Regime Shifts DataBase
Large persistent changes in ecosystem services

Regime Shifts: What are they and why do they matter?*

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Introduction

Regime shifts are large, abrupt, persistence changes in the function and structure of systems[1]. They have been documented in a wide range of systems including financial markets, climate, the brain, social networks and ecosystems[2]. Regime shifts in ecosystems are policy relevant because they can affect the flow of ecosystem services that societies rely upon, they are difficult to predict, and often hard or even impossible to reverse[2].

In ecosystems, regime shifts have been documented in a broad range of marine, terrestrial and polar ecosystems[1]. Two well-studied examples include the eutrophication of lakes, when they turn from clear to murky water, affecting fishing productivity and, in extreme cases, human health[3]; and the transition of coral reefs from coral dominated to macro-algae dominated reefs, leading to the loss of ecosystem services related to tourism, coastal protection and fisheries[4]. More contested examples include dryland degradation and Artic sea ice loss, where the possibility of regime shifts exist but researchers disagree about the nature and strength of the mechanisms producing the shifts. Proposed examples of regime shifts include the weakening of the Indian Monsoon and the weakening of the Thermohaline circulation in the ocean. Paleoclimatological evidence shows that both can occur, but how likely they are under present conditions is not well understood[5].

What these phenomena have in common is that their scientific understanding relies on the same underlying mathematical theory of dynamic systems[6]. By this understanding, the behavior of a system can be described by a set of equations that define all possible values of the key response variables in the system, for instance coral cover or fish abundance. These systems tend to fluctuate around regions of the parameter space (e.g., values of key driver variables) that are called basins of attraction. Systems prone to regime shifts have more than one basin or domain of attraction; this means that under roughly the same parameter values they can suddenly shift from one domain to another when a critical threshold is crossed (Fig 1).

The different domains of attraction can be metaphorically represented by a ball and cup diagram (Fig 1). In this diagram, the ball represents the state of the system at a particular point in time, the basin or cups represent different domains of attraction or regimes. The point separating the different basins represents a critical threshold or tipping point that divides these domains of attraction. However these regimes are not characterized by stable ecosystems at equilibrium, rather represent dynamic ecosystems that fluctuate and change within the boundaries of the basin of attraction. Thus for example, the species composition, abundance and distribution of a forest are always changing as a forest changes in response to fires, hard winters, storms or pests outbreaks. Yet the forest maintains its identity as a forest. The same persistence of identity is a key characteristic of a regime.

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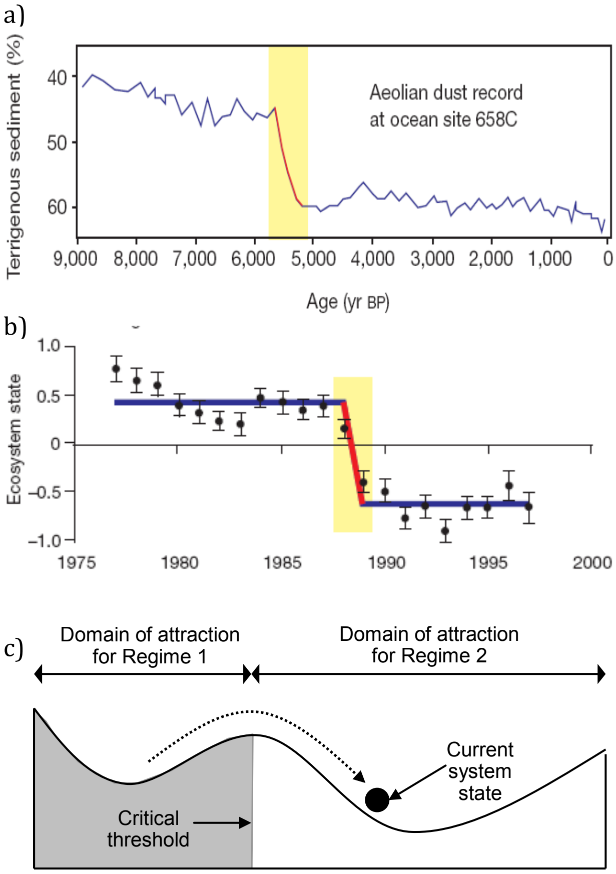

Figure 1. Regime shifts are characterized by large, abrupt, persistent changes in ecosystem structure and dynamics. a) For example, an abrupt change in the climate and vegetation of the Sahara occurred about 5,500 years ago, reflected in the contribution of land-based dust in the oceanic sediment. b) Regime shifts are also observed on much shorter time-scales, for example an abrupt shift in climatic and biological conditions was observed in the Pacific Ocean in 1989 (from Scheffer et al 2001). c) Different regimes can be mathematically represented by a stability landscape with different domains of attraction (valleys). A regime shift entails a shift in the current system state (represented as a ball) from one domain of attraction to another. While in a particular regime, the system does not remain stable but fluctuates dynamically around the equilibrium point for that regime. From Biggs et al 2012.

All changes in the structure or functioning of an ecosystem are not regime shifts. A regime shift must affect the feedback structure of the system that maintains its emergent structure and function; this is, a change that affects the identity of the system (e.g., forest, coral reef, mangrove). When scientists refer to regime shifts they often emphasize that regime shifts are abrupt and persistent changes. However, it worth noting that the abruptness and persistence of a shift are relative to the dynamics defining the system's identity, rather than human time scales. For example, if a generation of trees can persist for hundreds of years; a shift to a savanna over the timespan of a few decades is then abrupt relative to the dynamics that maintain the forest or savanna regimes.

History of the regime shift concept

The concept of systems exhibiting multiple domains of attraction was first developed in 1885 by French mathematician Henri Poincaré. However, it was only in the late 1960s that these mathematical developments were introduced into ecology when leading scientists began to debate ecosystem stability[6,7]. These debates led to development of mathematical and simulation models of proposed regime shifts in fisheries, disease outbreaks, and grazing or harvesting systems. After this initial profusion of models, in the early 1980s critics argued that the concept of regime shifts lacked an empirical foundation, and research on the concept slowed. By the early 2000s evidence of regime shifts had accumulated for coral reefs and lake ecosystems, which stimulated further research on their detection and management[8-10].

Diverse evidence now supports the existence of a variety of regime shifts, both in ecosystems as well as social-ecological systems[11]. This evidence consists of experimental evidence, observational evidence from long-term time series data, paleo-ecological evidence from sediments and ice cores, as well as mathematical evidence from process based models that represent the possible mechanisms explaining regime shifts. Table 1 presents a summary of some ecological regime shifts that have substantive impacts on society. More information about regime shifts can be found in the Regime Shifts Database www.regimeshifts.org.

Table 1. Examples of well-known regime shifts and their impacts on ecosystem services. Information from the Regime Shifts Database www.regimeshifts.org.

Regime shift	**Regime A**	**Regime B**	**Impacts of shift from A to B**	**Evidence**	**Source of evidence**
Freshwater eutrophication	Non-eutrophic	Eutrophic	Reduced access to recreation, reduced drinking water quality, risk of fish loss	Strong	Observations, experiments, models
Bush encroachment	Open grassland	Closed woodland	Reduced grazing for cattle, reduced mobility, increased fuelwood	Medium	Observations, experiments, models
Soil salinisation	High productivity	Low productivity	Yield declines, salt damage to infrastructure and ecosystems, contamination of drinking water	Strong	Observations, experiments, models
Coral reef degradation	Diverse coral reef	Reef dominated by macro-algae	Reduced tourism, fisheries, biodiversity	Strong	Observations, experiments, models
Coastal hypoxia	Non-hypoxic	Hypoxic	Fishery decline, loss of marine biodiversity, toxic algae	Strong	Observations, models
River channel position	Old channel	New channel	Damage to trade and infrastructure	Strong	Observations, models
Wet savanna-Dry savanna	Wet Savanna	Dry savanna or desert	Loss of productivity, yield declines, droughts/dry spells	Medium	Models

What causes regime shifts?

Modeling, observation and experimental work have shown that regime shifts typically result from a combination of an external shock, such as a storm or fire, and gradual changes in underlying drivers and internal feedbacks (Fig 2). While the consequences of a regime shift are usually highly visible, changes in the risk of a regime shift (i.e., changes in system resilience) often go unnoticed. This is because gradual changes in underlying drivers and internal feedbacks that move a system closer to or further away from a critical threshold usually have little impact on the system state until the point at which a regime shift is triggered. However, once a system is close to a threshold, a regime shift can be precipitated by even a small shock to the system. Due to these dynamics, most regime shifts are experienced as a complete surprise to the people living in or managing the ecosystem.

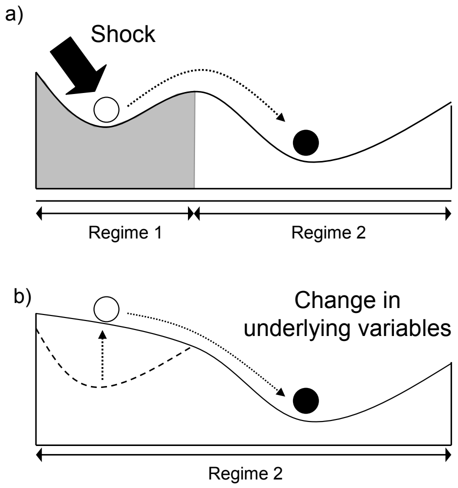

Figure 2. Regime shifts are usually due to a combination of a) A shock such as a drought or flood, and b) slow changes in underlying variables and internal feedbacks that change the domains of attraction (or resilience) of the different regimes. Gradual changes in underlying variables can lead to the disappearance of some domains of attraction, or the appearance of new domains of attraction that did not previously exist. The critical thresholds that separate different regimes are typically determined by multiple underlying variables, rather than a single variable. From Biggs et al 2012.

A good example is the increased risk of soil salinization associated with rising groundwater table levels in semi-arid regions such as Australia. Rising water tables often go unnoticed since they have little or no impact on the production of agricultural crops until the water table reaches about 2 m below the surface. At this point, capillary action rapidly pulls the water to the soil surface, bringing with it dissolved salts which lead to salinization of the topsoil and dramatically reduce crop growth. Once the water table is close to the 2 m threshold, the shift to the saline regime can be triggered by even a relatively small rainfall event.

Changes in the relative strength and balance of feedbacks in a system are central to understanding regime shifts. All complex systems contain both damping (also known as negative or balancing) and amplifying (also known as positive or reinforcing) feedback loops. Usually damping feedbacks dominate and keep the system within a particular domain of attraction. However, these damping feedbacks may be overwhelmed if there is a particularly large shock to the system, or if a slow variable (e.g. gradual loss of habitat) erodes the strength of the damping feedbacks. Amplifying feedbacks may then come to dominate and drive the system across a threshold into an alternate regime where a different set of damping feedbacks dominate. It is this ability for different sets of feedbacks to dominate and structure a system that creates the possibility for different regimes and explains the abruptness of regime shifts.

An illustrative example is the rapid shift from clear water to turbid, eutrophic conditions that occurs in shallow lakes when nutrient input levels (especially phosphorous) exceed those which can be absorbed by rooted aquatic plants (Fig 3). When this threshold is exceeded, the excess nutrients in the water lead to dense growth of planktonic algae. The algae reduce light penetration, leading to the death of the rooted vegetation that stabilizes sediments on the lake floor. This in turn results in resuspension of nutrients that have been trapped in the sediments by the rooted plants, further increasing algal growth, and creating an amplifying feedback. Even if the external input of nutrients is then reduced, the turbid, algal-dominated state is maintained through constant recycling of nutrients from the lake sediment. In order to return to the clear water state, nutrient inputs usually have to be reduced significantly below the level at which the system originally shifted to the eutrophic state. This phenomenon, where the critical threshold that triggers the shift from Regime A to B differs from the threshold at which the system shifts from Regime B to A, is known as *hysteresis*, and characterizes many regime shifts.

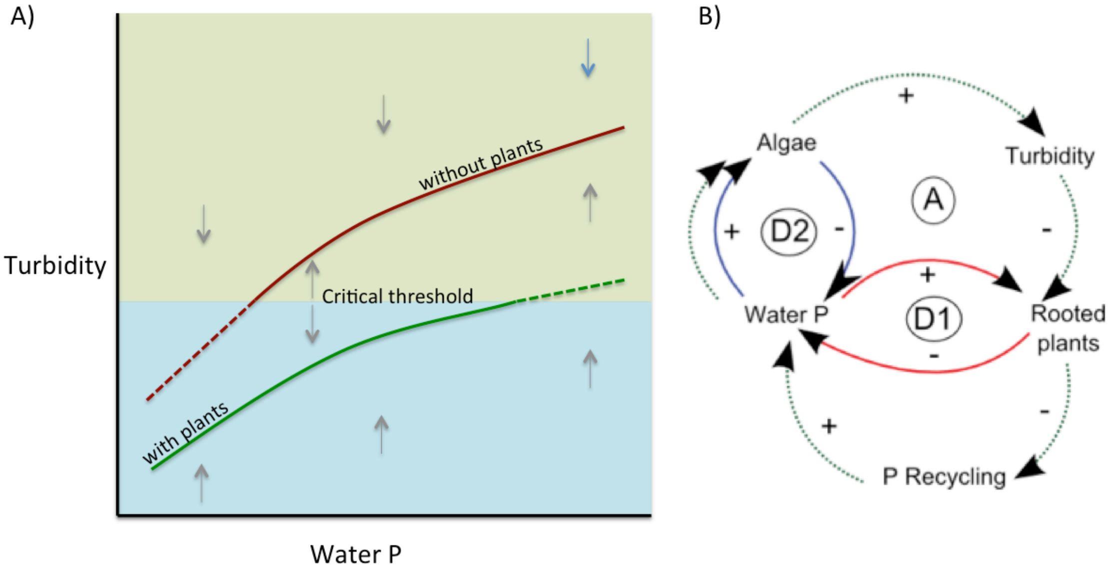

Figure 3. A) Changes in the strength and balance between competing feedback loops in a shallow lake shift the system from one domain of attraction to another (shown as the blue low nutrient and plant regime and green shaded turbid, no-plants regime). Adapted from Scheffer & van Nes 2007. B) The clear water regime is characterized by the dominance of feedback D1 (shown in red). As phosphorous levels increase, D1 weakens, and the amplifying feedback A (green) starts to dominate, driving the system into a eutrophic state limited by feedback D2 (blue). From Biggs et al. 2012.

How can regime shifts be detected?

Empirically identifying regime shifts is a challenging task that requires clearly defining the system and alternate regimes in terms of time, space, and focal variables. These definitions must match the spatial and temporal scales at which the underlying feedback mechanisms of the system in question operate. For instance, the appropriate spatial and temporal scale of the data required to identify regime shifts in coral reef ecosystems will differ if the focal variable is water chemistry as opposed to fish diversity. Similarly, identifying regime shifts in soil structure can be done using data that span only a few years and were collected at the field scale, while the scale of the processes underlying the shift from wet to dry savanna requires regional scale data that spans decades to centuries (Fig 4).

Identifying regime shifts in time series data can be done using a variety of statistical approaches. Sometimes regime shifts are identifiable from historical data by looking at jumps in the time series; however statistical techniques are required to test whether it is a significant shift in dynamics compared to previous fluctuations. Amongst the most common approaches used are chronological clustering, and sequential t-tests. Often principal component analysis is used to compresses time series of several related variables into a few uncorrelated synthetic time series for more systemic analysis.

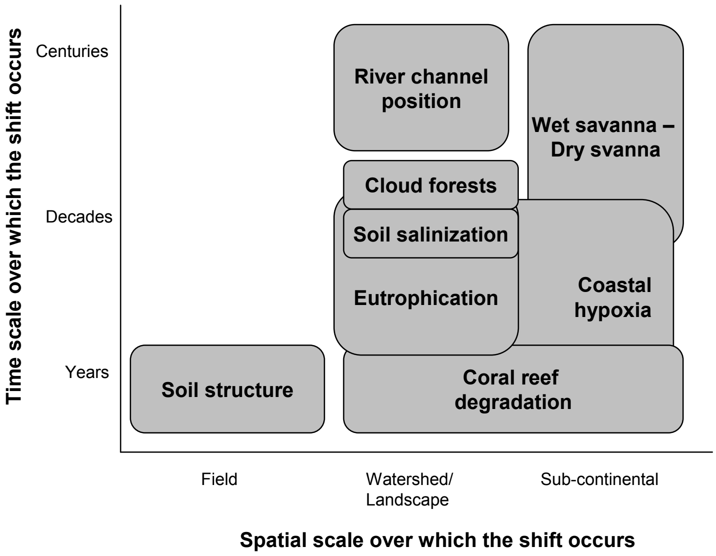

Figure 4. Regime shifts operate at different spatial and temporal scales. Identifying and defining regime shifts therefore requires i) deciding on the focal system variables of interest, and ii) data at appropriate spatial and temporal scales that capture the key processes underlying the focal system variables. From Biggs et al 2012.

Recent efforts have focused on early warning signals to allow the predict of possible future regime shifts[12]. These signals are based on changes in the statistical behaviour of a system as it approaches a regime shift. These approaches are based upon the idea that as a system approaches a critical threshold the feedback processes maintaining a regime become weaker. Based upon this idea researchers use statistics to detect signs of weakening of stabilizing feedbacks. Some of the statistical signatures that have been used are increased autocorrelation (temporal or spatial), as well as increased variability and changes in skewness[12].

How to manage regime shifts?

Managing regime shifts can involve either avoiding unintentional regime shifts, or reversing such shifts once they have occurred.

Enhancing resilience to avoid undesired regime shifts can be achieved in multiple ways[13]. From an ecological perspective, one important strategy is to maintain response diversity, that is species that perform more or less the same function in an ecosystem (e.g. nutrient fixation, or predation), but respond differently to disturbances or stresses (e.g. fire or climate variation). Response diversity is similarly an important strategy for building resilience to regime shifts in social and social-ecological systems. In these settings, diversity can take the form of economic diversity or livelihood diversity.

Spatial heterogeneity can also be important for building resilience to unwanted regime shifts. The influence of drivers and the strength of feedbacks is often not homogeneous across space, providing the opportunity to use spatial heterogeneity to reduce risk. For example, degraded coral reefs that have shifted to algae-dominated reefs can be recolonized by adjacent coral patches, provided there is sufficient connectivity. Similarly, where fishermen spread their fishing pressure across space and leave some areas protected or closed for recovery, fisheries are less likely to collapse.

In order to restore the system to a previous regime (or transform the system to an entirely new regime) one has to manage key drivers (usually slow variables), often needing to bring them to a point well below the critical tipping point at which the regime shift originally occurred (Figure 3). In addition, active management is usually needed to

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weaken the feedbacks that keep the system locked in the undesirable regime while strengthening the feedbacks that will provide stability in the desirable regime. Referring back to the example of eutrophication, lake management often requires reducing nutrient inputs to a level lower than that at which the system shifted to a eutrophic regime. This not only involves reduction of fertilizers use, but also means locking nutrients already present in the lake by using other substances such as iron to weaken the nutrient recycling feedback. Other options include bio-manipulation, that is, artificially increasing the abundance of species that will consume algae to avoid the likelihood of more algae blooms, or direct removal of sediments by dredging.

Glossary

Attractor A set of conditions towards which a dynamical system evolves over time. An attractor is often a point, but can also be a curve, a manifold, or a more complicated set with a fractal structure known as a strange attractor. Also known as an *equilibrium point*.

Critical threshold The point that separates two dynamic regimes. Also known as a *tipping point* or a *bifurcation*.

Regime The set of system states that lead to a particular attractor, or represent fluctuations around a specific attractor. Within this set of states the system self-organizes into a specific structure and behaves in essentially the same way. Also known as a *domain of attraction, basin of attraction* or *stable state.*

Feedback loop A set of cause-effect relationships that form a closed loop, so that a change in any particular element eventually feeds back to affect the element itself. Feedback loops can either be damping (also known as negative or balancing) or amplifying (also known as positive or reinforcing).

Hysteresis The tendency of a system to remain in the same state when conditions change due to lag effects and system memory. As a consequence the critical threshold for a forward shift from Regime A to B often differs from the critical threshold for a return shift from Regime B to A.

Regime shift A large, abrupt, persistent change in the structure and function of a system that occurs when a critical threshold is crossed and the system shifts from one dynamic regime to another. Also known as a *critical transition* or a *phase shift.*

Resilience The magnitude of change or disturbance that a system can tolerate before undergoing a shift to an alternate regime.

System state The condition of a system at a particular point in time, described in terms of specific variables such as pH or population size.

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