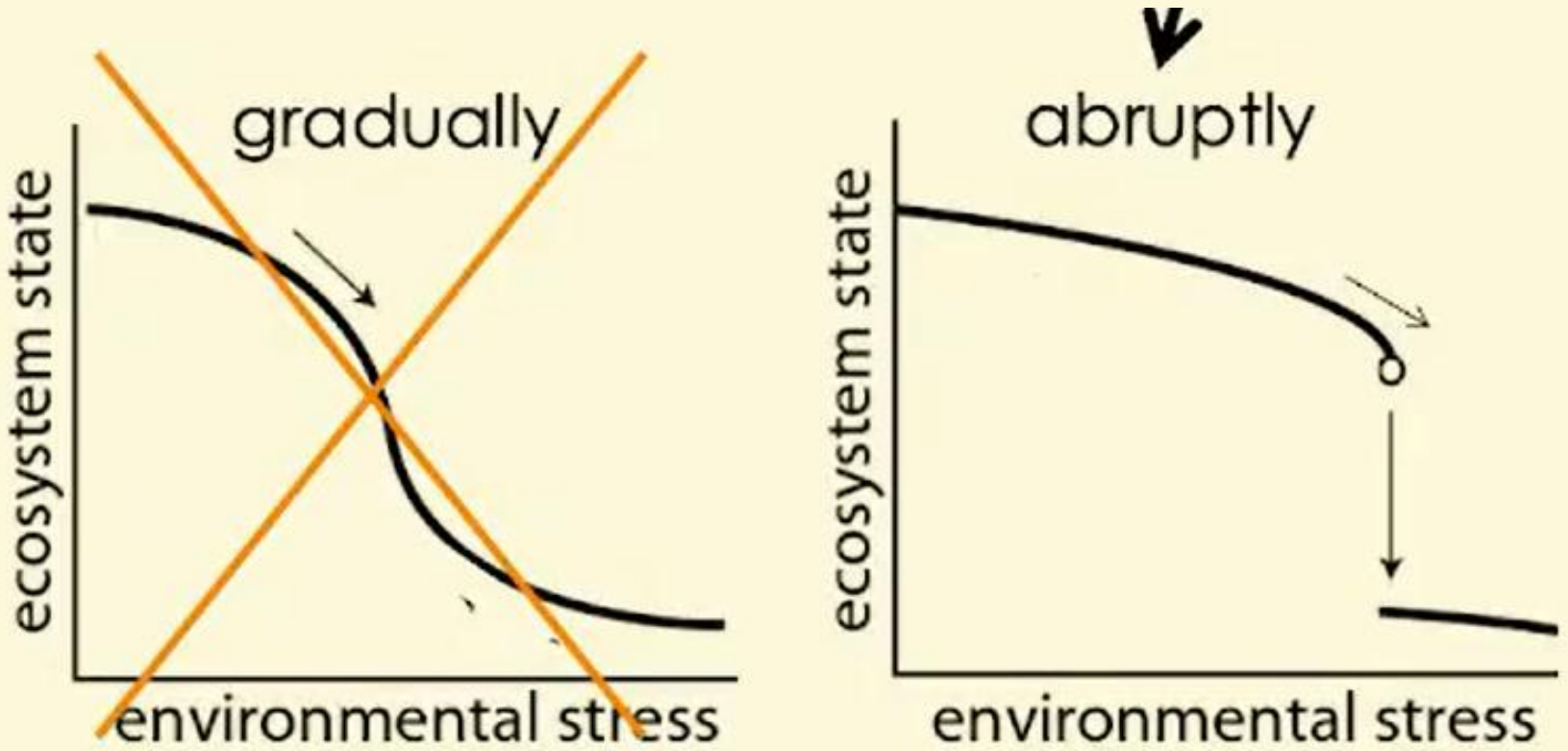
- Abrupt (relative to the driver)
- Unexpected (triggered by small perturbations)
- Substantial (catastrophic)
- Often (but not always) difficult to reverse



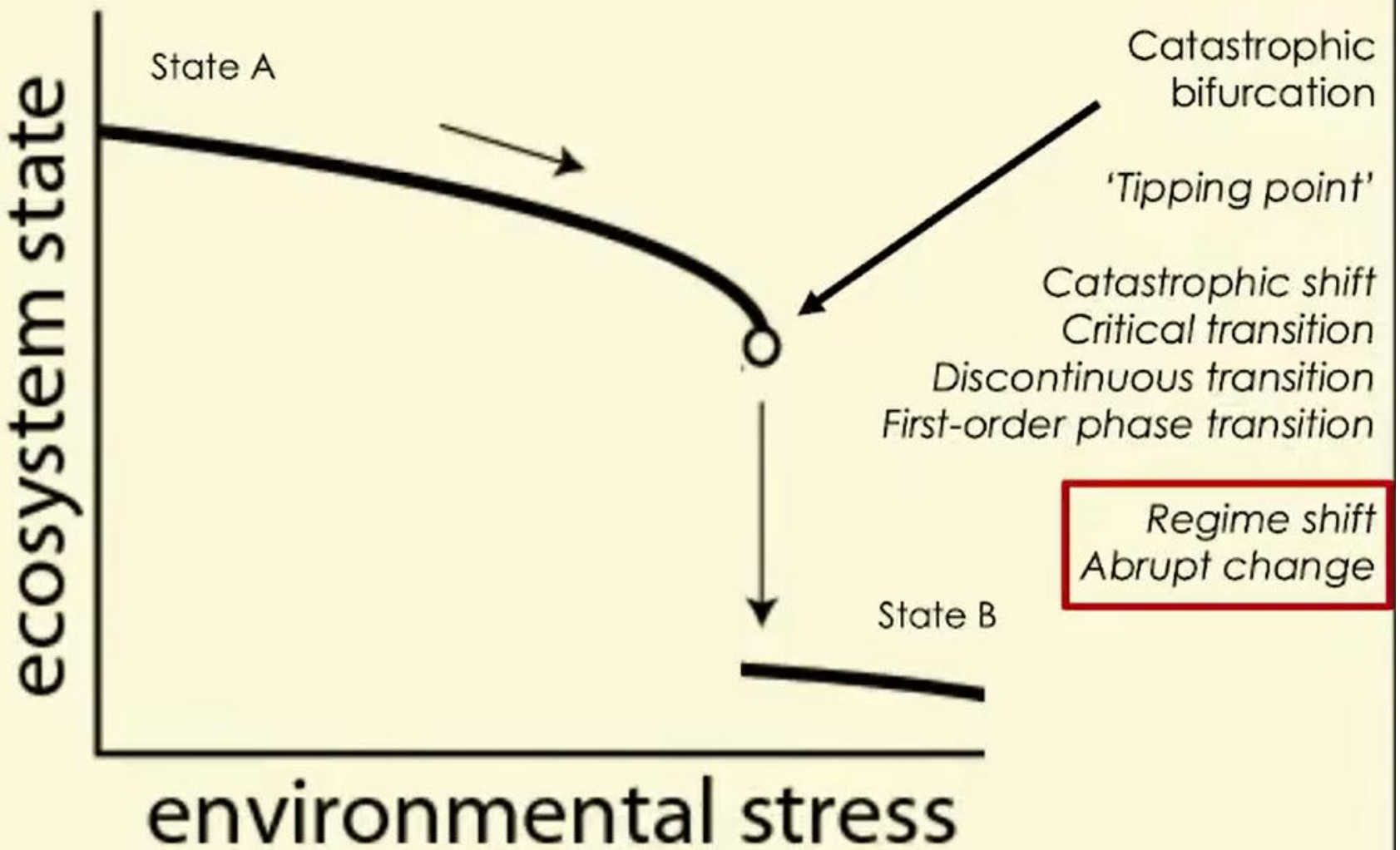
Tipping point:

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

(van Nes et al TREE 2016)

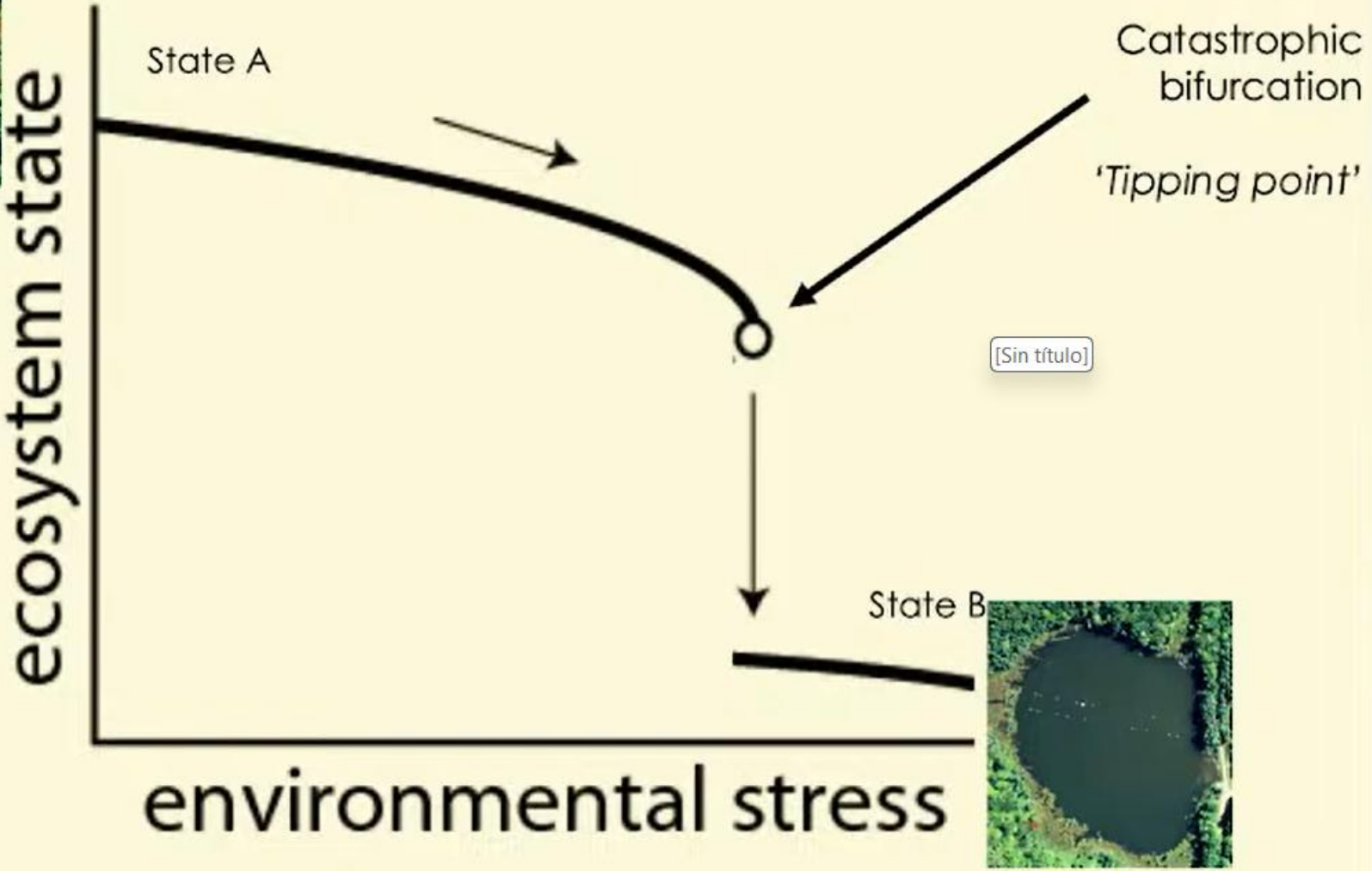


tipping points between alternative stable states



tipping points between alternative stable states





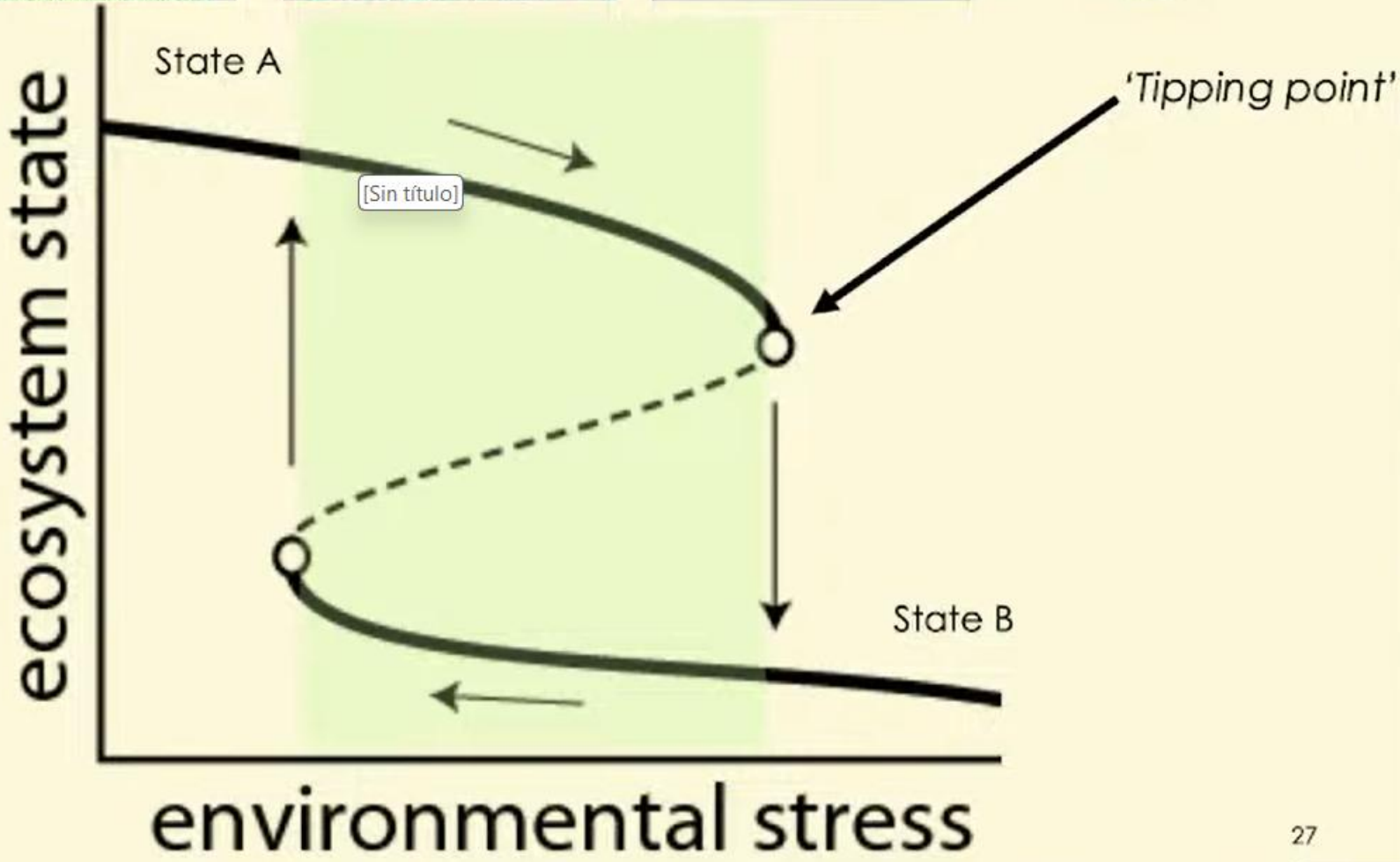
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tipping points between alternative stable states





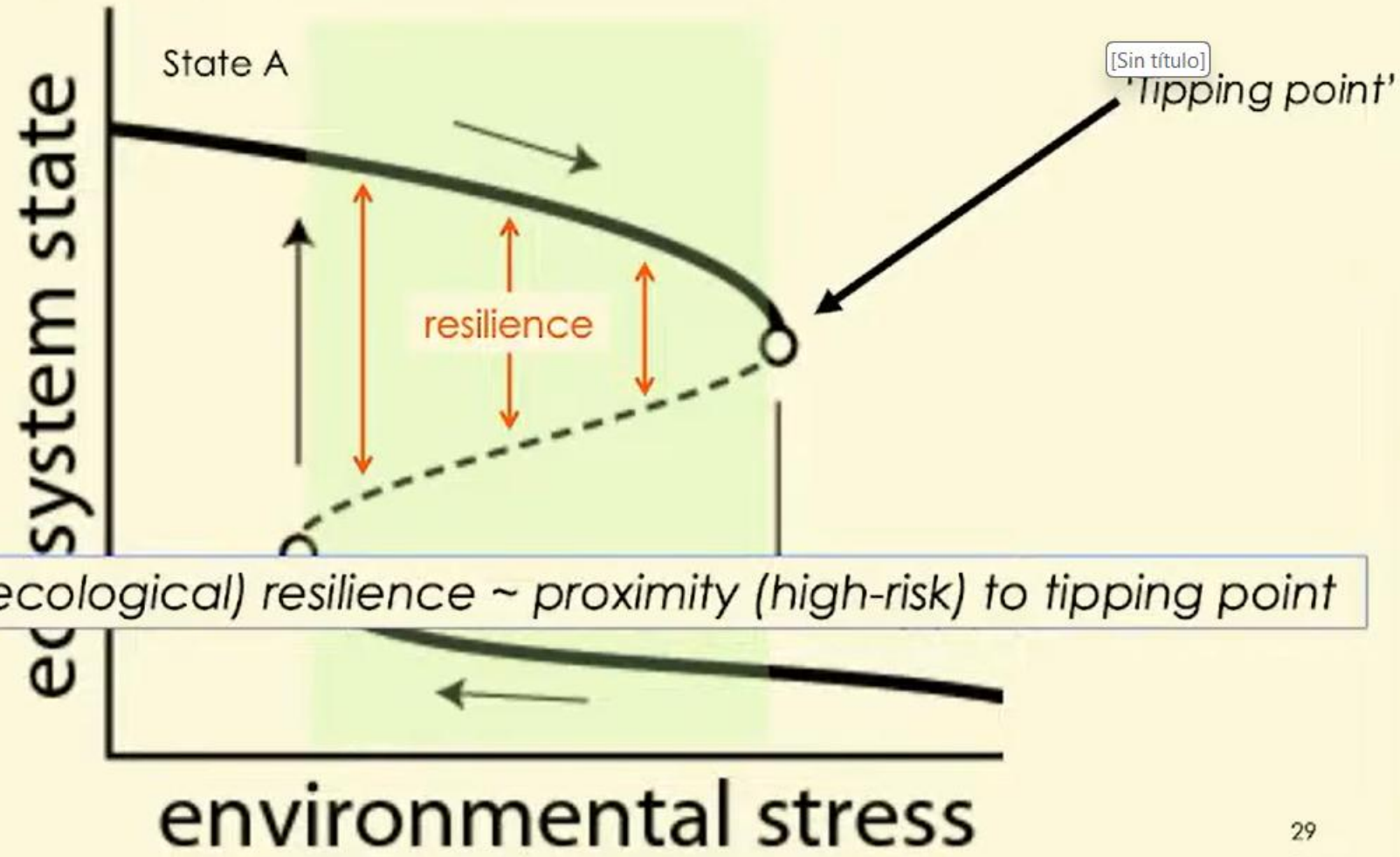
Can we detect tipping points in advance?



Ecological Resilience:

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

tipping point indicators

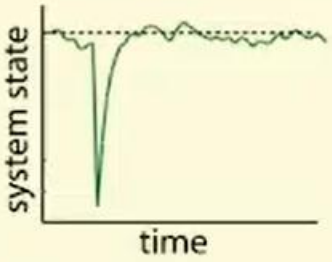


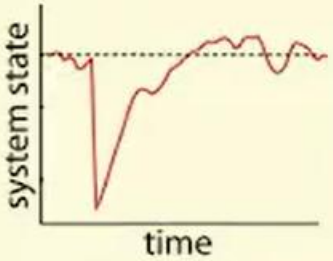
Critical Slowing Down (CSD)

far from tipping

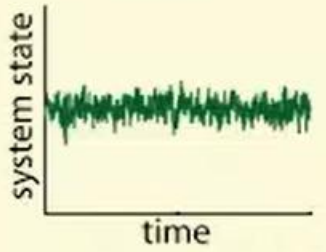
close to tipping

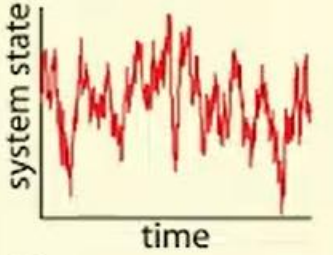
Resilience Indicators (or Early Warnings)



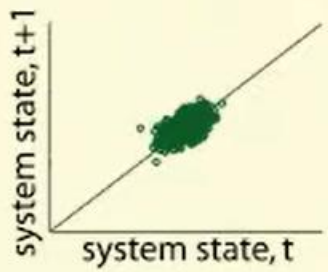


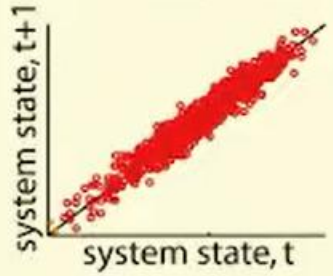
recovery time increases





variance increases

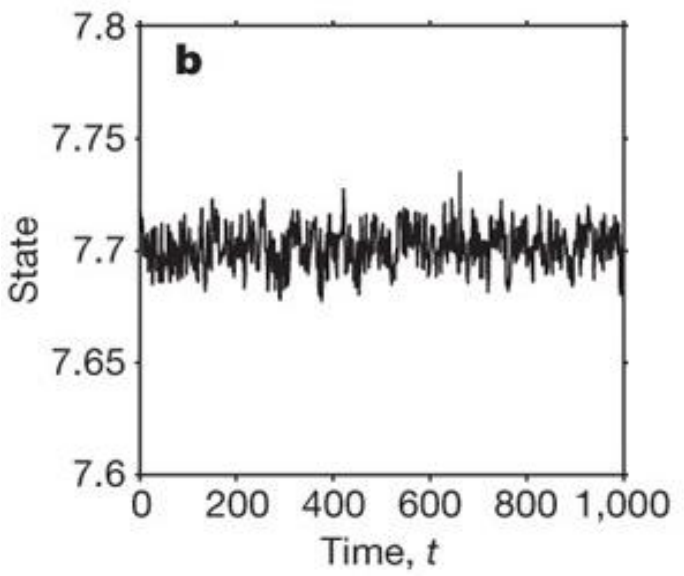




autocorrelation rises

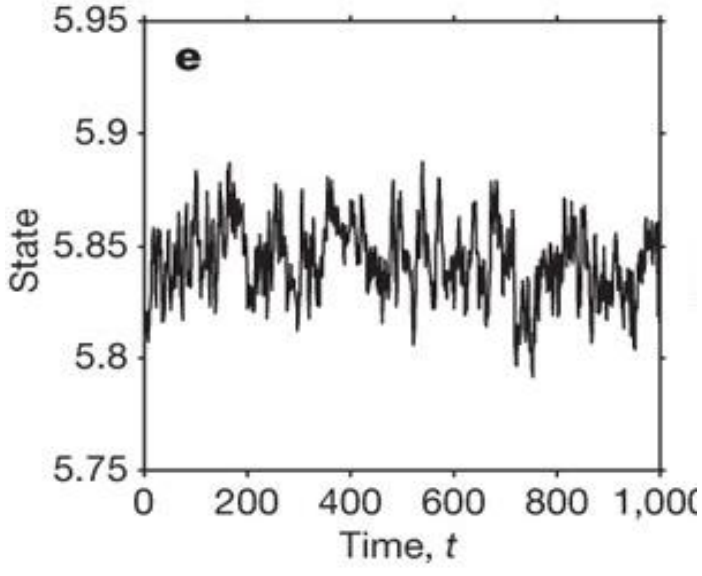
A slowing recovery can leave a statistical fingerprint

Faster recovery



Lag-1 correlation: 0.76

Slower recovery



Lag-1 correlation: 0.90

VARIABILITY

How widely values fluctuate around their local average.

AUTOCORRELATION

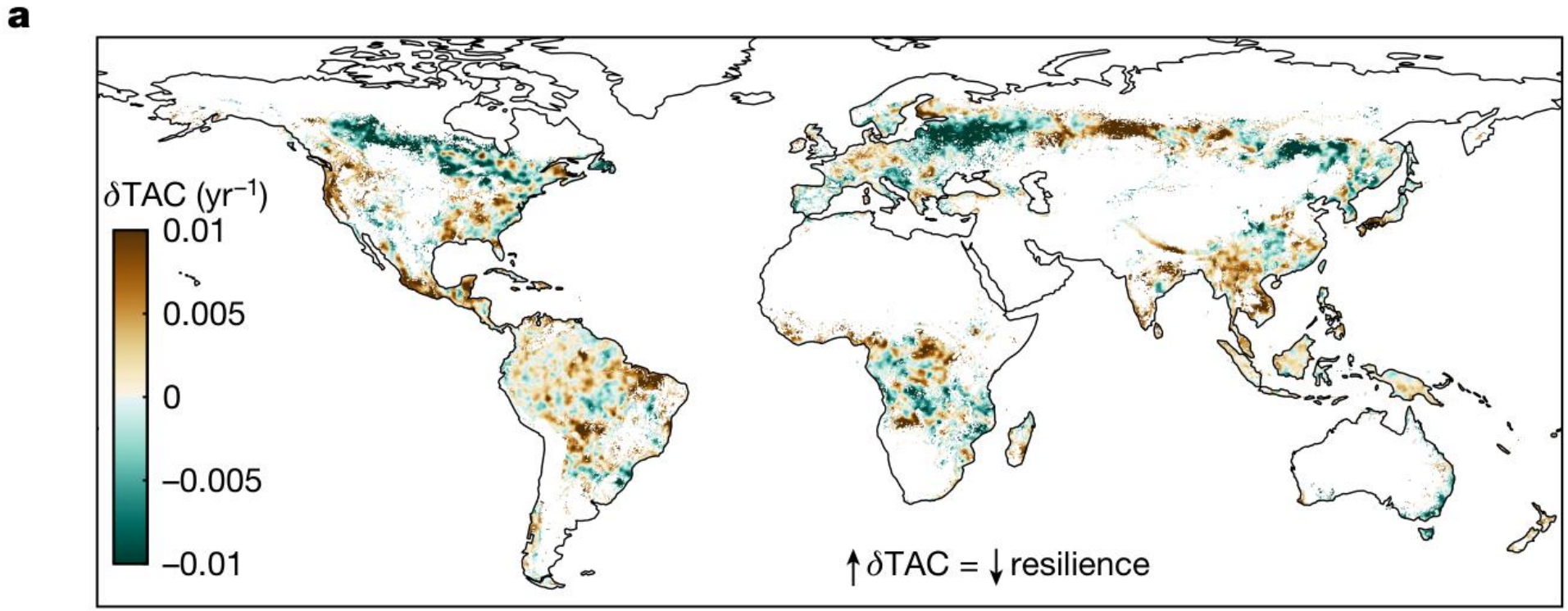
How strongly a deviation persists into the next observation.

Slower recovery can make fluctuations larger and departures more persistent.

Scheffer et al. (2009), Fig. 1b,e • Model time series, not field measurements

Satellite observations can reveal changing persistence

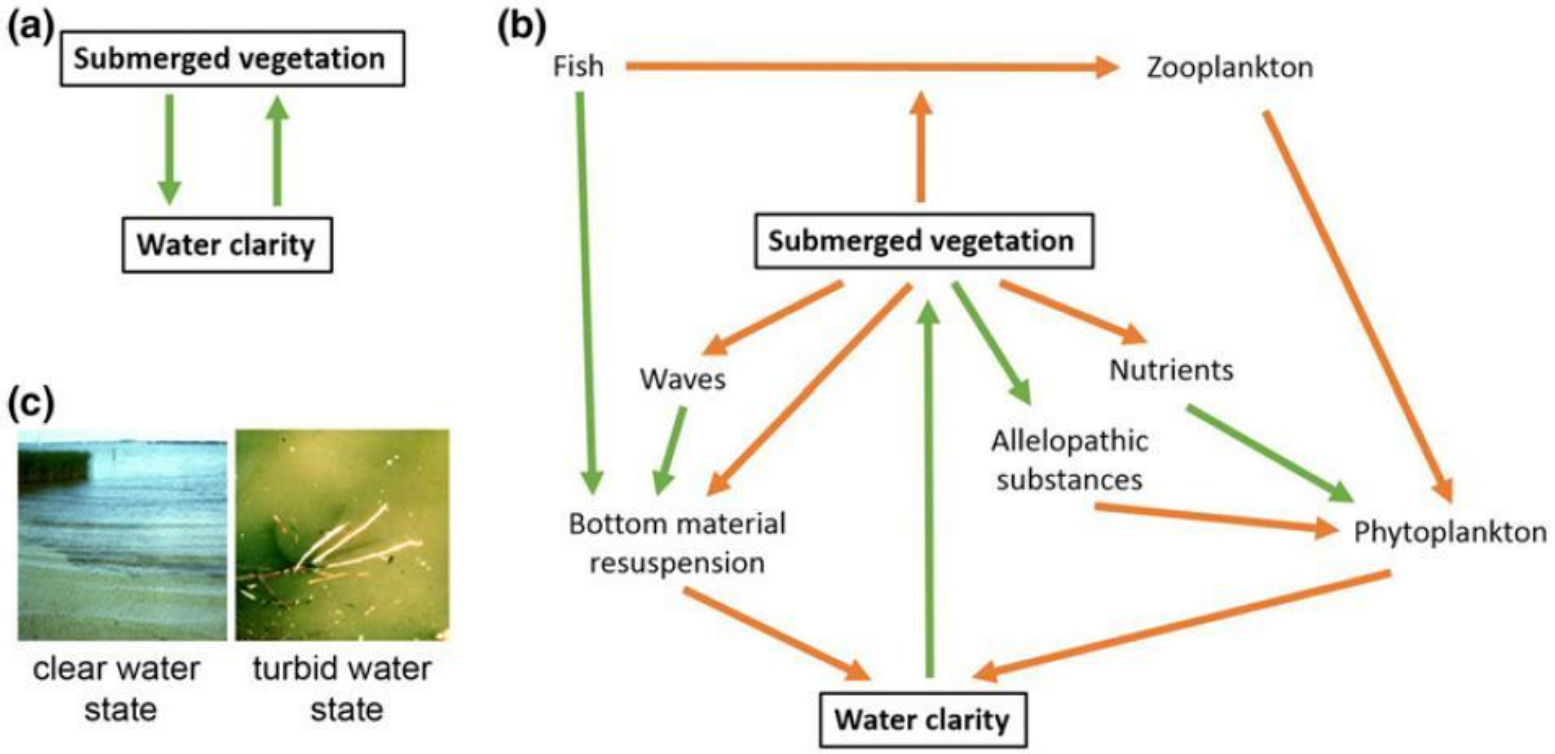
Kernel NDVI time series, 2000–2020



Rising autocorrelation can indicate slower recovery. Interpreting risk needs context.

Forzieri et al. (2022), Nature, Fig. 1a. Original published map.

In shallow lakes, vegetation can reinforce water clarity



REINFORCEMENT

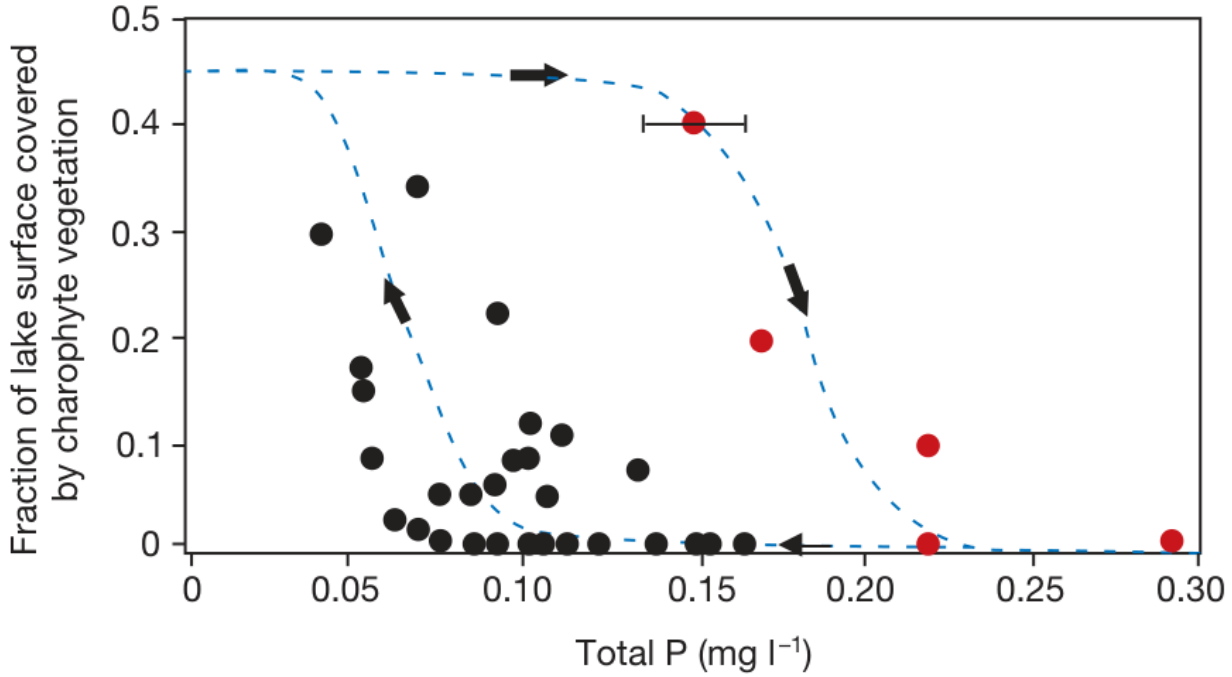
Plants improve clarity.

Clearer water increases light for plants.

Feedback strength determines whether a mechanism can maintain alternative states.

Kéfi et al. (2016); Scheffer et al. (1993) • Published feedback diagram

Lake Veluwe: recovery followed a different trajectory



WHAT WAS OBSERVED

Vegetation recovery did not simply reverse the earlier decline.

WHAT NEEDS EXPLANATION

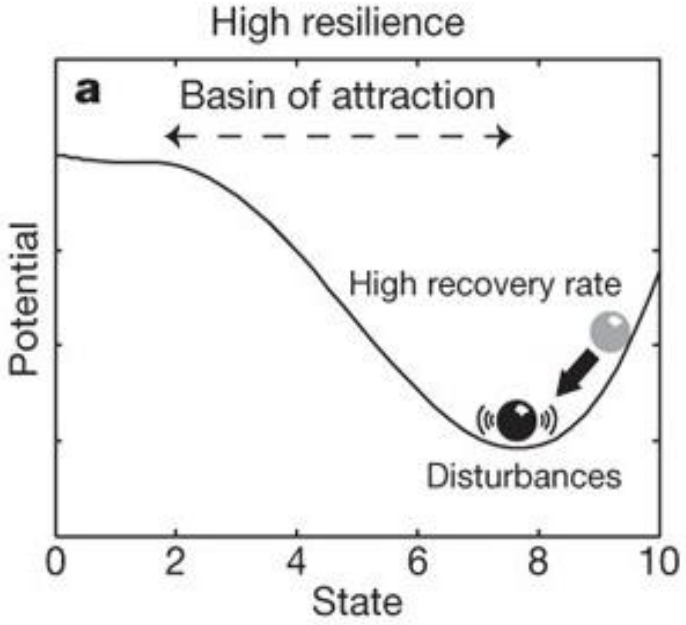
Nutrients, sediments, fish and plants changed the conditions for recovery.

A historical loop supports path dependence; mechanisms still need testing.

Scheffer et al. (2001), Fig. 4; Ibelings et al. (2007)

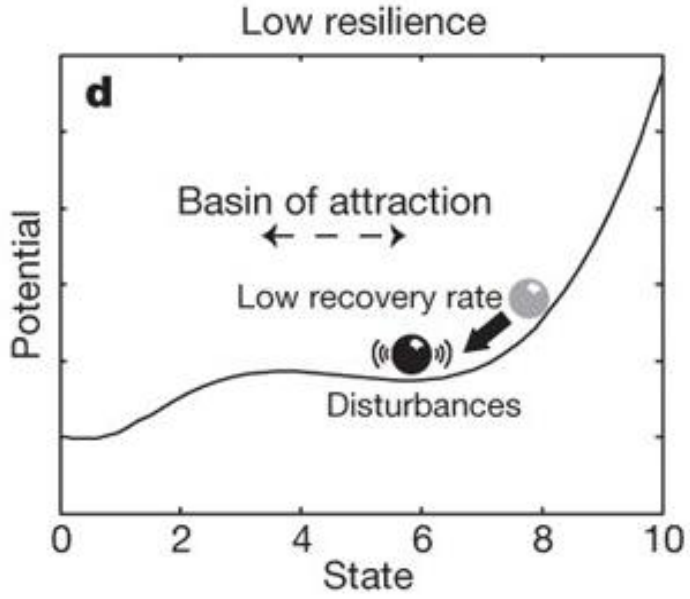
A smaller basin can absorb a smaller disturbance

HIGHER RESILIENCE



A wider range of states can return towards the same equilibrium.

LOWER RESILIENCE



A smaller displacement can cross the basin boundary.

The system can lose resilience before its average state changes dramatically.

Scheffer et al. (2009), Fig. 1a,d. Published conceptual model.

What makes a warning credible?

Question	Evidence needed
Is recovery slowing?	A mechanistic link between the observed variable and system dynamics
Could something else create the signal?	Checks for trends, seasonal cycles, changing noise and sampling
Does the signal distinguish change?	A reference, an explicit alarm rule and performance evaluation
Can it guide an intervention?	Enough lead time to alter a driver that affects the outcome

A warning supports a decision when its meaning and response are specified.

Scheffer et al. (2009); Pace et al. (2017)

Can a warning change an ecosystem’s trajectory?



Peter Lake

Nutrients added
Bloom developed
Inputs then stopped

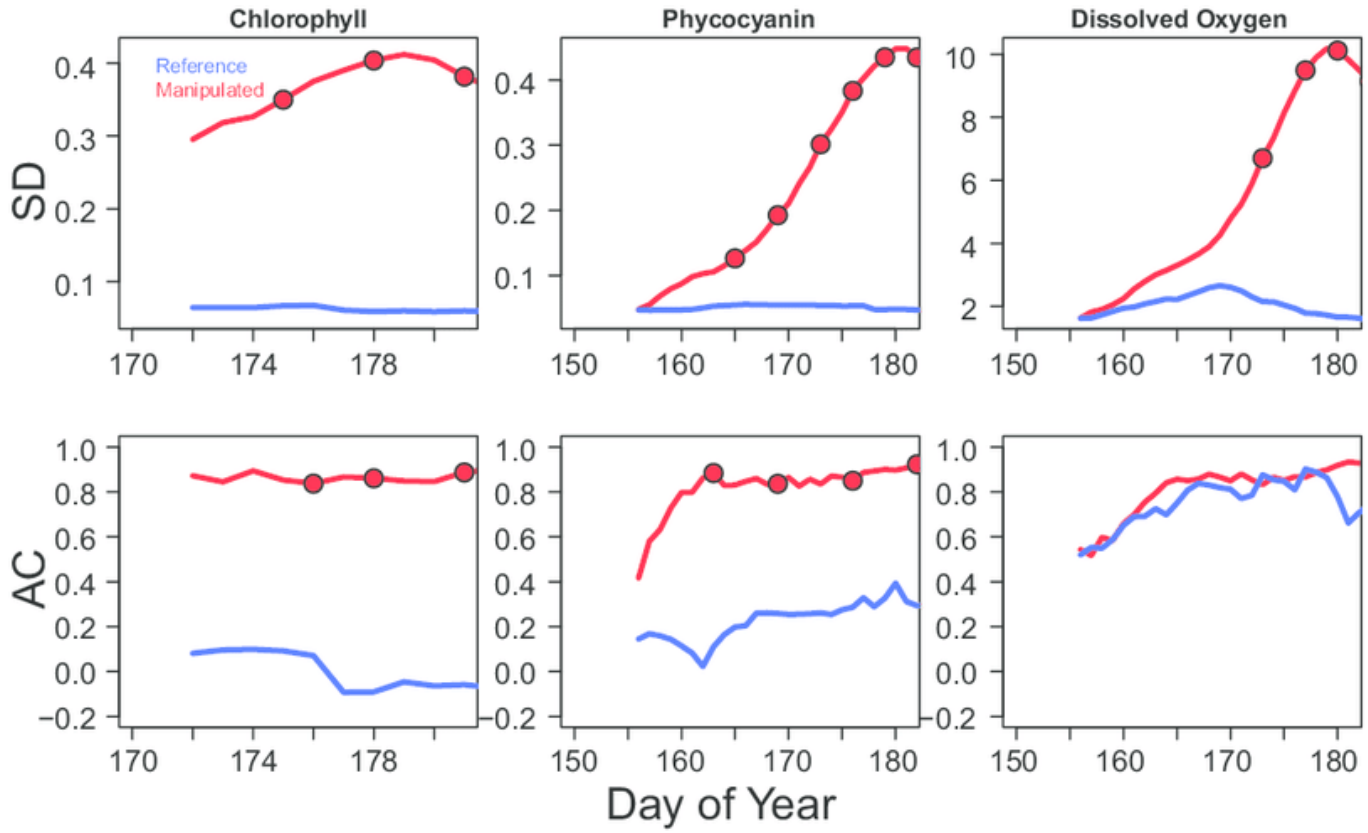
Paul Lake

Unenriched reference for comparison

A photograph shows a contrast. The experiment explains how it arose.

Pace et al. (2017), PNAS • Whole-lake nutrient experiment

The experiment specified its stopping rule in advance



MEASUREMENT

28-day windows
SD and lag-1 correlation

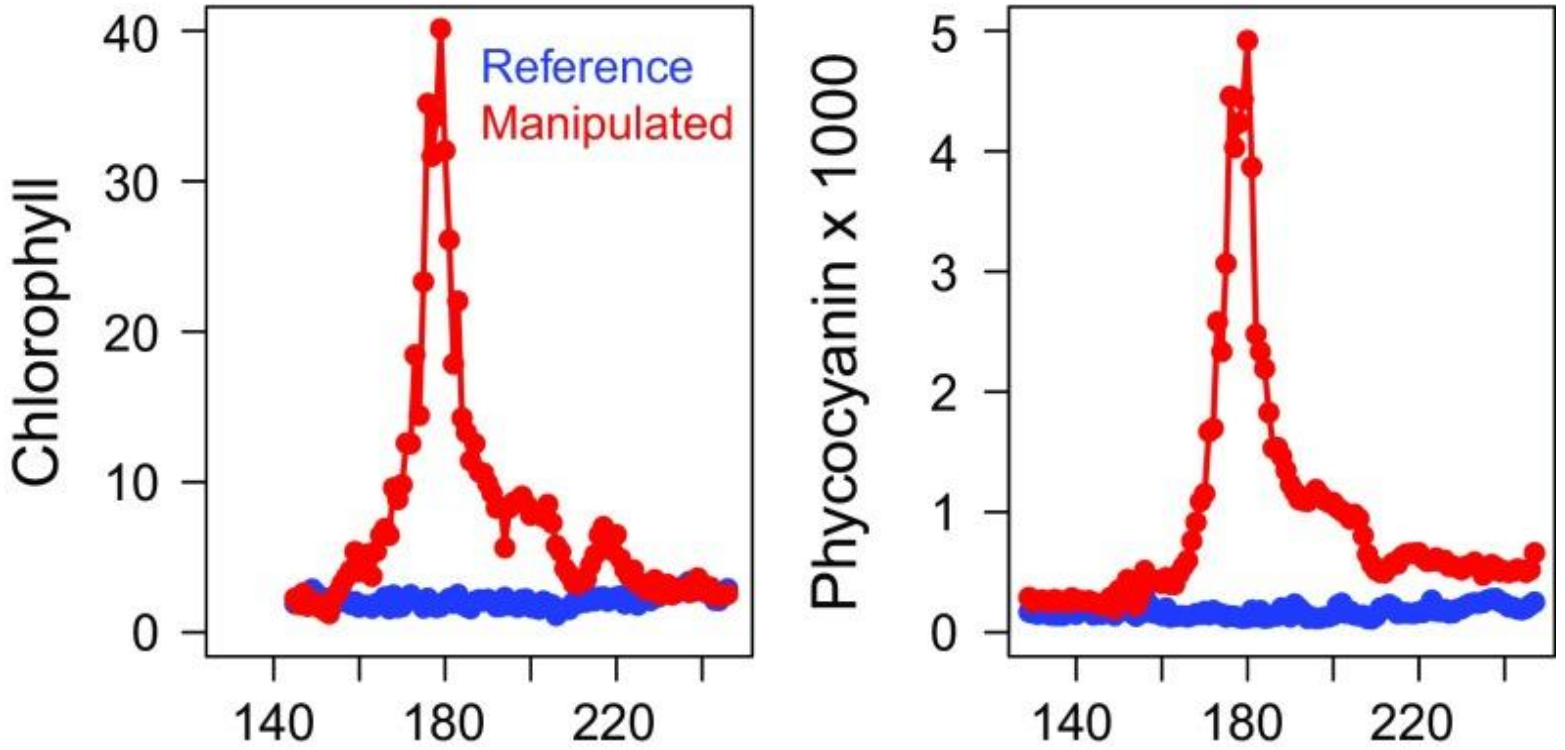
DECISION RULE

An alarm from each of
the four pigment indicators

The fourth pigment indicator signalled on day 176. Inputs stopped on day 180.

Pace et al. (2017), Fig. 2 and Methods

Peter Lake: an alarm informed the decision to stop inputs



Day of year (2015) • Chlorophyll a: µg/L; phycocyanin: fluorescence units

DAY 163

First phycocyanin autocorrelation alarm

DAY 180

Nutrient additions stopped at the bloom maximum

ABOUT DAY 210

Measured state returned close to the reference

The intervention reversed bloom conditions; it did not prevent the initial bloom.

Pace et al. (2017), Fig. 1, upper panels • 2015 nutrient-enrichment experiment

A decision needs a trigger, an action and a test

Component	Question for management
Reference and objective	What departure matters, and what outcome are we protecting?
Trigger	Which evidence is sufficient to act, given uncertainty and costs?
Action and responsibility	Who can change the driver, and how quickly?
Evaluation	Did the state recover relative to the reference? What changes next?

The action threshold can precede the ecological transition.

Teaching synthesis from Pace et al. (2017) and Scheffer et al. (2009)

When would you act?

Your lake is still below the chosen bloom limit.
Departures are becoming more persistent,
and nutrient inputs remain controllable.

What evidence would trigger a reduction in inputs?

What is the cost of acting too early or too late?
What would you measure to judge the intervention?

State the ecological evidence separately from the chosen tolerance for risk.

Discussion based on the lake experiment. Hypothetical management choices.

From reference conditions to timely decisions

BASELINE	The recorded starting condition
REFERENCE	The comparison that gives change its meaning
RESILIENCE	The dynamics of persistence and recovery
TIPPING POINT	A critical condition that can amplify a small change
EARLY WARNING	Evidence that can justify a timely intervention

Protecting low-pressure ecosystems preserves the evidence needed to recognise change.

Stoddard et al. (2006); Holling (1973); Scheffer et al. (2009); Pace et al. (2017)

Baselines, reference conditions and resilience

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Alternative states, tipping points and hysteresis

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Resilience, early warnings and decisions

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