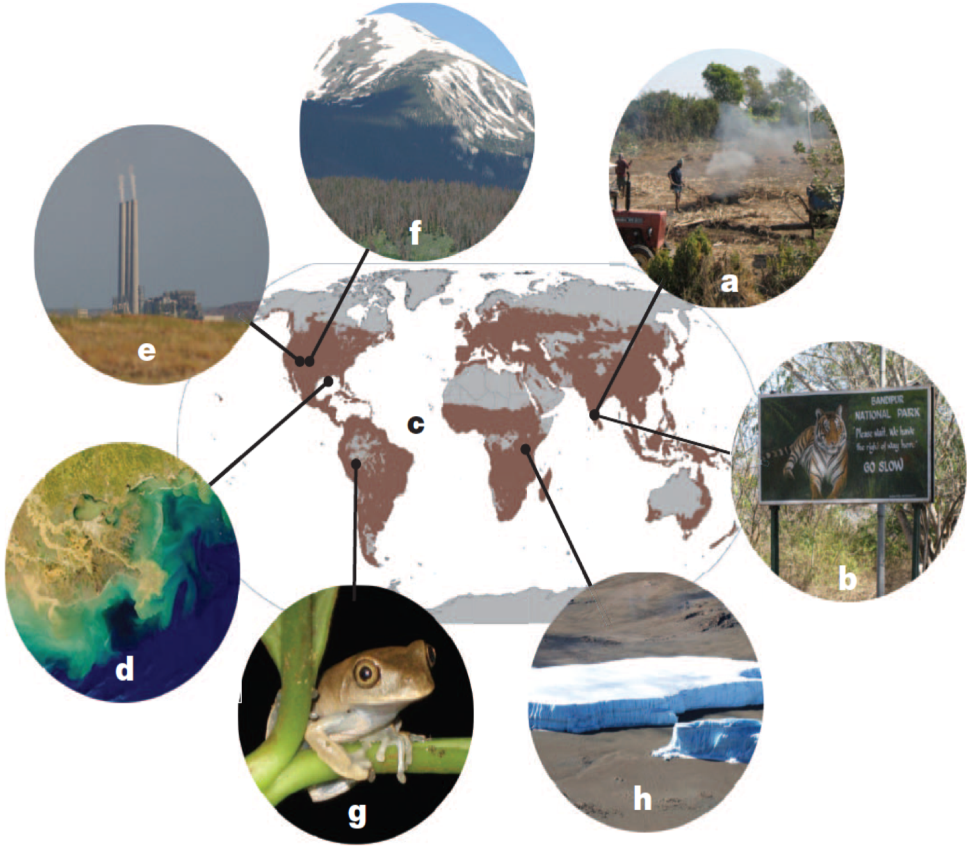
REVIEW

doi:10.1038/nature11018

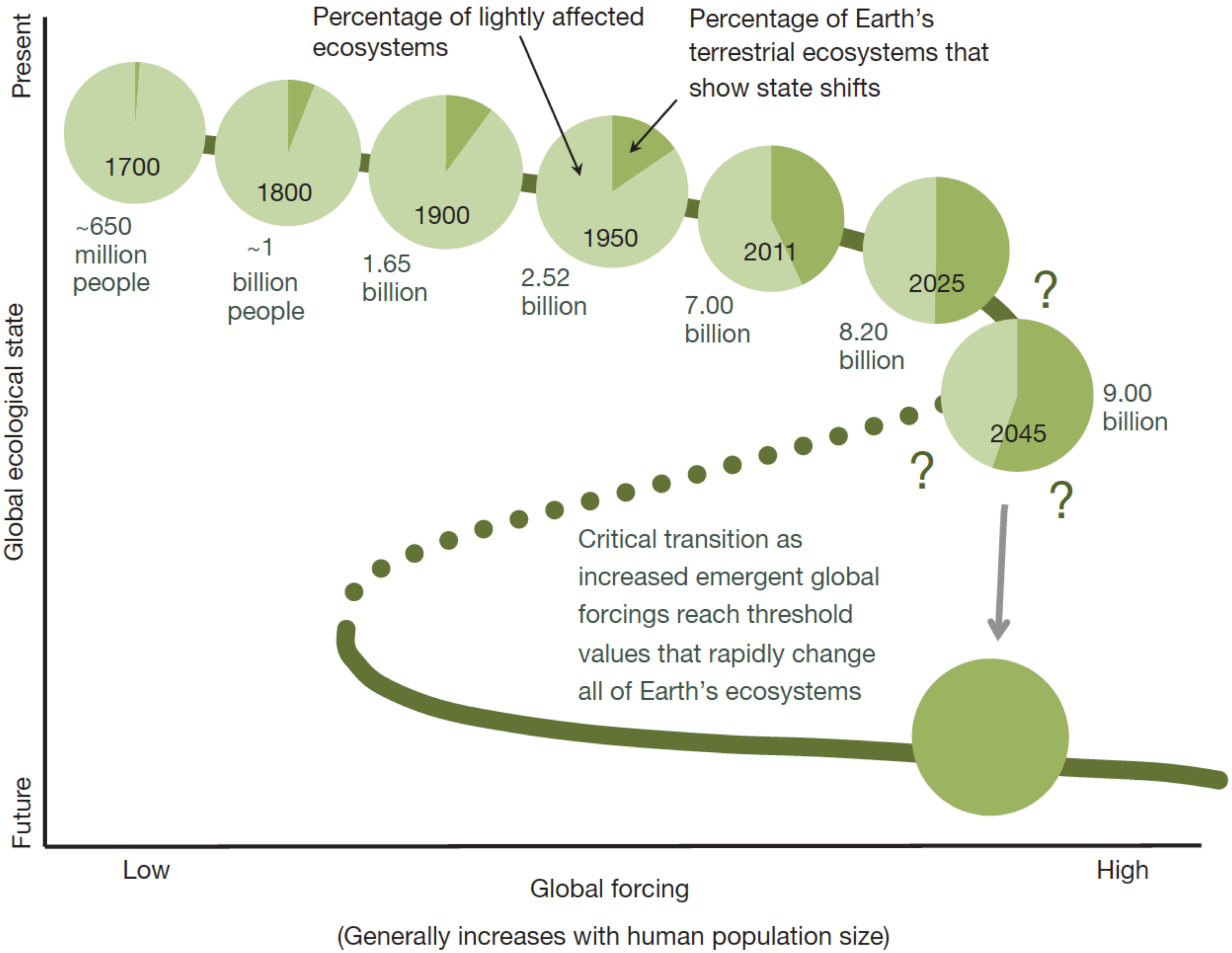
Approaching a state shift in Earth's biosphere

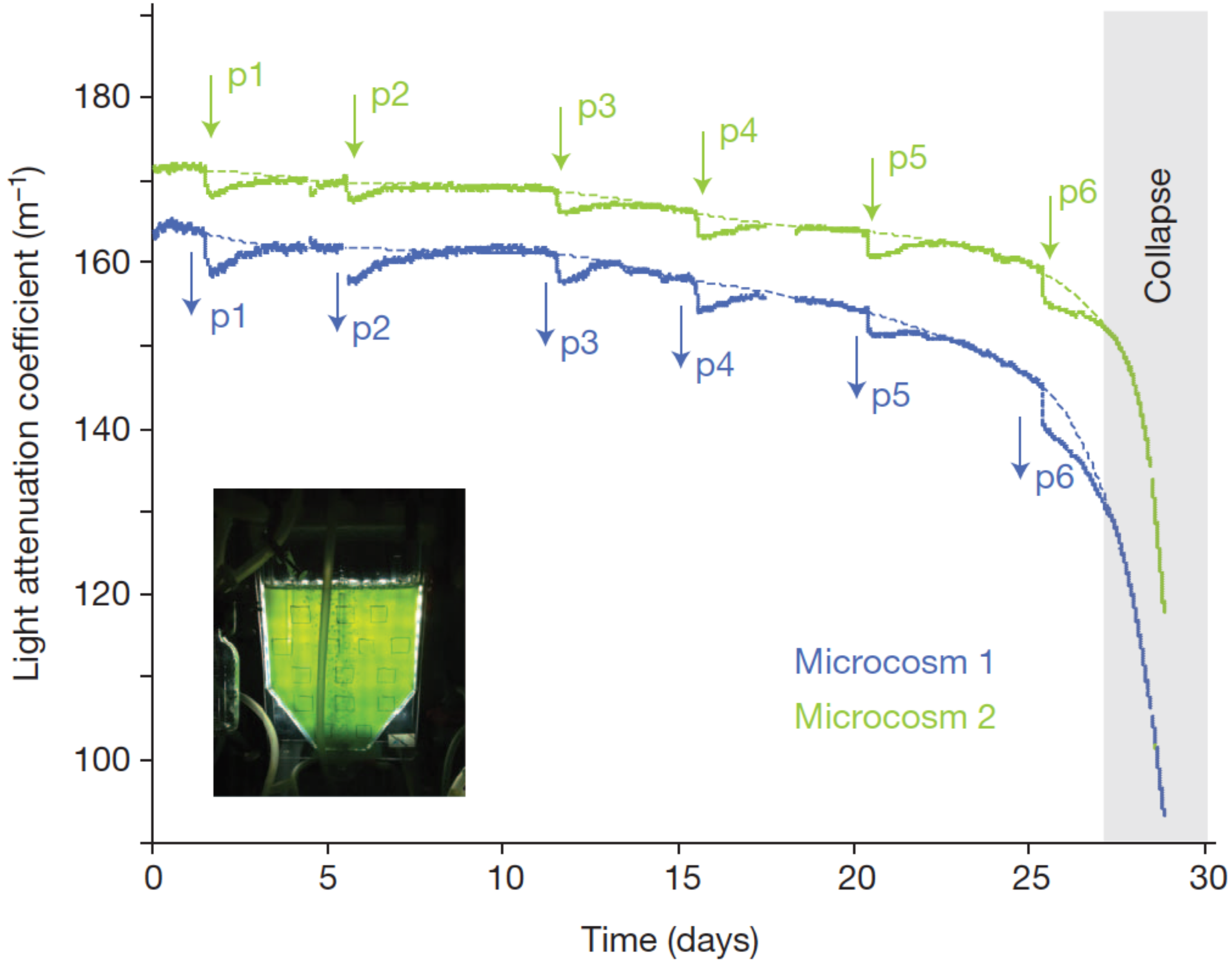
Anthony D. Barnosky[1,2,3], Elizabeth A. Hadly[4], Jordi Bascompte[5], Eric L. Berlow[6], James H. Brown[7], Mikael Fortelius[8], Wayne M. Getz[9], John Harte[9,10], Alan Hastings[11], Pablo A. Marquet[12,13,14,15], Neo D. Martinez[16], Arne Mooers[17], Peter Roopnarine[18], Geerat Vermeij[19], John W. Williams[20], Rosemary Gillespie[9], Justin Kitzes[9], Charles Marshall[1,2], Nicholas Matzke[1], David P. Mindell[21], Eloy Revilla[22] & Adam B. Smith[23]

Localized ecological systems are known to shift abruptly and irreversibly from one state to another when they are forced across critical thresholds. Here we review evidence that the global ecosystem as a whole can react in the same way and is approaching a planetary-scale critical transition as a result of human influence. The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

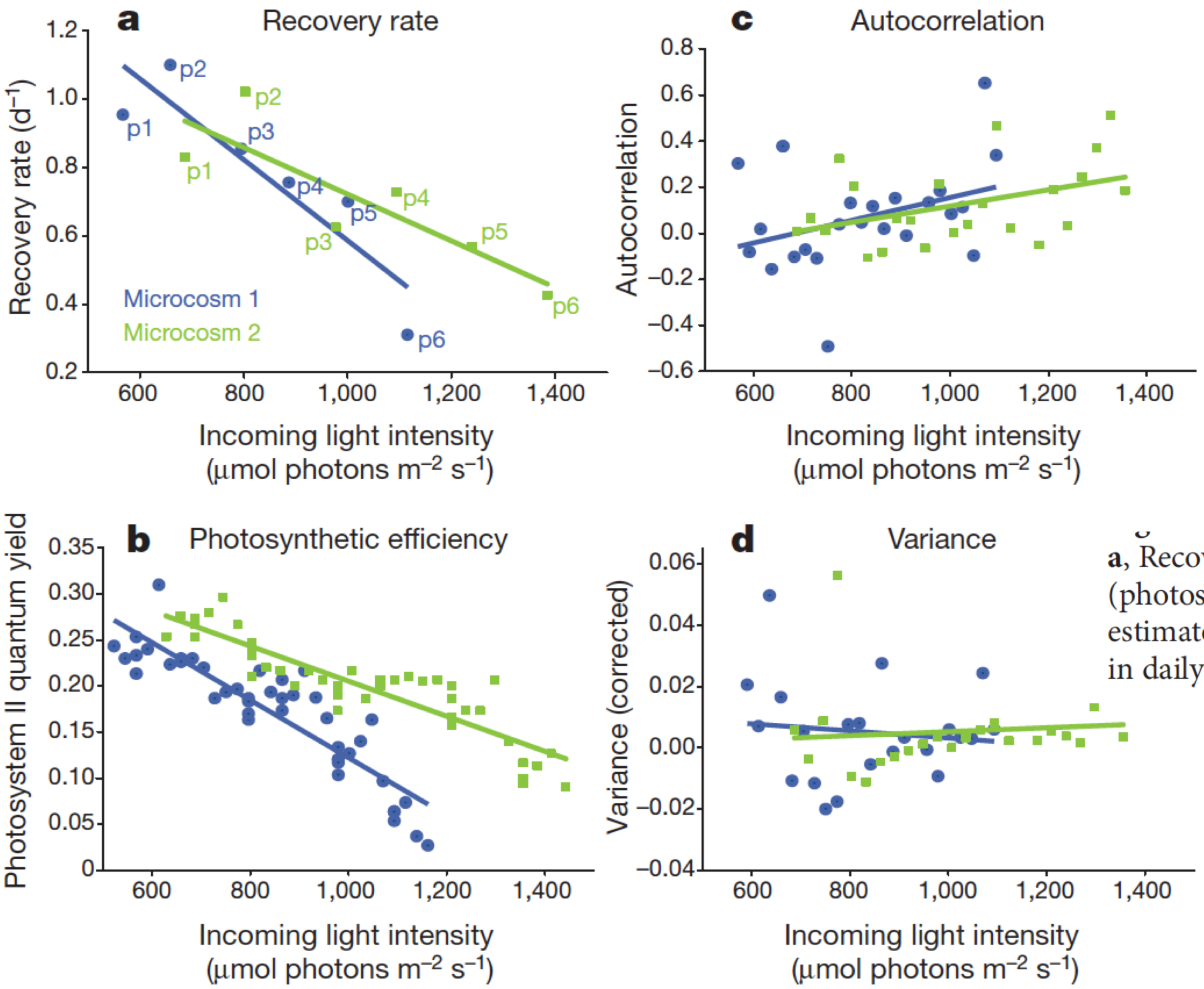


1 | Drivers of a potential planetary-scale critical transition. **a**, Humans locally transform and fragment landscapes. **b**, Adjacent areas still harbouring natural landscapes undergo indirect changes. **c**, Anthropogenic local state shifts accumulate to transform a high percentage of Earth's surface drastically; brown colouring indicates the approximately 40% of terrestrial ecosystems that have now been transformed to agricultural landscapes, as explained in ref. 34. **d**, Global-scale forcings emerge from accumulated local human impacts, for example dead zones in the oceans from run-off of agricultural pollutants. **e**, Changes in atmospheric and ocean chemistry from the release of greenhouse gases as fossil fuels are burned. **f–h**, Global-scale forcings emerge to cause ecological changes even in areas that are far from human population concentrations. **f**, Beetle-killed conifer forests (brown trees) triggered by seasonal changes in temperature observed over the past five decades. **g**, Reservoirs of biodiversity, such as tropical rainforests, are projected to lose many species as global climate change causes local changes in temperature and precipitation, exacerbating other threats already causing abnormally high extinction rates. In the case of amphibians, this threat is the human-facilitated spread of chytrid fungus. **h**, Glaciers on Mount Kilimanjaro, which remained large throughout the past 11,000 yr, are now melting quickly, a global trend that in many parts of the world threatens the water supplies of major population centres. As increasing human populations directly transform more and more of Earth's surface, such changes driven by emergent global-scale forcings increase drastically, in turn causing state shifts in ecosystems that are not directly used by people


Present
Global ecological state
Future
Percentage of lightly affected ecosystems
Percentage of Earth's terrestrial ecosystems that show state shifts
1700
~650 million people
1800
~1 billion people
1900
1.65 billion
1950
2.52 billion
2011
7.00 billion
2025
8.20 billion
?
2045
9.00 billion
?
?
Critical transition as increased emergent global forcings reach threshold values that rapidly change all of Earth's ecosystems
Low
Global forcing
High
(Generally increases with human population size)



| **The response of two populations of cyanobacteria (*Aphanizomenon flos-aquae*) to dilution events under a regime of gradually increasing light levels.** Dilution events are indicated as perturbations p1–p6. The light attenuation coefficient is a measure of population density. Thin curve segments represent the baselines that were used for computing recovery rates. The inset shows the experimental system.



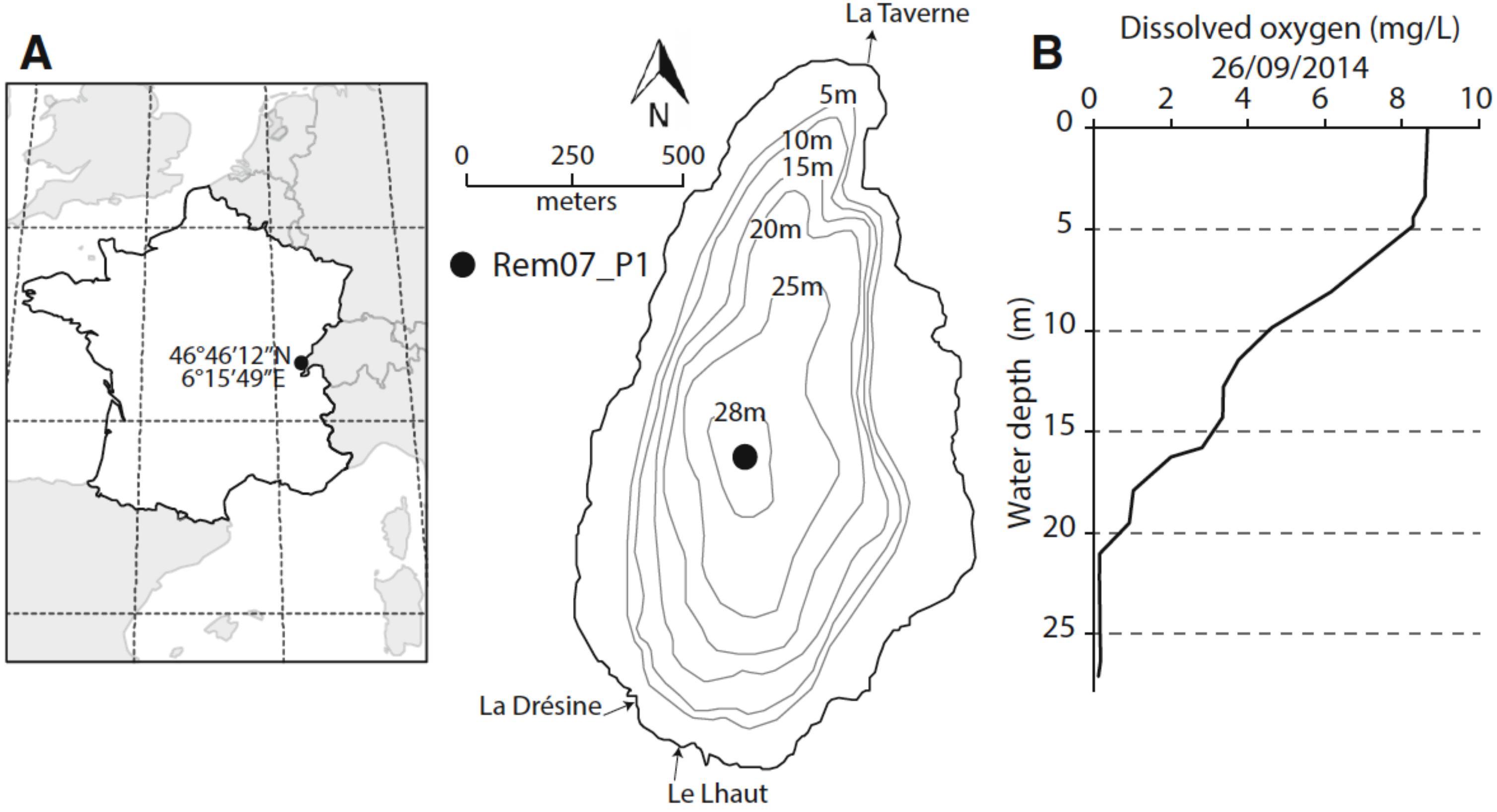
| **Indicators of slowing down as a function of light intensity.** **a**, Recovery rates after perturbation (p1–p6). **b**, Photosynthetic efficiency (photosystem II quantum yield). **c**, Autocorrelation in the population density estimator for each day based on 30 min average I_{out} data. **d**, Corrected variance in daily time series (see Methods and Supplementary Notes 4). Fisher's

Rising variance and abrupt shifts of subfossil chironomids due to eutrophication in a deep sub-alpine lake

Simon Belle · Virgile Baudrot · Andrea Lami · Simona Musazzi · Vasilis Dakos

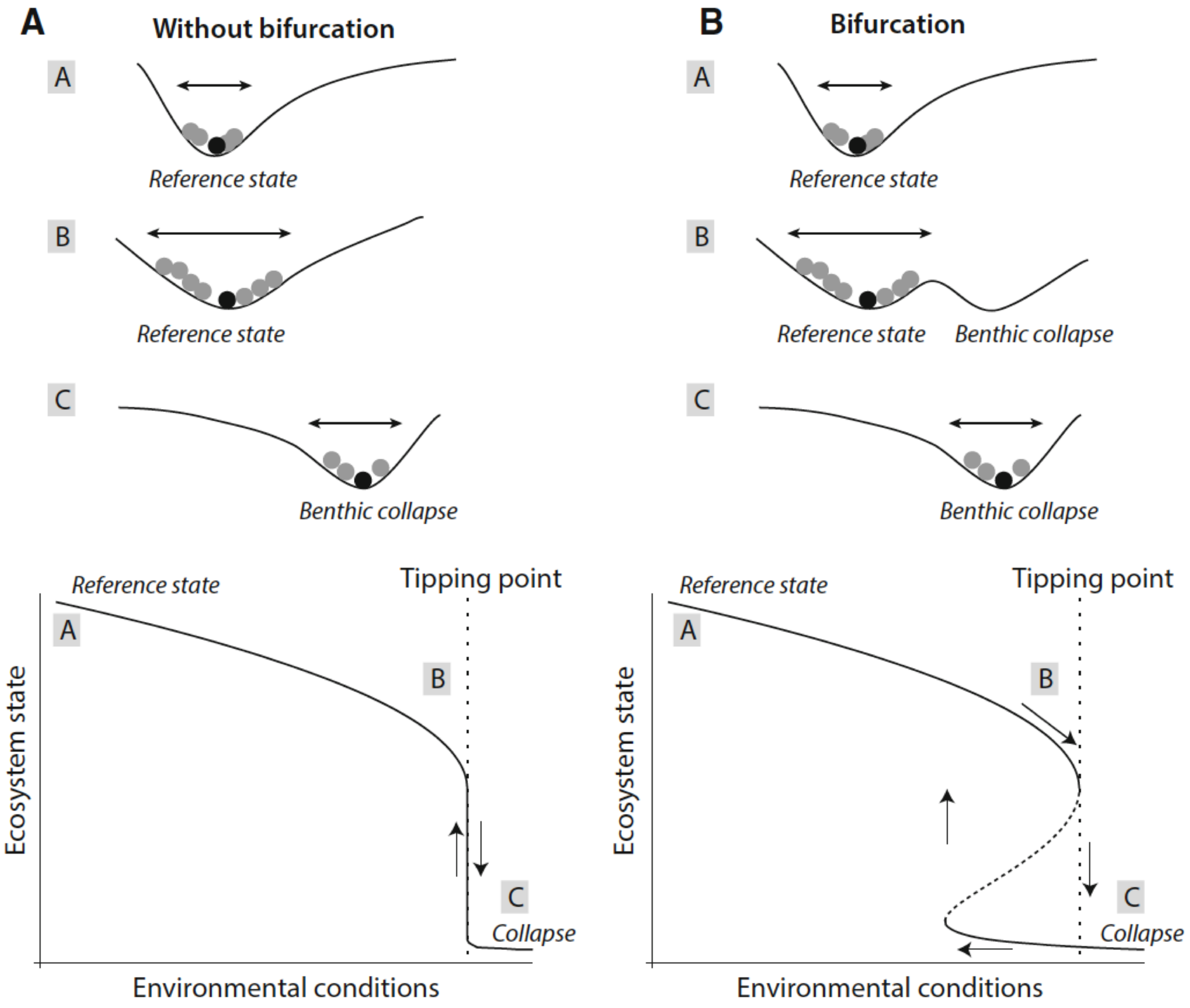
Aquat Ecol (2017) 51:307–319

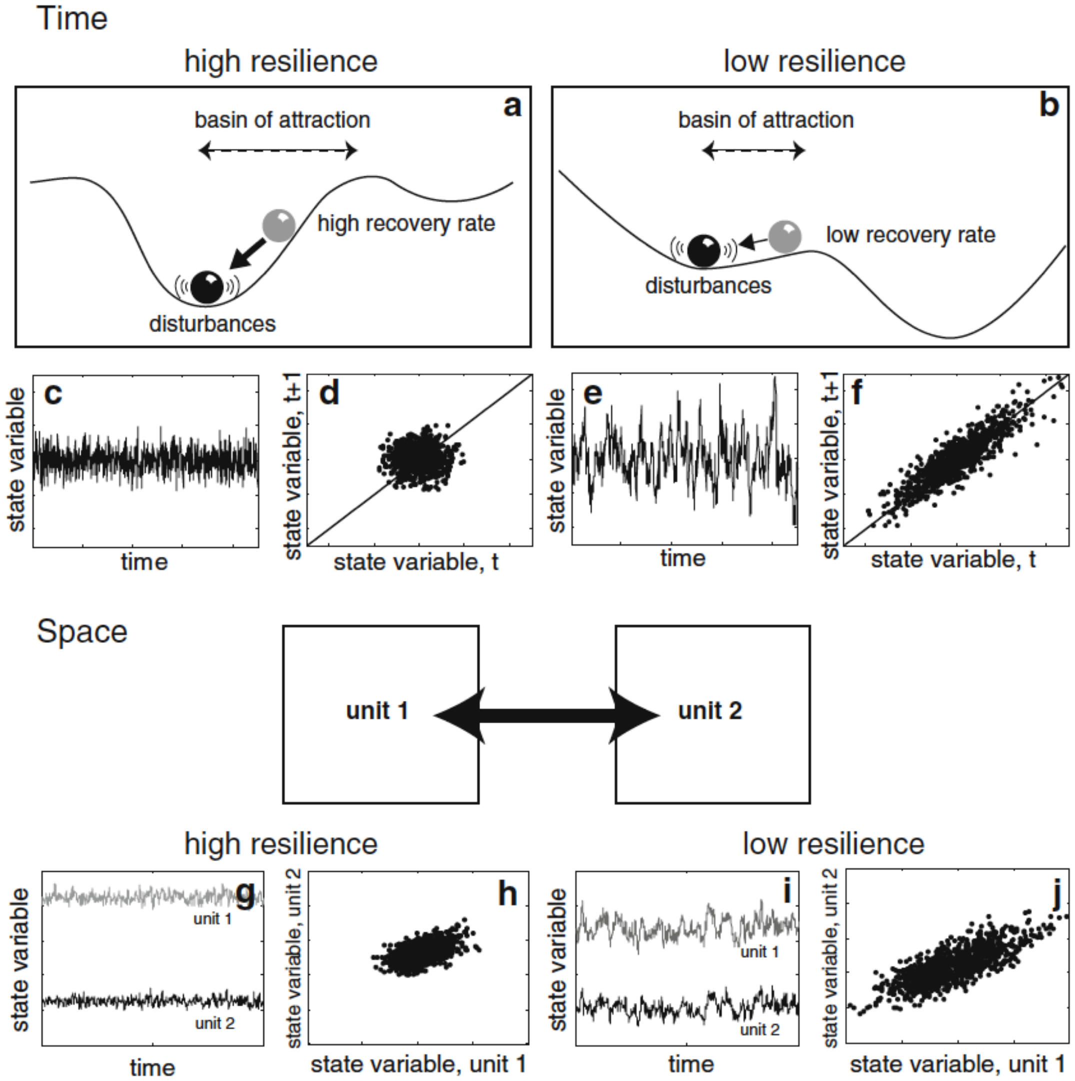
In response to anthropogenic eutrophication and global warming, deep-water oxygen depletion is expected to have large effects on freshwater lake biogeochemistry and resident communities. In particular, it has been observed that deep-water hypoxia may potentially lead to regime shifts of lake benthic communities.



a Location and bathymetric map of Lake Remoray. In the bathymetric map, *black circle* marks the coring position at the maximal water depth. **b** Oxygen profile measured on September 26, 2014, at the vertical of maximum water depth.

a A regime shift to chironomid collapse explained as an abrupt (continuous) response without a bifurcation. **b** A regime shift to chironomid collapse explained as an abrupt (discontinuous) response with bistability (fold bifurcation). *Letters* refer to different positions along the ecological trajectory of Lake Remoray. Stability landscapes have been graphically drawn to show changes in the basins of attraction of the ecosystem states. Note that in both cases **a**, **b**, variance is expected to rise before the regime shift





Time: balls and cups representation of the stability properties of a system exhibiting alternative stable states. **a** At high resilience, small disturbances to the equilibrium are counterbalanced by high recovery rates back to equilibrium. As a result, when monitoring the state variable in time, the collected time-series is characterized by low correlation between subsequent values (panels **c**, **d**). **b** At low resilience, the basin of attraction shrinks and the system is closer to the transition point. Small disturbances not only increase the chance of pushing the system to the alternative state, but they are not anymore effectively damped due to low recovery rates back to equilibrium. The resulting time-series is highly autocorrelated (panels **e**, **f**). *Space*: dynamics of two strongly connected units embedded in a hypothetical spatial system. When the system is far away from the transition (*high resilience*), dynamics in each unit are defined more by their own reaction processes than by dispersion (panel **g**) and appear weakly correlated (panel **h**). Close to the transition (*low resilience*), reaction processes are minimized due to critical slowing down and dispersion dominates (panel **i**). Units now are strongly correlated (panel **j**)

Simple tipping or complex transition? Lessons from a green Sahara

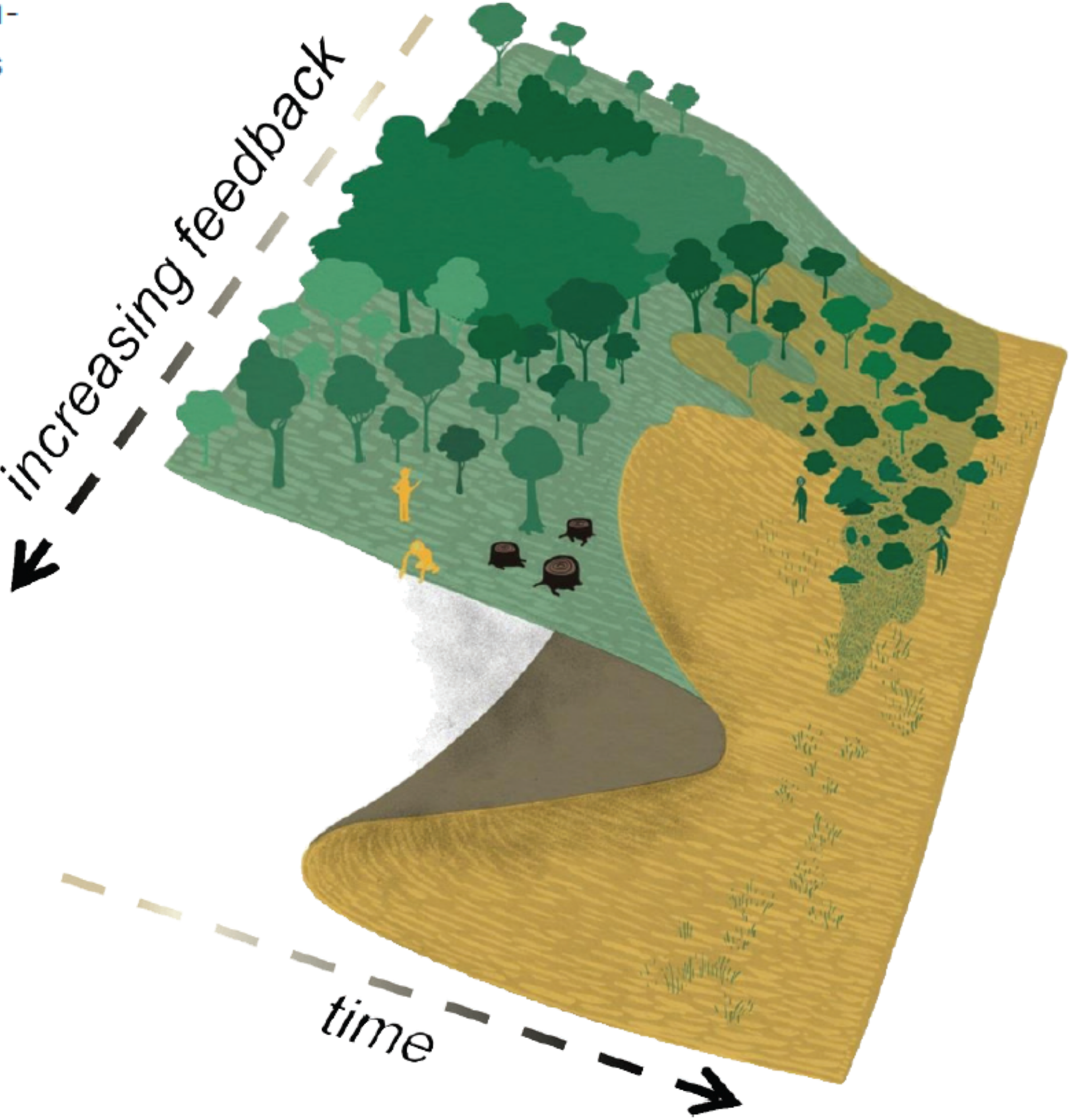
Sebastian Bathiany[1,2], M. Claussen[2,3], V. Brovkin[2], M. Scheffer[1], V. Dakos[4] and E. van Nes[1]

The history of the Sahara provides an example for our changing perspective on abrupt change in the Earth system. The emerging concepts can help us to understand past transitions and assess potential future tipping points.

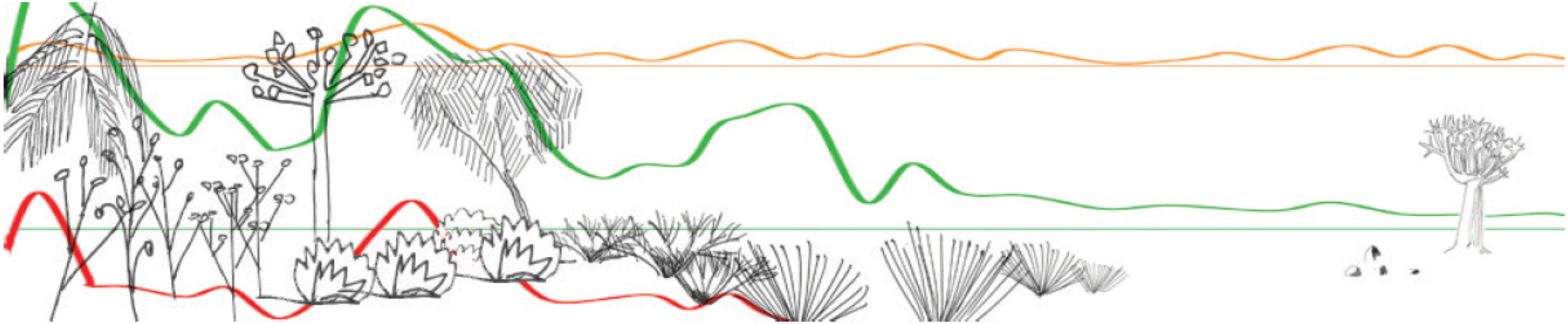
Little does the monotonous and hostile environment of today's Sahara Desert tell us about its colorful past. However, climate and vegetation reconstructions reveal that several thousand years ago, parts of the Sahara resembled a flourishing garden with extensive vegetation and lakes (Jolly et al. 1998). This green Sahara was only the most recent of many green episodes in North Africa's history. The most important driver of these landscape transformations was the permanent change in the Earth's orbital parameters (Kutzbach 1981). When the distance between Earth and Sun is smallest during boreal summer, the larger solar irradiation intensifies the West African monsoon and thus increases rainfall.

While it is obvious that rainfall is beneficial for vegetation, climate models indicate that vegetation can also enhance rainfall. First, the dark vegetation absorbs more sunlight than the bright desert and provides energy for convection (Charney et al. 1975). Second, the evaporation from vegetation and lake surfaces feeds the water back into the atmosphere (Rachmayani et al. 2015). Vegetation and rainfall are therefore linked in a self-amplifying process, a positive feedback. The stronger this feedback, the more abrupt the transition from a green Sahara to a desert

Whereas orbital parameters change gradually over thousands of years, model results (Claussen et al. 1999) and a dust record from the Atlantic (de Menocal et al. 2000) suggested a quite rapid vegetation loss at the end of the green Sahara. This seemed to support the view of a switch from a green state to a desert state, a natural climate catastrophe comparable to a chair suddenly tipping over when it is slowly tilted. Such tipping points have been found not only in atmosphere-vegetation models (Brovkin et al. 1998), but also in simple models representing ocean circulation, Arctic sea ice, ice shields, savannah and lake ecosystems, and the East Asian and Indian monsoons.



: Stability landscape of green Sahara and desert. The larger the atmosphere-vegetation feedback, the sharper the transition between the two states. From: Model Calendar 2015, designed by Elsa Wikander at Azote, funded by the Beijer Institute of Ecological Economics and the Stockholm Resilience Centre.



: Idealized abundance of East Saharan plant types from 6000 to 3500 years ago (from left to right) with Acacia (orange), Poaceae (green) and tropical plant taxa (red). Pollen records after Kroepelin et al. (2008), drawing by Dominique Donoval, Max Planck Institute for Meteorology, Hamburg.

Early warning signals (EWS) for abrupt change are one of the fastest-growing subfields in ecology. The general idea of EWS is that key system parameters should show characteristic statistical signals as the system approaches a transition, and that tracking these signals should provide information about the likelihood of abrupt change.

Alternative stable states: Different configurations of a system that are able to exist at the same set of external conditions, corresponding to a stable equilibrium or basin of attraction in nonlinear response to external conditions.

Critical slowing down: Reduced speed of recovery from perturbation as a critical transition is approached, due to a decline in engineering resilience.

Critical transition: Abrupt shift in a system caused by nonlinear responses to external conditions.

Early warning signal/early warning indicator: Model- or metric-based statistic able to warn that the system is approaching a sudden change, most often associated with a critical transition.

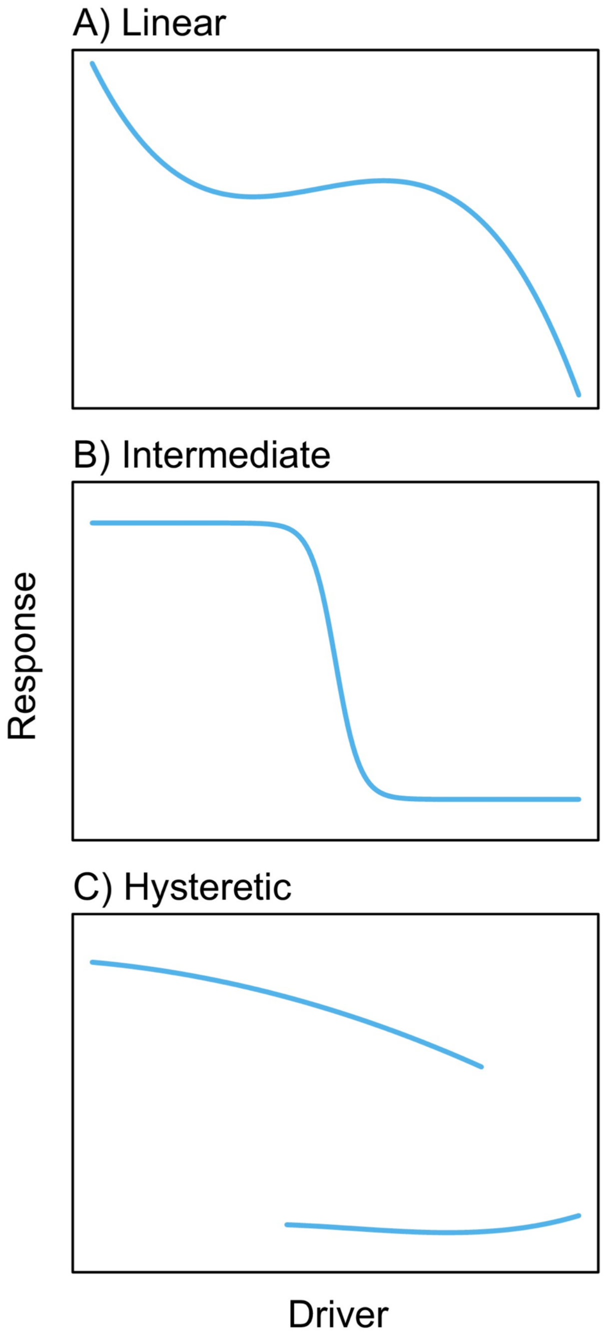
Fold bifurcation/saddle-node bifurcation: A critical transition between alternative stable states, corresponding to the threshold in external conditions at which stable and unstable equilibria meet.

Hysteresis: Different critical transitions in response to increasing and decreasing external conditions; responses to external conditions that depend on system state and the direction of change in external conditions.

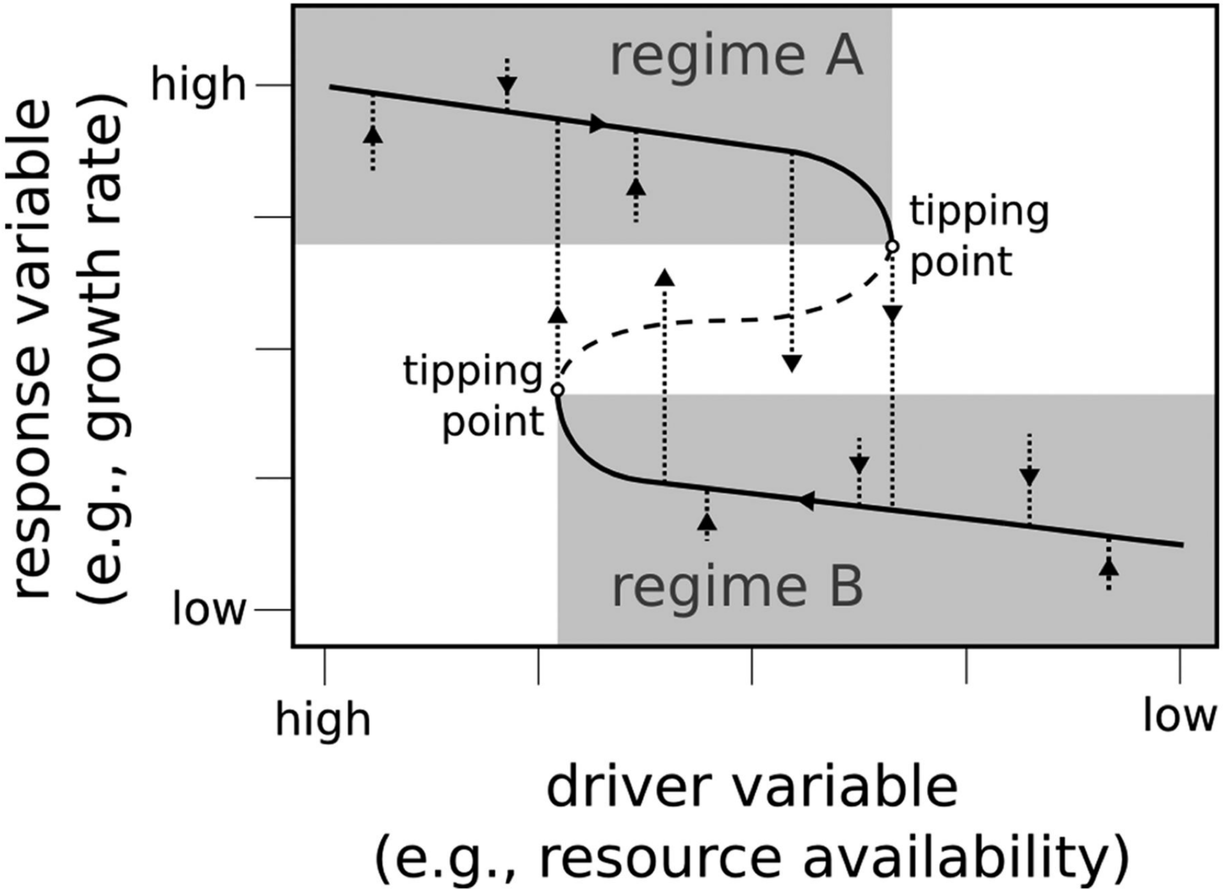
Linear: Systems with dynamics that can be expressed statistically by models in which the estimated parameters are combined by addition. Thus, a linear regression ($y = a + bx$) or a quadratic regression ($y = a + b_1x + b_2x^2$) both describe linear systems. In a linear system, the effect of any small perturbation decays in time.

Nonlinear: In a nonlinear system, a small perturbation may propel the system to another stable state, and dynamics are both state-dependent and sensitive to initial conditions. Statistically, the response variable cannot be summarized as a linear combination of estimated parameters.

Resilience: Ecological resilience is the ability of a system to remain in its current state when exposed to perturbation. Engineering resilience is the speed with which a system returns to equilibrium after perturbation.

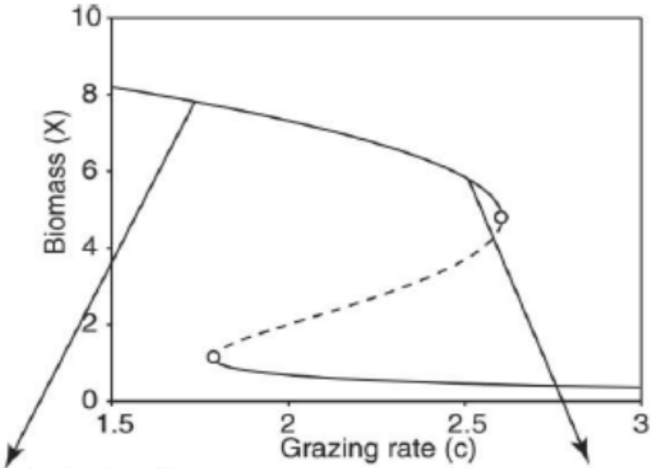


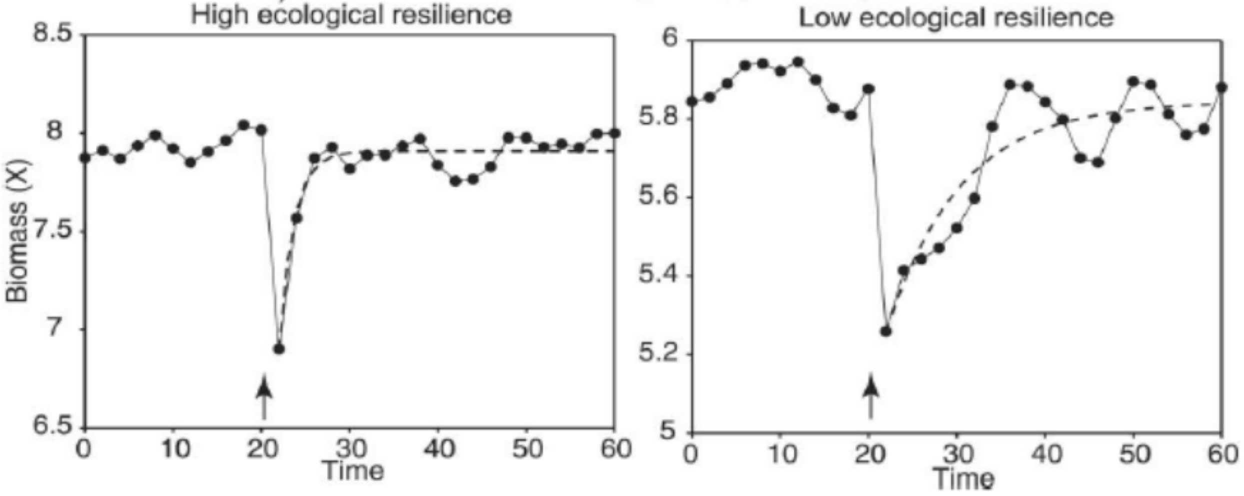
Schematic of range of possible driver–response relationships, from (A) linear tracking of environmental conditions (in this case illustrated by a cubic function, which is a linear combination of model parameters); to (B) an intermediate response with a strong threshold; and (C) a state-dependent response consistent with hysteresis. Note that both (B) and (C) are nonlinear relationships.



recovery time after a temporal perturbation

underexploited

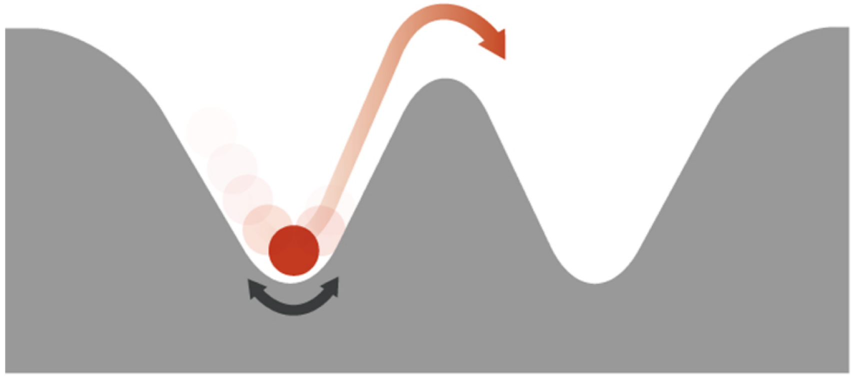




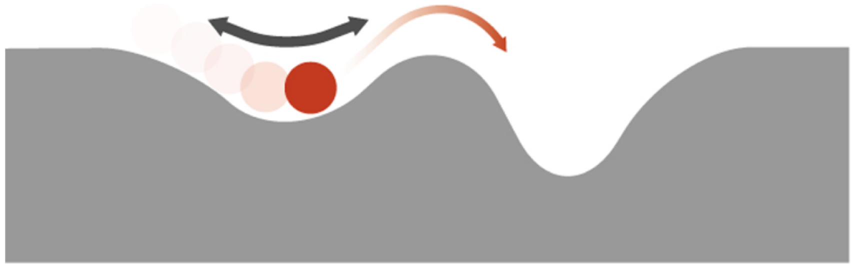
overexploited

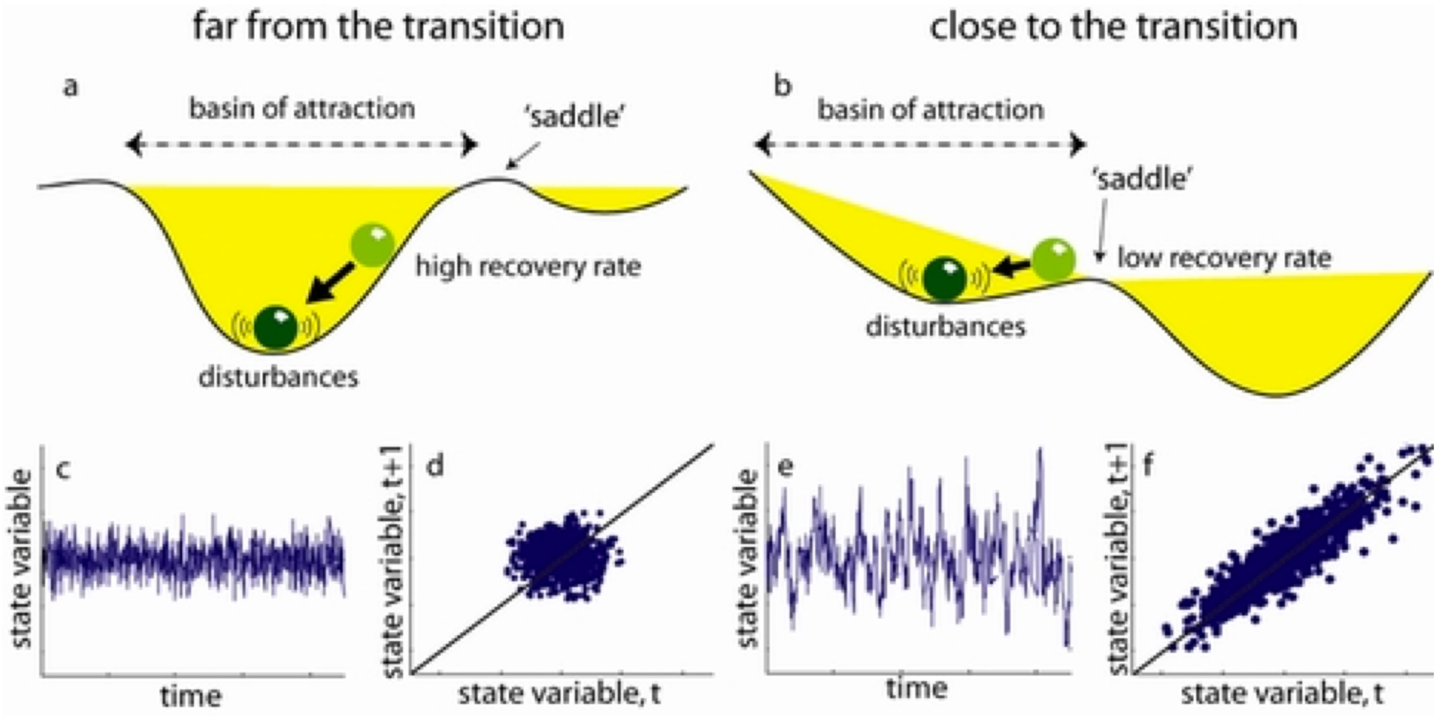
Scheffer uses accessible diagrams to illustrate tipping point concepts.

A resilient system returns to equilibrium quickly after a small push (**black**). It takes a major push (**red**) to tip the system into a new stable state.



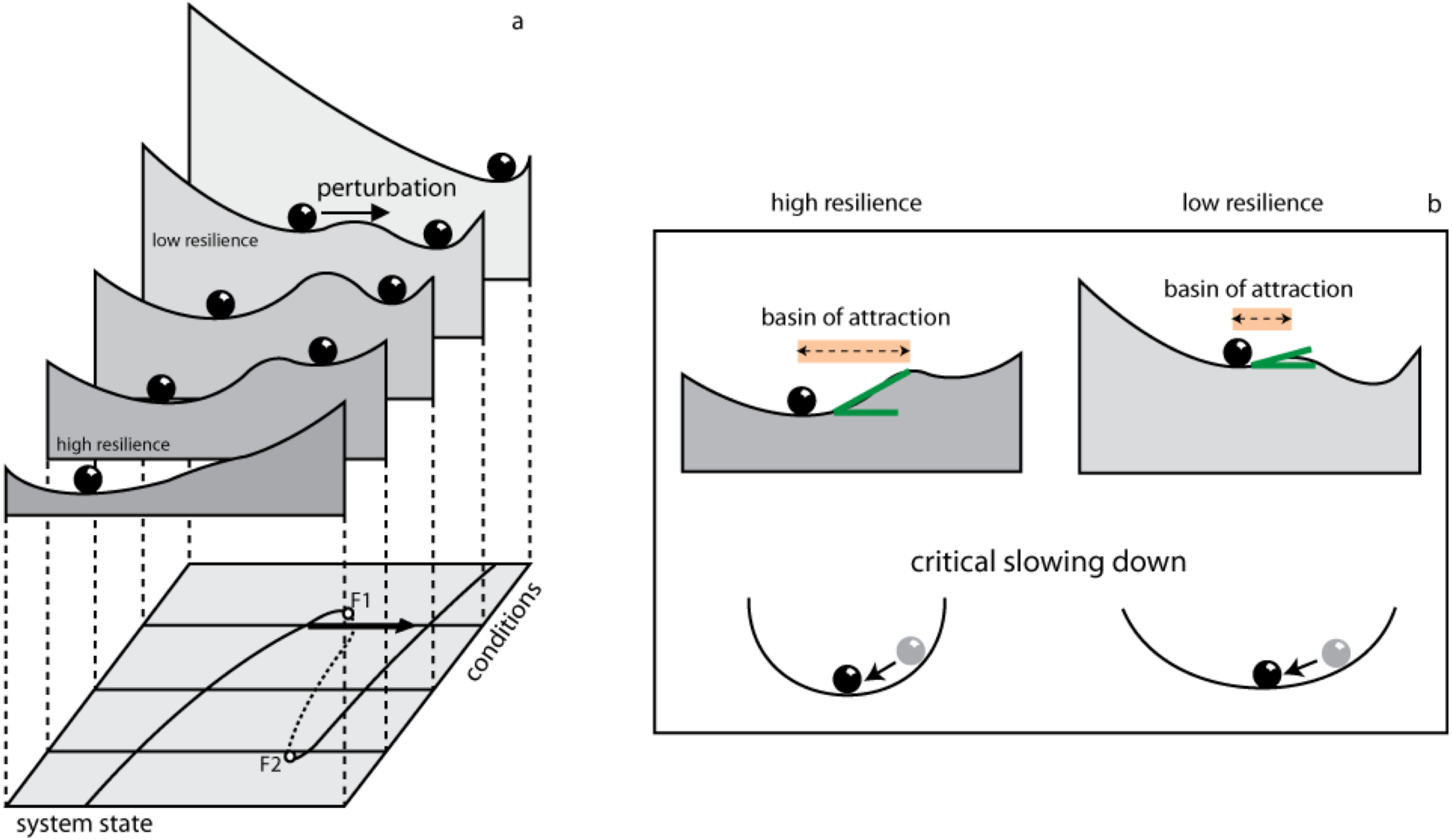
A less resilient system recovers more slowly from small pushes (**black**). This “critical slowing down” can be a warning sign that the system could easily tip into a new state (**red**).

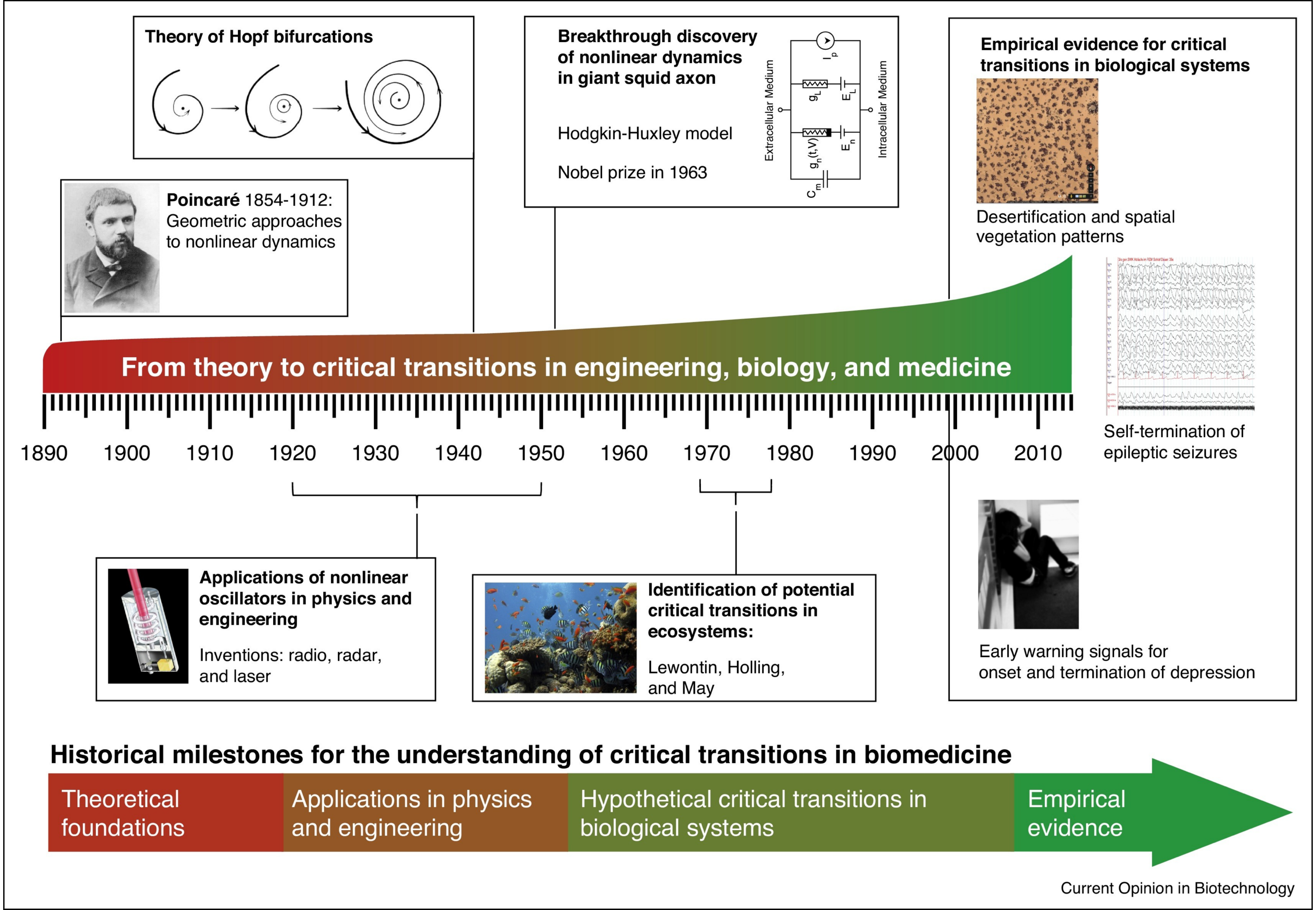




far from the transition

close to the transition


a
perturbation
low resilience
high resilience
F1
F2
conditions
system state
b
high resilience
low resilience
basin of attraction
basin of attraction
critical slowing down



Theory of Hopf bifurcations

Poincaré 1854-1912:
Geometric approaches
to nonlinear dynamics

Breakthrough discovery of nonlinear dynamics in giant squid axon

Hodgkin-Huxley model

Nobel prize in 1963

Empirical evidence for critical transitions in biological systems

Desertification and spatial vegetation patterns

Self-termination of epileptic seizures

Early warning signals for onset and termination of depression

From theory to critical transitions in engineering, biology, and medicine

Applications of nonlinear oscillators in physics and engineering

Inventions: radio, radar, and laser

Identification of potential critical transitions in ecosystems:

Lewontin, Holling, and May

Historical milestones for the understanding of critical transitions in biomedicine

Theoretical foundations

Applications in physics and engineering

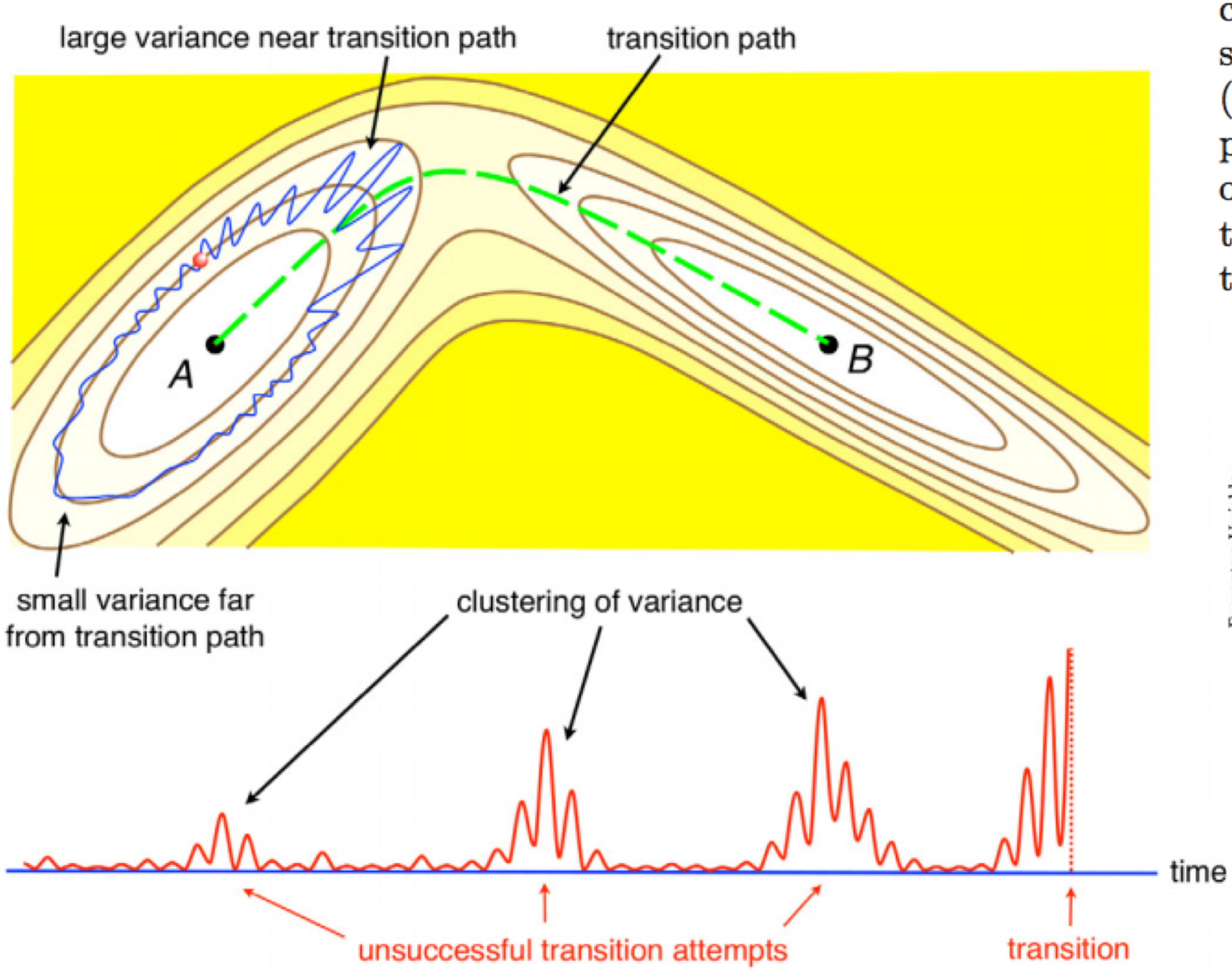
Hypothetical critical transitions in biological systems

Empirical evidence

Current Opinion in Biotechnology

Potential indicators for early warning.

Early warning signal	Definition	Observed system variable
Variance	Scatter of data	Phosphorus concentration in lake [10] Pollutant across multiple regions [31] Interleukin-6 levels [20] Spiking patterns in neurons [57]
Coefficient of variation	Standard deviation normalized by the mean	Population density [32] Spatial heterogeneity of ventilation [16] Infectious population dynamics [55] Ozone levels [49•]
Lag-1 autocorrelation	Correlation of data with itself shifted by one time point	Rate of resource harvesting [33•] Connected population density [32]
Flickering	System states are driven back and forth between alternate stable states by intrinsic noise	Sediment diatom composition [35•] Ice conductivity [34] Phosphorus dynamics [36] Invasive electrocorticogram recordings [22•]
Skewness	Third standardized moment of the distribution of system states	Vegetation biomass [37] Phosphorus density [37]
Dynamical network biomarkers	Evolution over time of difference in molecular networks	Gene expression profiles [18,19,38,51]
Critical slowing down	Recovery rates tend to zero after small external perturbation	Calcium carbonate levels [41] Cyanobacteria population density [42•] Nutrient cycling in lakes [39] Macrophyte cover [39] Vegetation growth [40] Mood dynamics [17•]
Spatial distribution	Non-random distribution of elements in a biological entity	Vegetation patchiness [8]
Conditional heteroscedasticity	Variance is conditional on past time points	*E. coli* population growth [28] Chlorophyll-*a* concentration [43]



An illustration showing the noisy trajectory (blue solid curve) of a complex system moving within attractor A, and sometimes coming close to the tipping point for the transition (green dashed curve) to attractor B. If the complex system approaches this tipping point several times before the transition occurs, we will see a feature called *clustering of variance* in the time series data, whereby the local variance is enhanced near the transition, as well as the unsuccessful transition attempts.