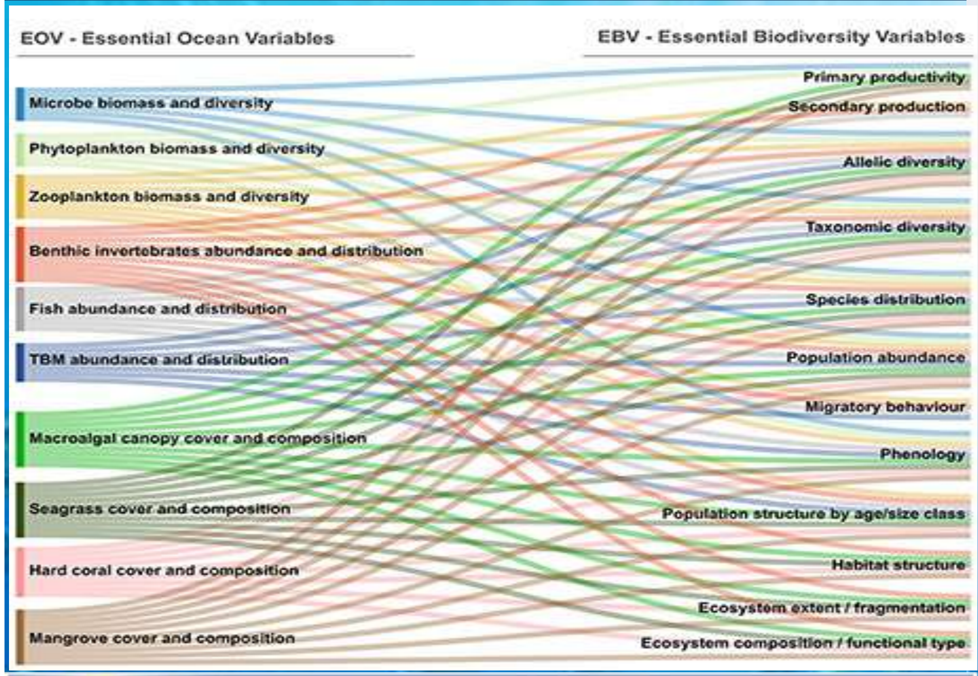
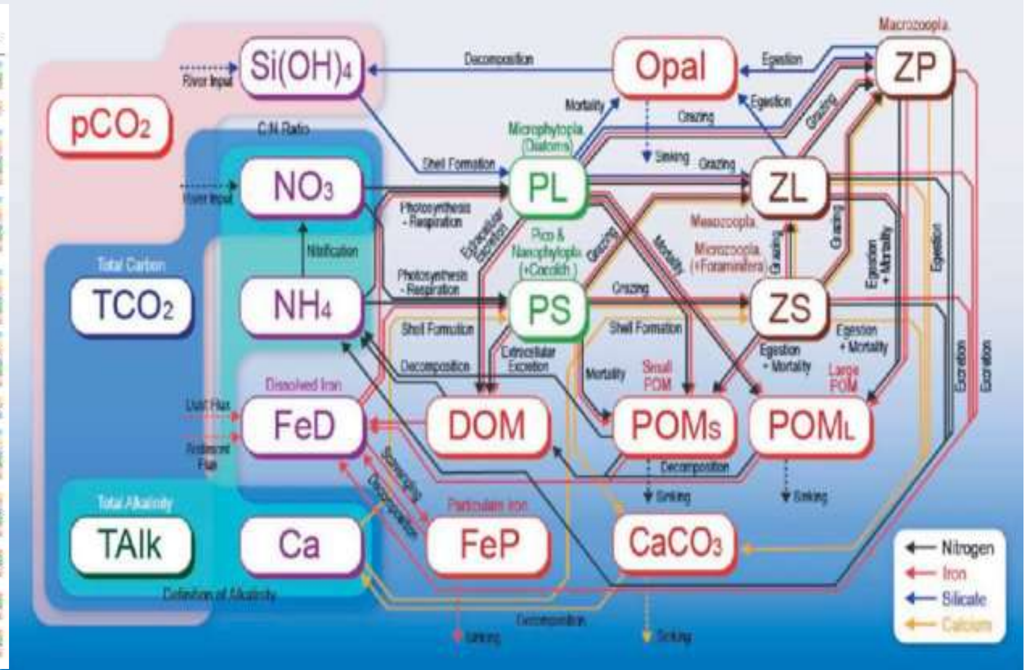
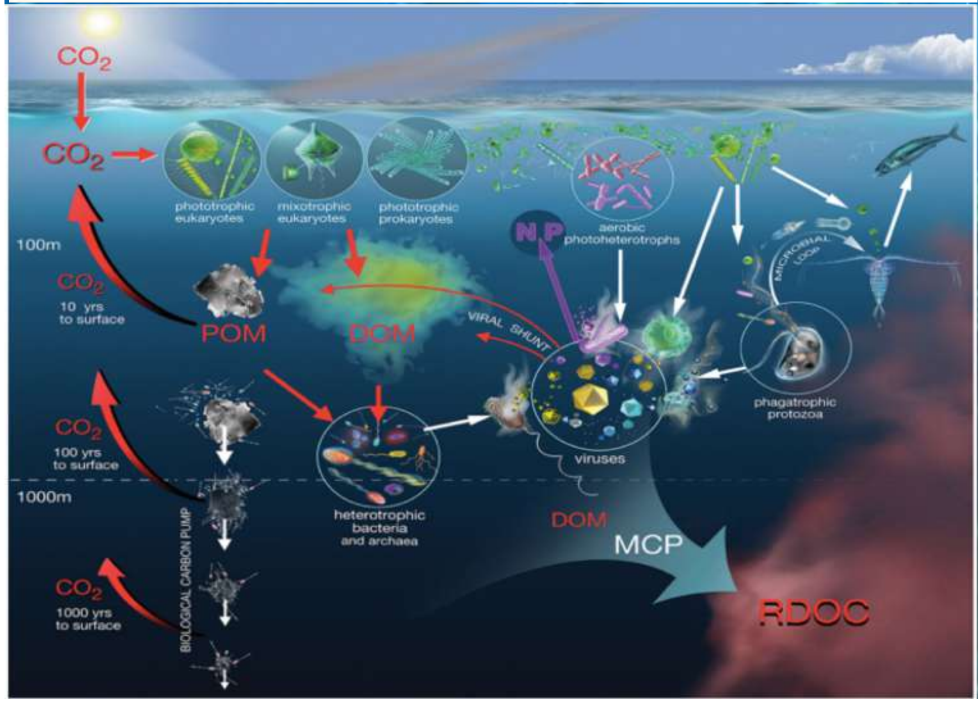
Ecosystem complexity

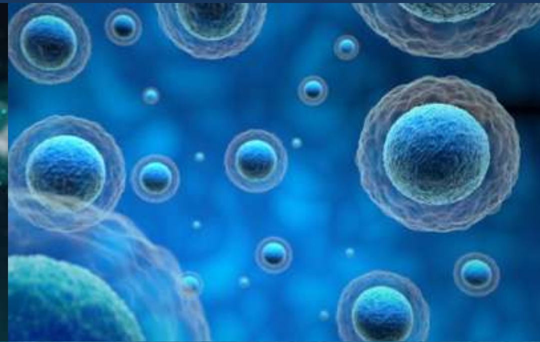




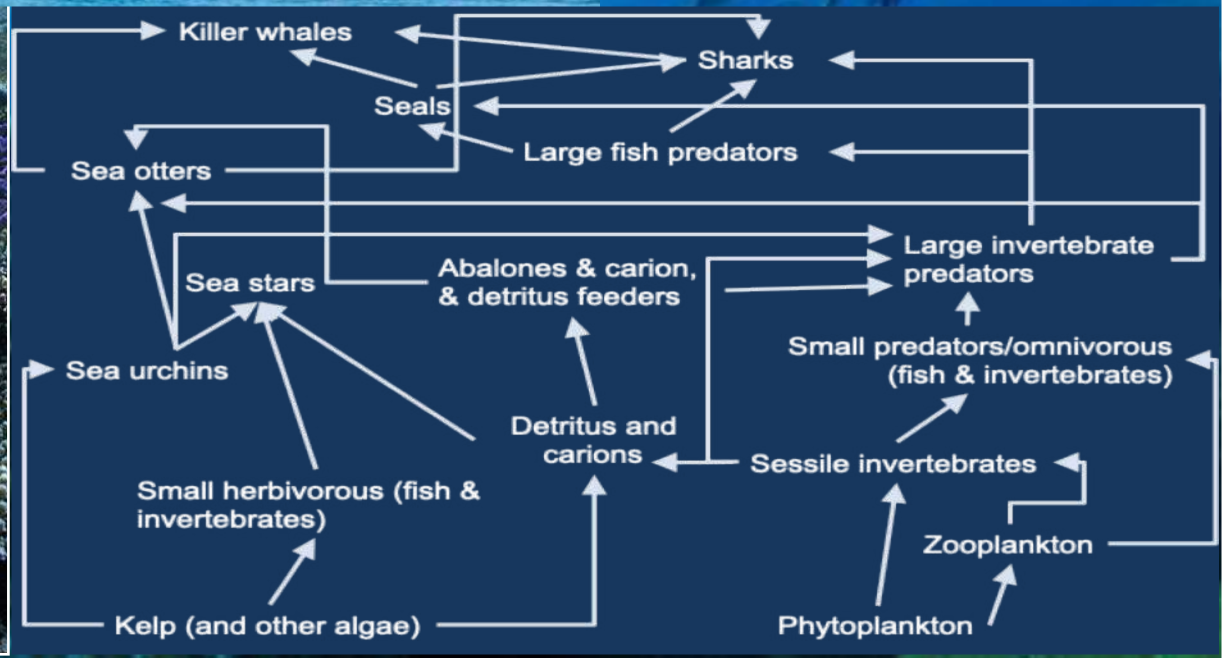


Ecosystems are complex. This stems from the huge number of components (abiotic and biological) and their respective interactions (predation, competition, parasitism, trophic relations, cycling of organic and inorganic matter, decomposition, and many others). Complexity is so high that generate emergent properties. These properties allow ecosystems to self-sustaining, self regulating, and self-repairing.

Emergent properties



The whole is more than the sum of components



Ecosystem state(s)

Attractor—The dynamic regime to which a system converges under constant environmental condition.

Alternative stable states—The different attractors to which a system may converge. Also known as alternative dynamic regimes or alternative attractors.

Critical threshold—The point at which the qualitative behaviour of a system changes. It is usually associated with the shift between two alternative dynamic regimes. Also known as tipping point or bifurcation.

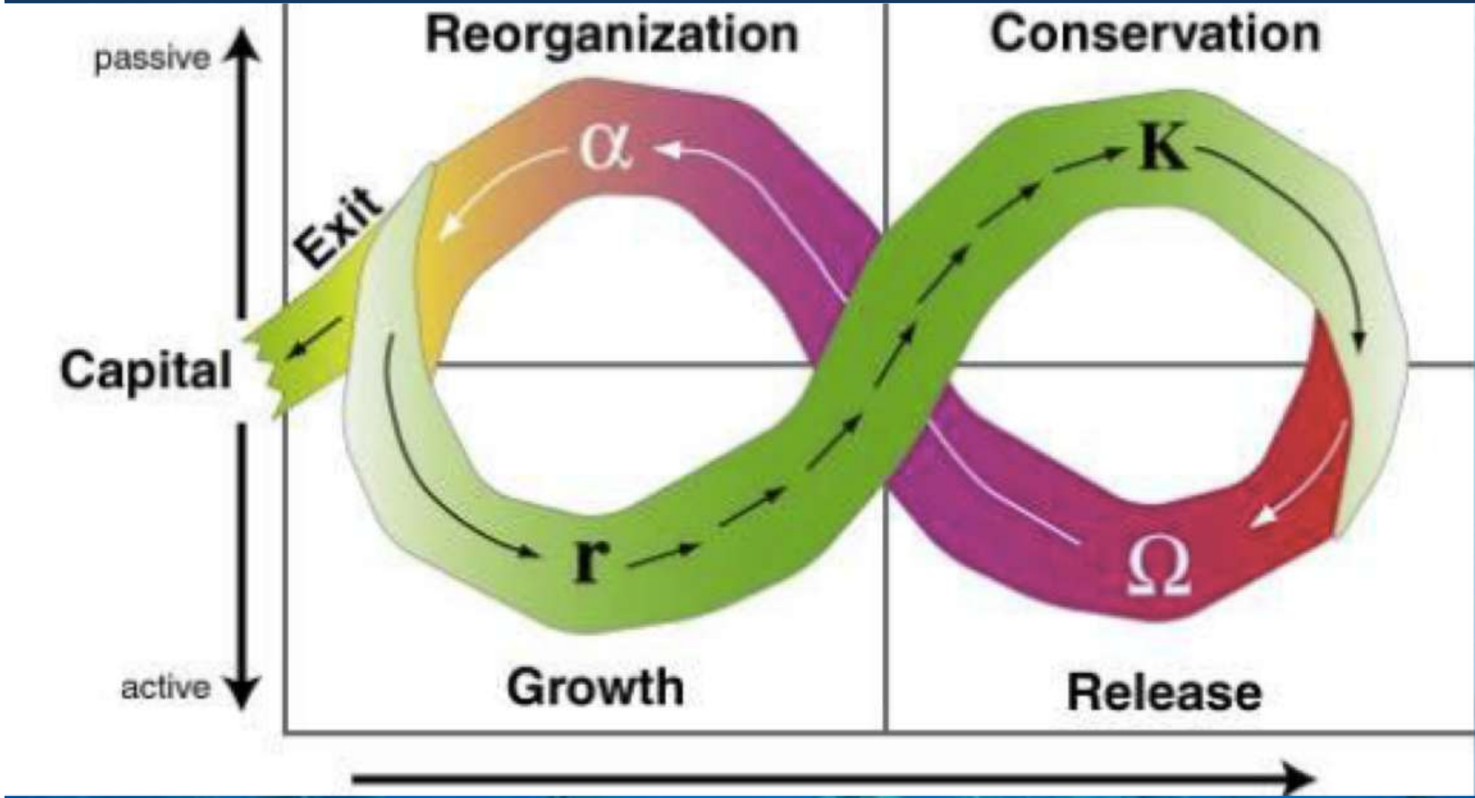
Resilience, resistance, persistence

RESISTANCE: One of the components of resilience—a measure of difficulty in moving a system within a basin of attraction (Walker et al. 2004); the ability of an ecosystem to resist displacement from its reference state during a perturbation stress

RECOVERY: The capacity of a system return to previous conditions after being perturbed

RESILIENCE: The capacity of a system to absorb disturbance and reorganize while undergoing change so as to maintain essentially the same functions, structure, identity and feedbacks

Cycle of Holling



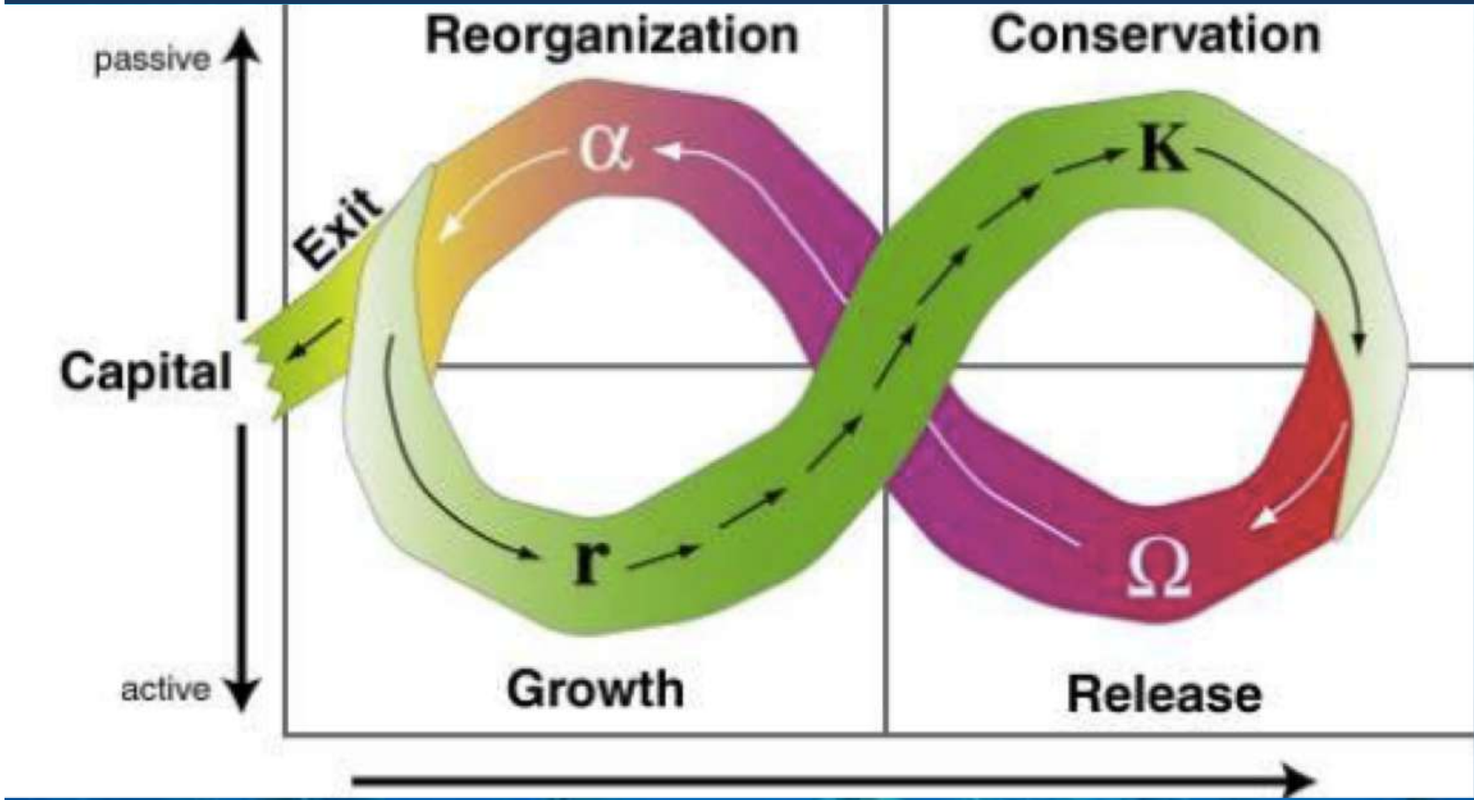
Gunderson e Holling, 2002

connectivity

Adaptative cycle within the stability domain (basin of attaction) of a given system

1. **Growth phase**
2. **Conservation phase**
3. **Release phase**
4. **Reorganization phase**

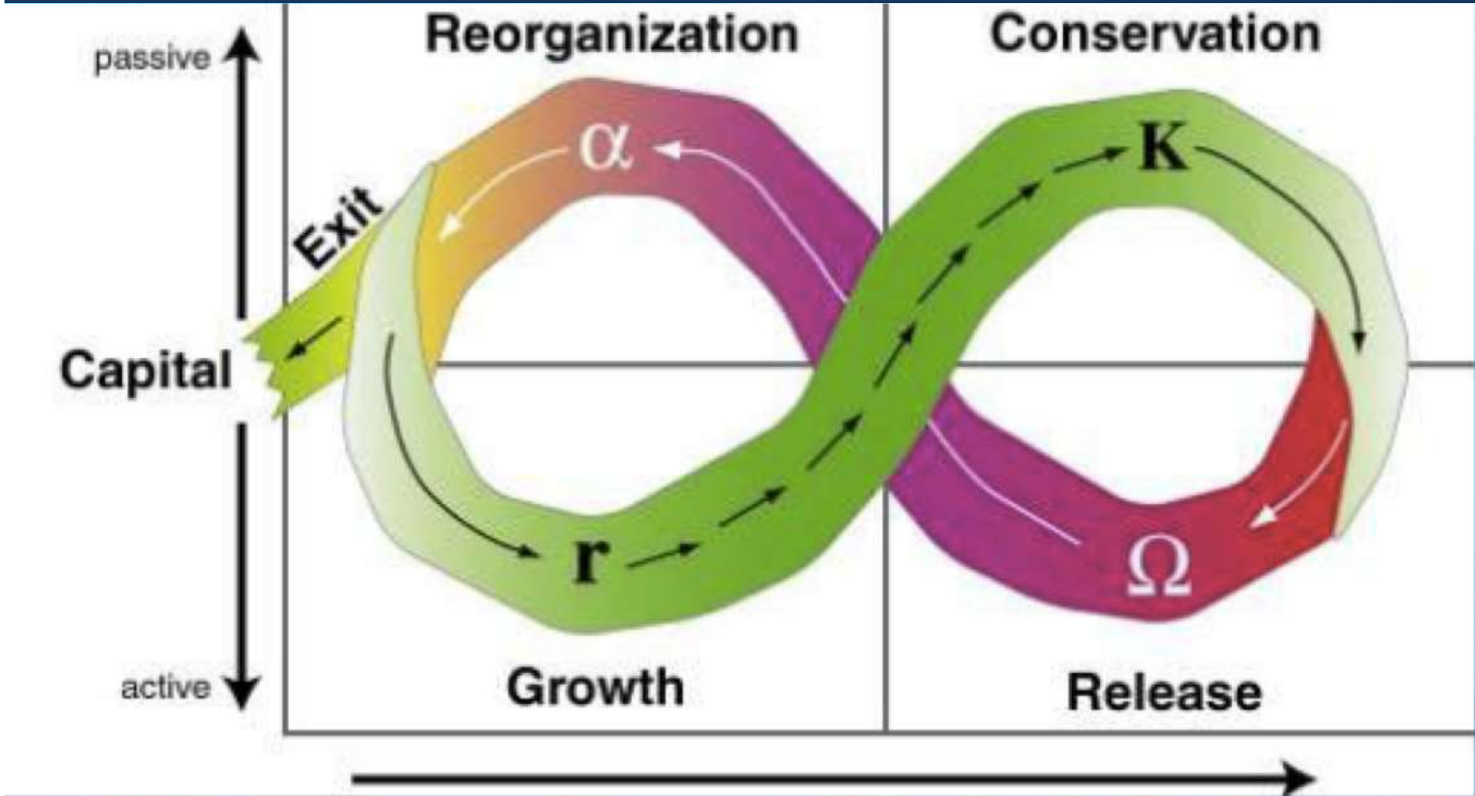
Growth



connectivity

Rapid growth with r species, resources are available and not capitalized. Connection among species are limited. This is the phase in which the system is forming and structuring.

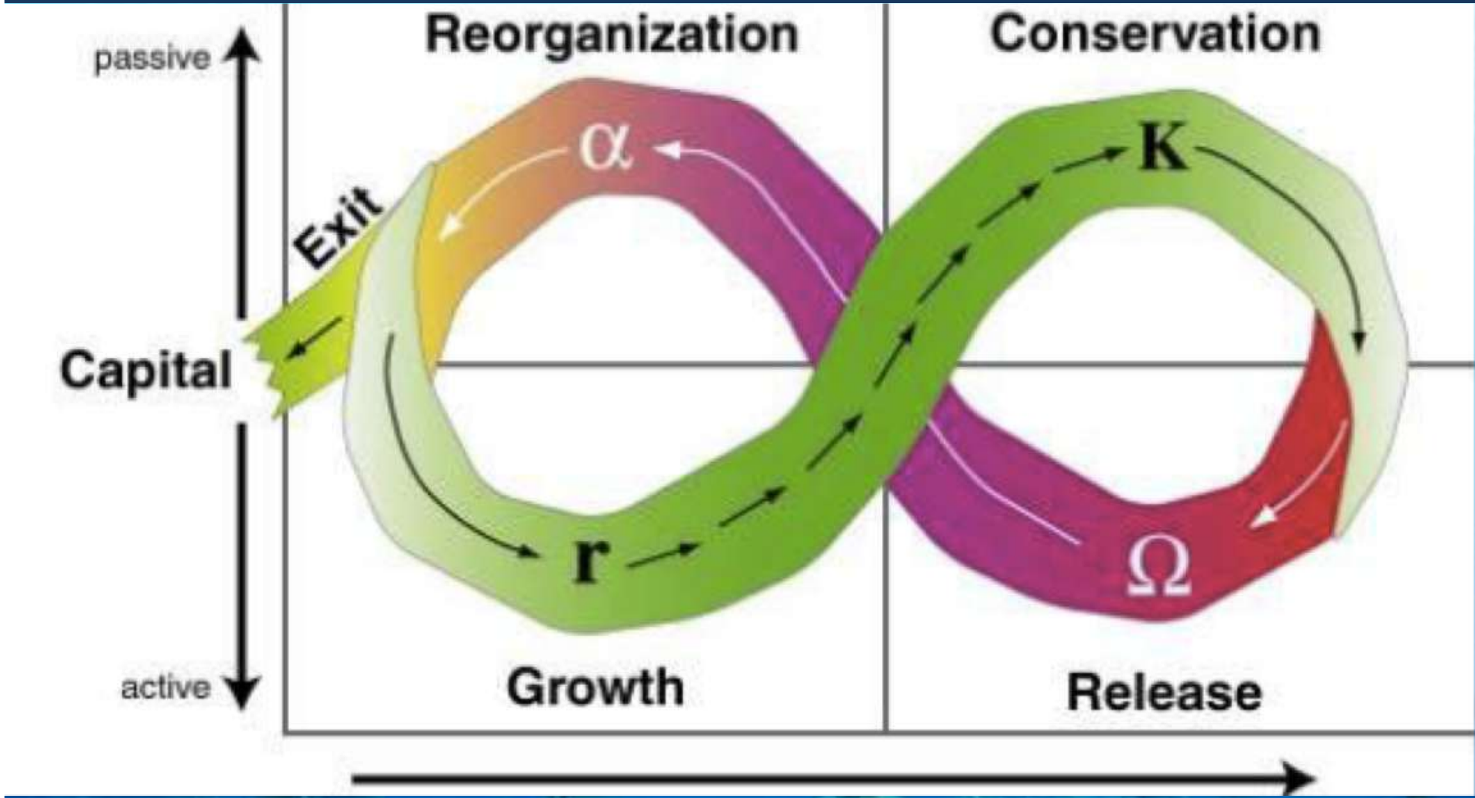
Conservation



connectivity

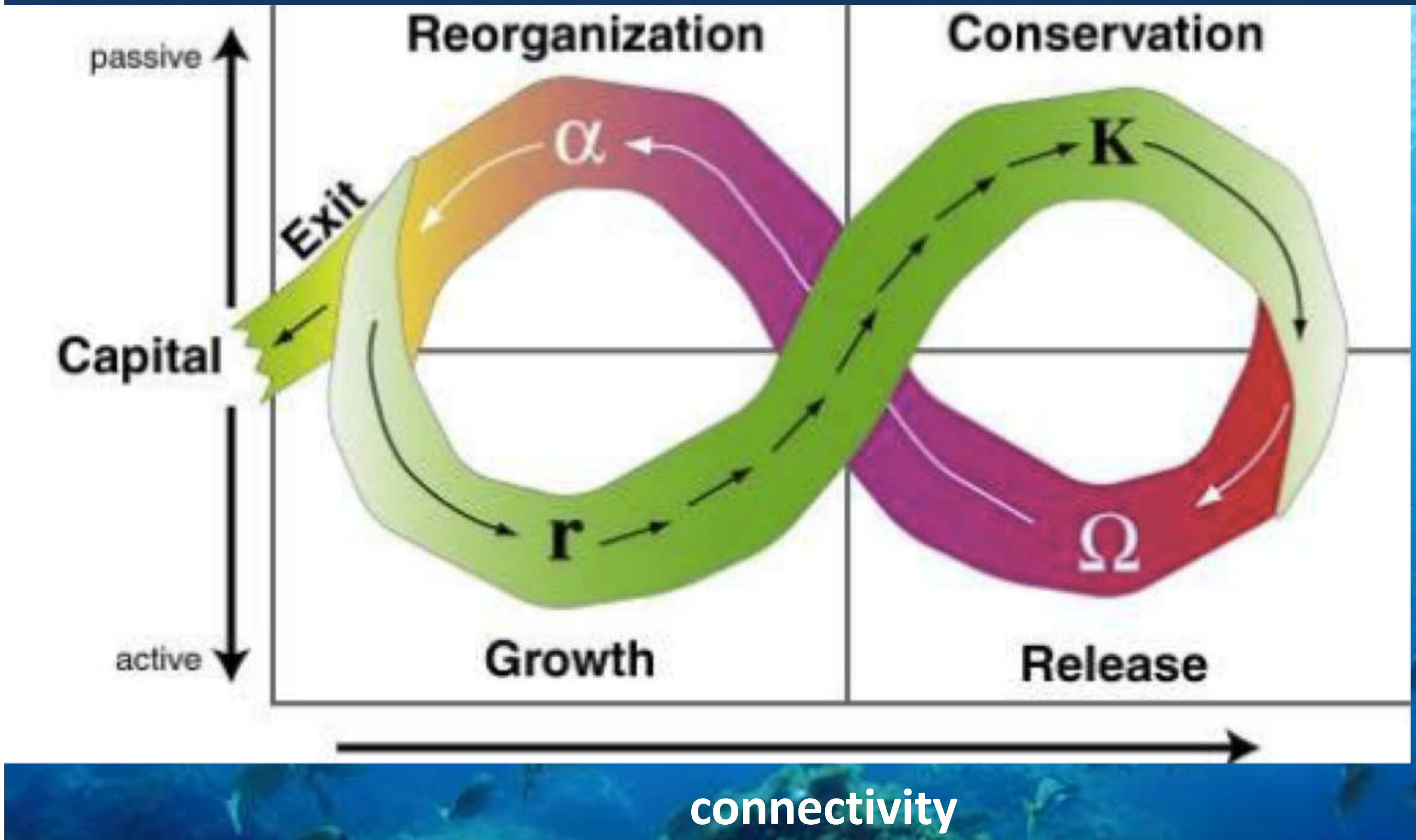
Period of conservative status, with k species. Resources are capitalized, and connections among species are strong and structured. Specialization and conservation of functions.

Release



Following a perturbation the system is destabilized, resources are released and available. Connections start to break eventually

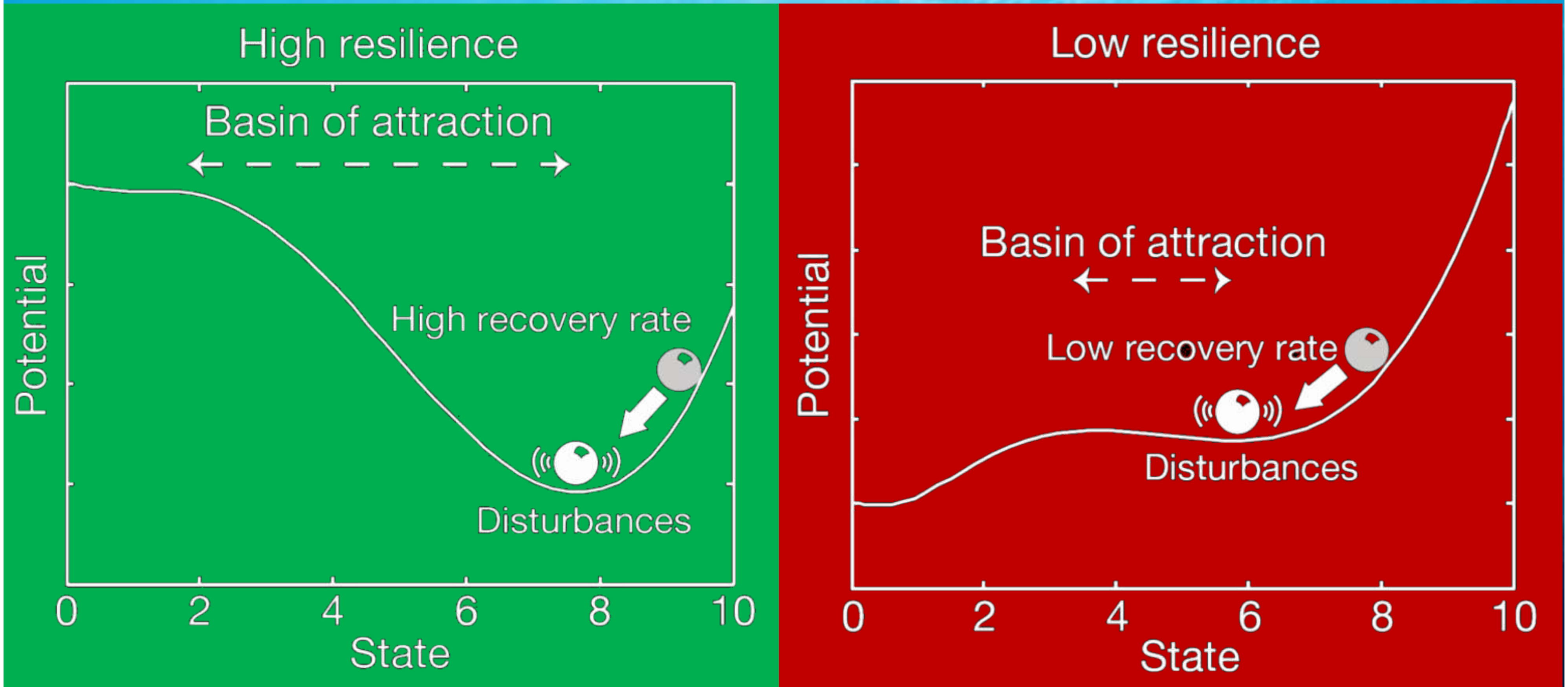
Reorganization



Resources are available for reorganizing the system, to restablish the original structure and connections passing by a new growth phase…or shifitng towards a different regime

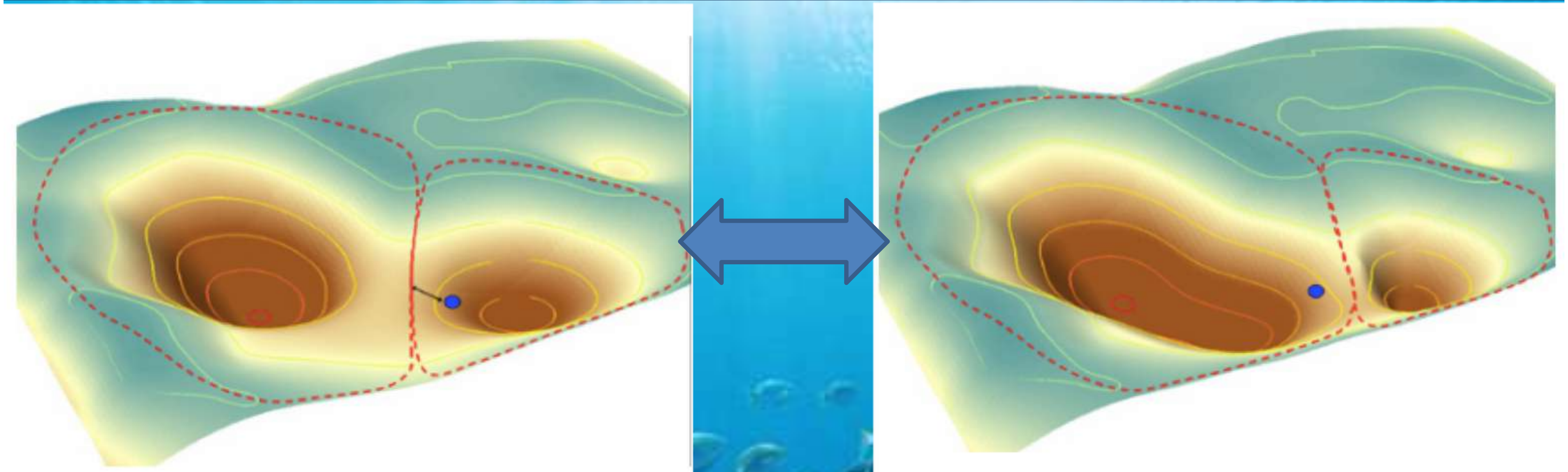
Ecosystem stability

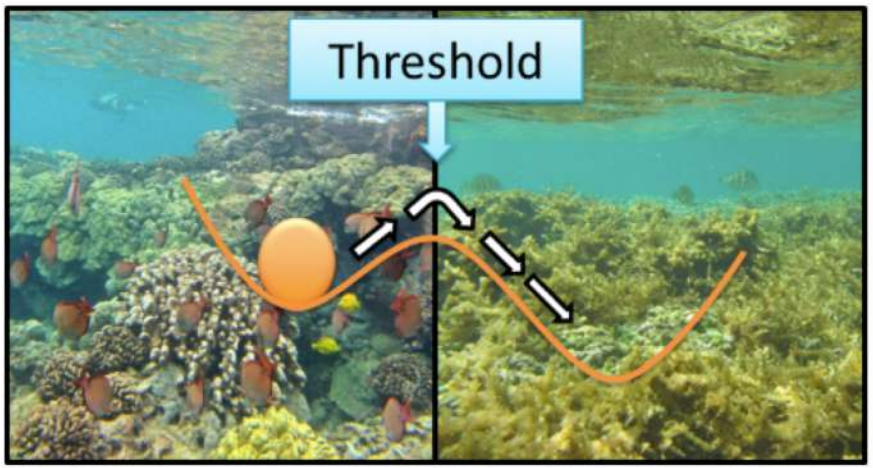
Modified from Scheffer et al., 2009



Decreasing stability

Phase shifts





Changes in landscape of conditions and basins of attraction (enlargement, reduction) as a consequence of resilience erosion, smoothing thresholds

Phase shifts

Box 1. Definitions

Ecological regime shift—Dramatic, abrupt changes in the community structure, encompassing multiple variables, and including key structural species (*definition from this Theme Issue*) (figure 1). Note that the term *regime shift* is synonymous with *phase shift*, the former being used prevalently in open ocean systems, the latter in spatially fixed systems such as reefs. Also termed *state shifts* or *ecosystem reorganizations*. Regime shifts that involve the crossing of a tipping point and pertain to systems with alternative states are also called *critical transitions*.

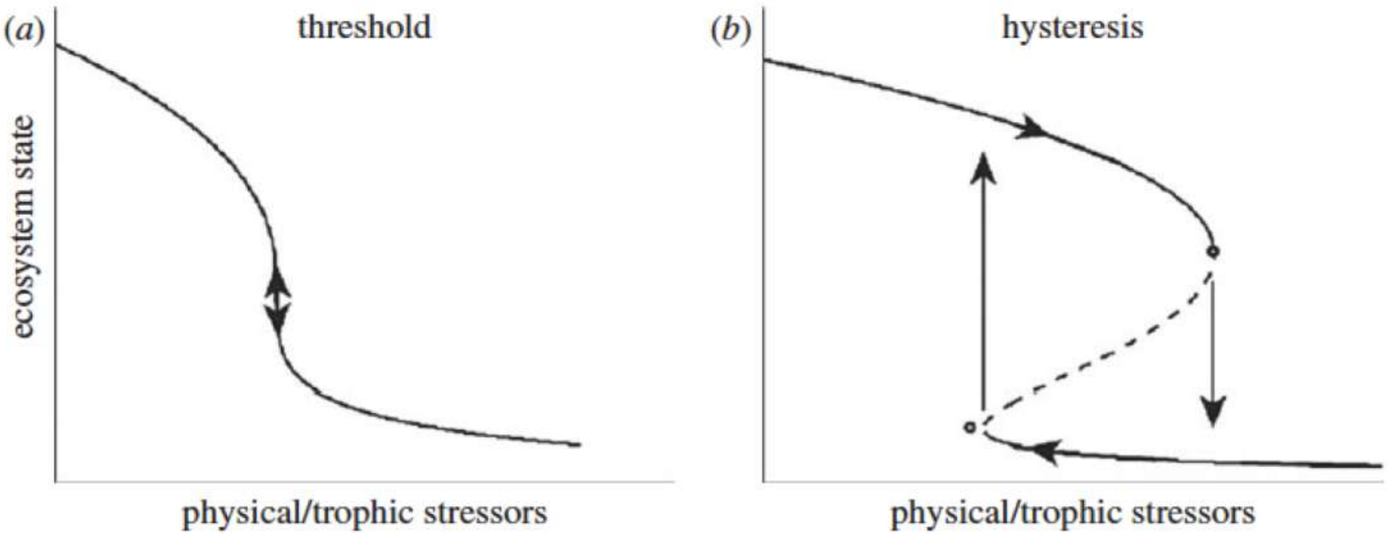
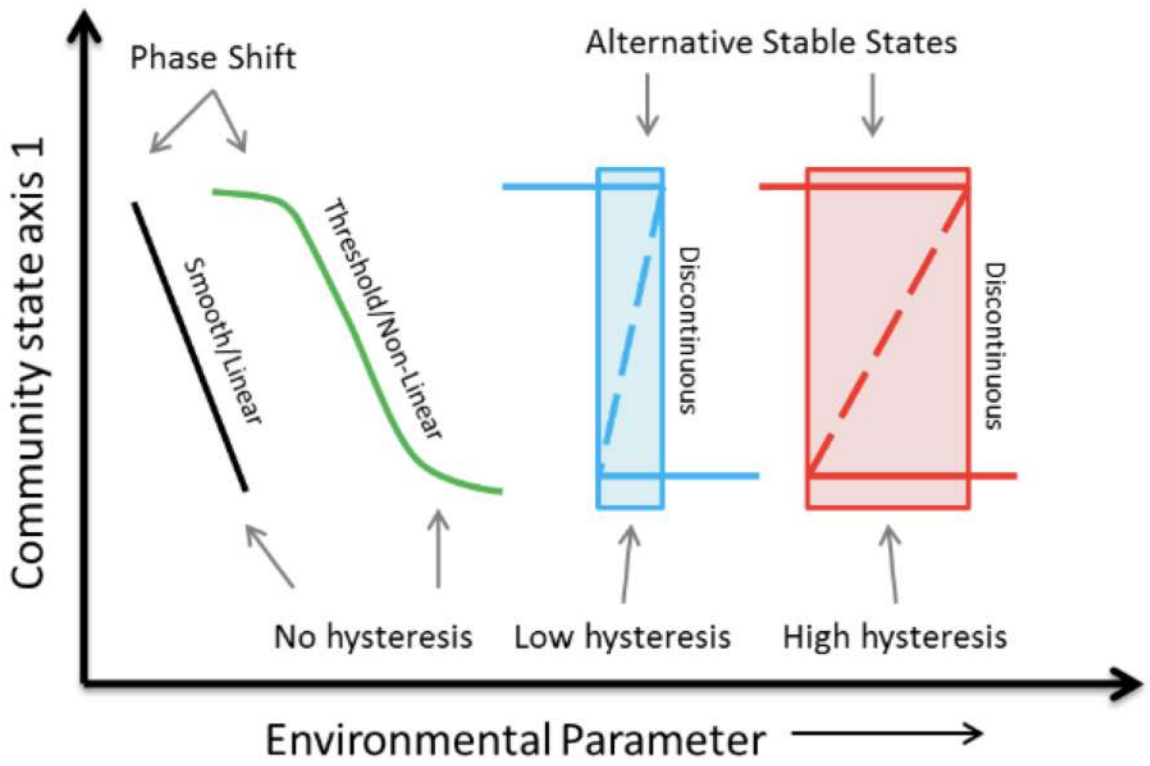


Figure 1. Examples of regime shift. Two different responses are shown, one without (*a*), and the other with hysteresis (*b*), both of which are encompassed by our working definition of regime shifts (adapted from [5]).

Regime and phase shifts – tipping point/bifurcations/critical transitions

Phase shifts



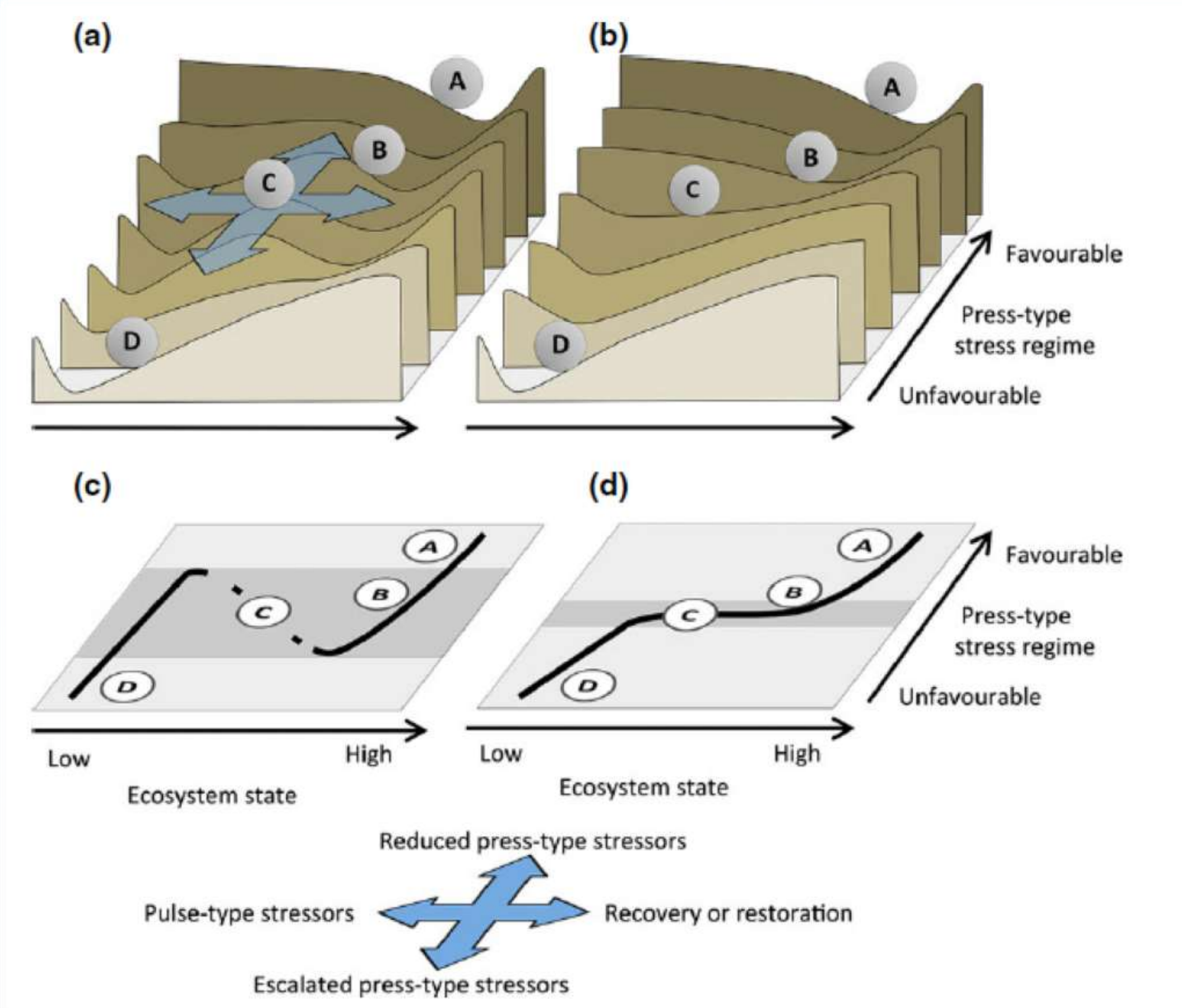
Smooth or Linear- characterized by a linear or nearly linear relationship between the stressor (e.g. fishing effort) and the ecosystem state (e.g. fish abundance) variables

Non-linear- characterized by a non-linear relationship between conditions and the ecosystem state variables. The rate of change in ecosystem state speeds up when crossing the threshold between regimes

Hysteretic or Discontinuous- characterized by a non-linear relationship with hysteresis – in which the path from state A to B (degradation) is different from the path from B to A (recovery) and may be very hard to reverse. For a given range of conditions two or more state are possible

Ecosystem phase shifts: a conceptual model

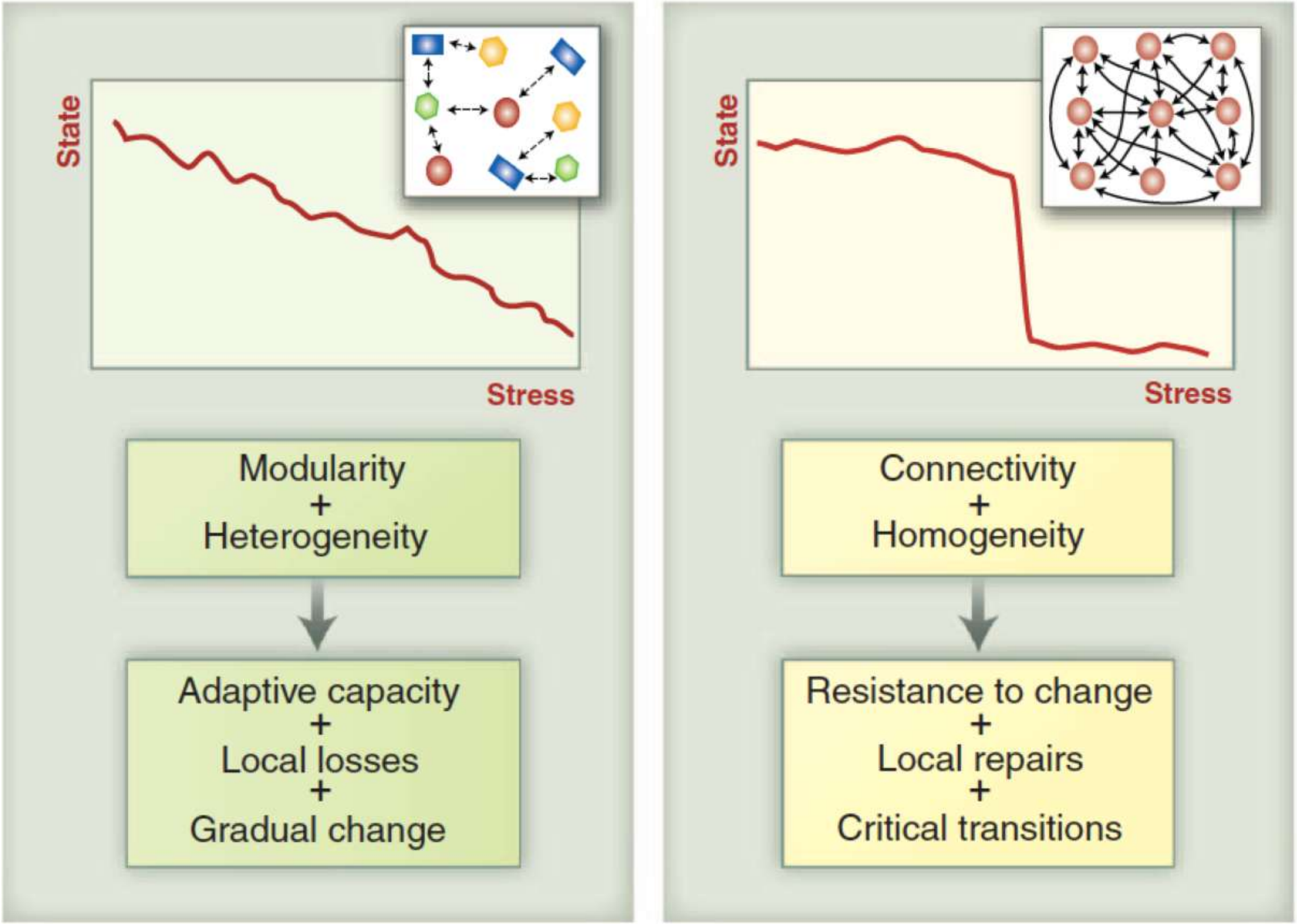
Two stable states are possible. Normally, the ‘good state’ is A. Increasing deterioration leads to fragile equilibrium where even a relative minor perturbation could cause a shift



As the case on the left. However, no bifurcation. The system gradually change from A to the worse state

Anthony et al., 2015

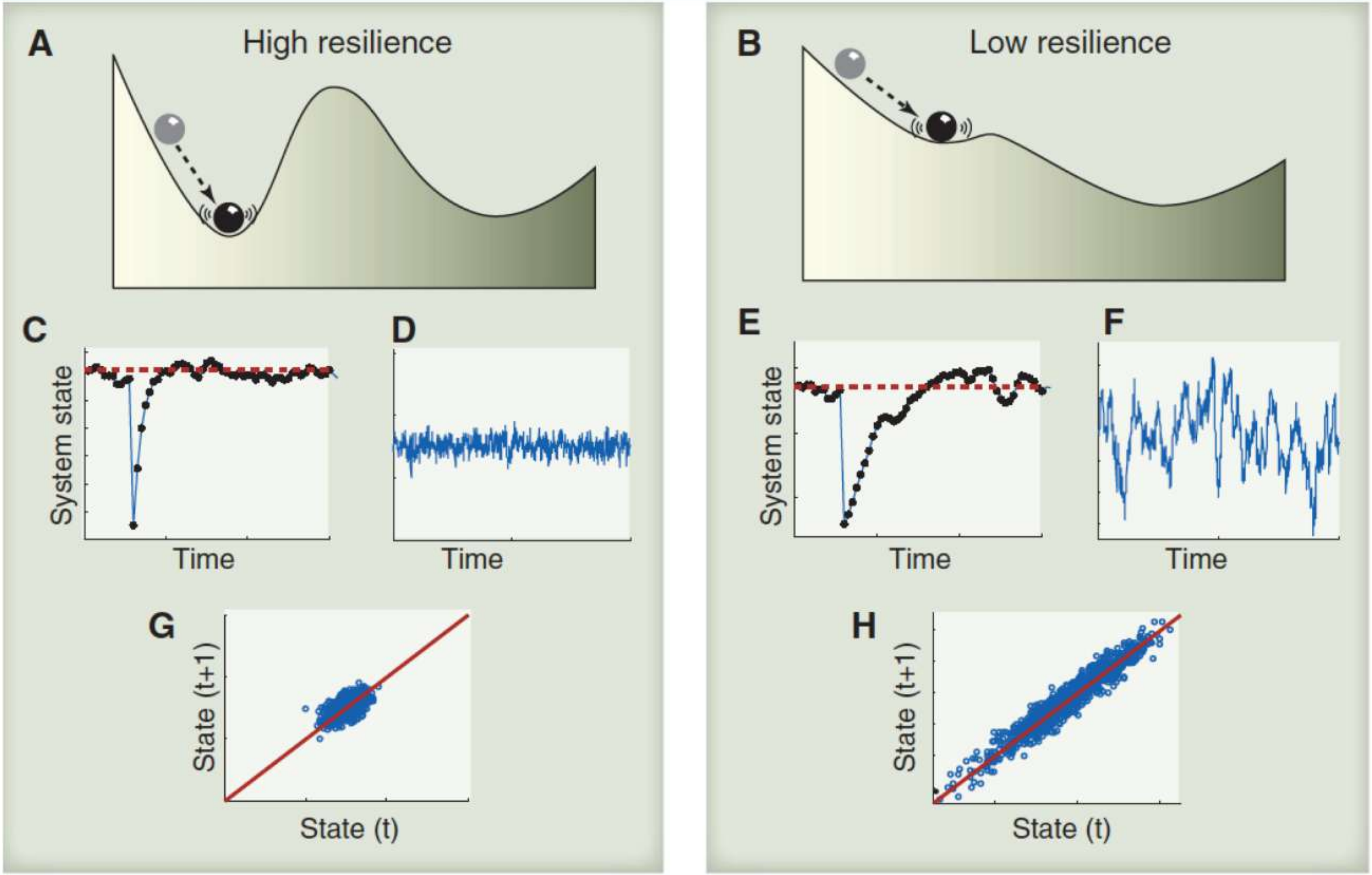
Architecture of fragility



The connectivity and homogeneity of the units affect the way in which distributed systems with local alternative states respond to changing conditions. Networks in which the components differ (are heterogeneous) and where incomplete connectivity causes modularity tend to have adaptive capacity in that they adjust gradually to change.

By contrast, in highly connected networks, local losses tend to be "repaired" by subsidiary inputs from linked units until at a critical stress level the system collapses.

Signals of potential transition



Scheffer et al 2012

Slowing down recovery **Autocorrelation** **Increased variance**

Flickering between alternative states

Shifts and drivers

regime shift name	key drivers	ecosystem services impacted
Arctic sea ice	atmospheric CO_2	water cycling
	global warming	biodiversity
	greenhouse gases	fisheries
	temperature	wild animal and plant foods
		climate regulation
		water purification
		water regulation
		aesthetic values
		knowledge and educational values
		spiritual and religious

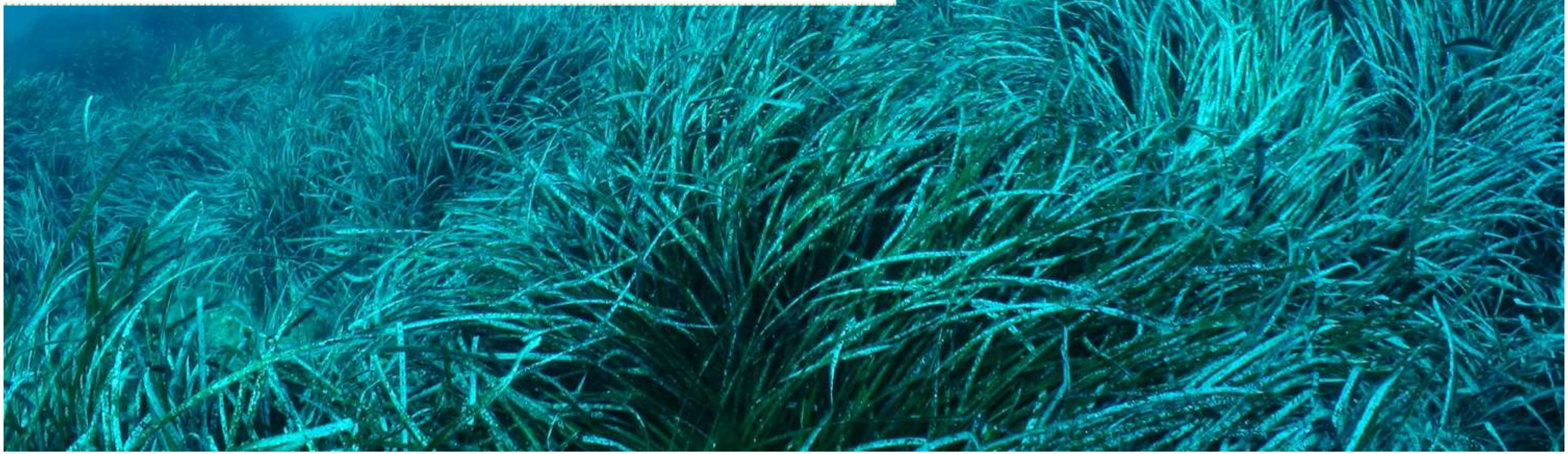
Shifts and drivers

regime shift name	key drivers	ecosystem services impacted
mangroves transitions	agriculture	soil formation
	aquaculture	water cycling
	atmospheric CO_2	biodiversity
	deforestation	fisheries
	droughts	wild animal and plant foods
	erosion	timber
	floods	wood fuel
	global warming	climate regulation
	hurricanes	water purification
	infrastructure development	regulation of soil erosion
	irrigation infrastructure	natural hazard regulation
	landscape fragmentation	aesthetic values
	ocean acidification	
	rainfall variability	
	sea-level rise	
	sea surface temperature	
	sediments	
	sewage	
	temperature	
	urbanization	

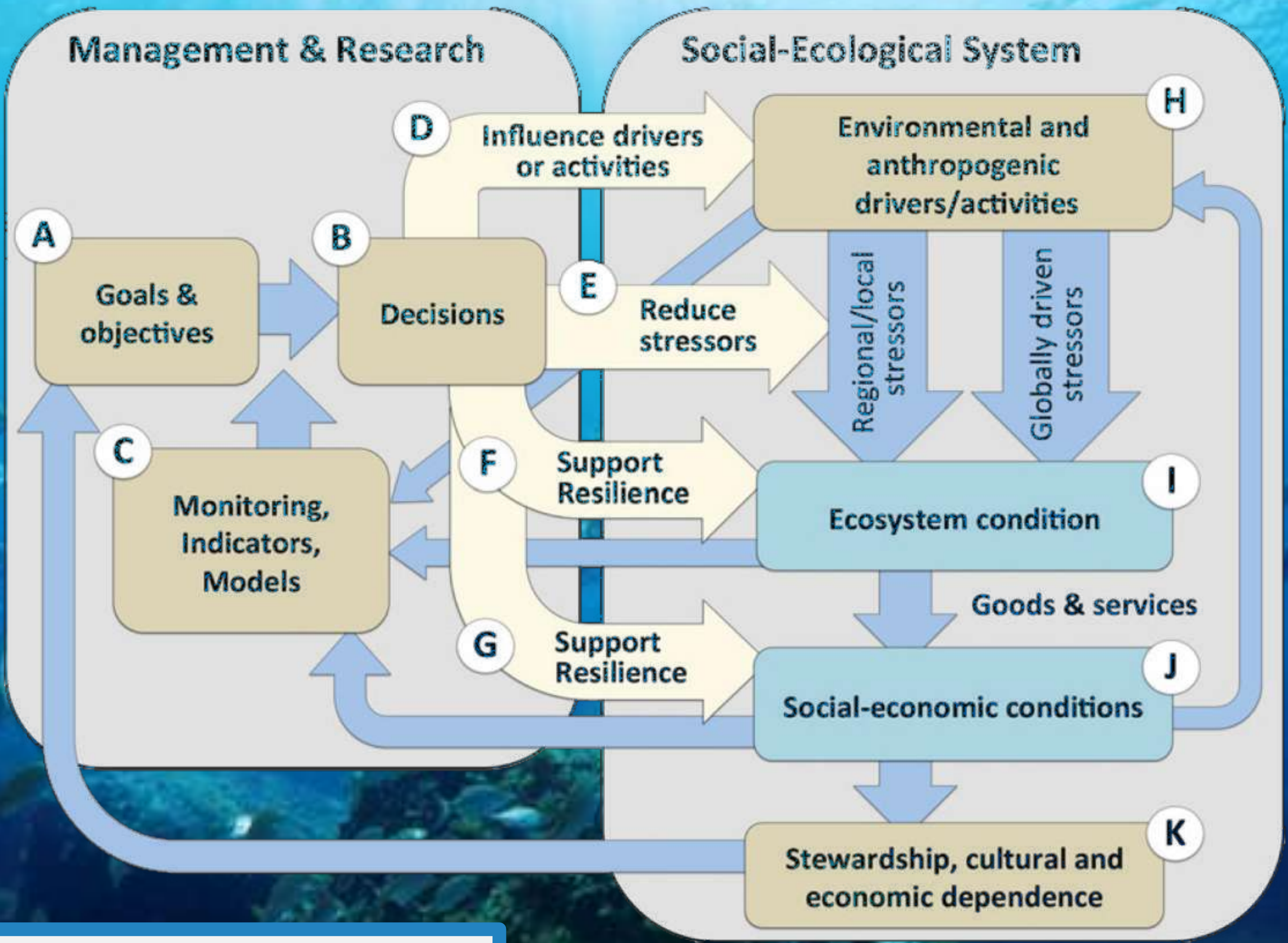
Rocha et al. 2015

Shifts and drivers

key drivers	ecosystem services impacted
atmospheric CO_2	primary production
deforestation	nutrient cycling
disease	biodiversity
fishing	fisheries
infrastructure development	wild animal and plant foods
nutrient input	climate regulation
rainfall variability	water purification
sea-level rise	regulation of soil erosion
sediments	natural hazard regulation
sewage	recreation
temperature	aesthetic values
urbanization	



Management



Reduce anthropogenic stressors

Support system's resilience

Monitoring the state of systems

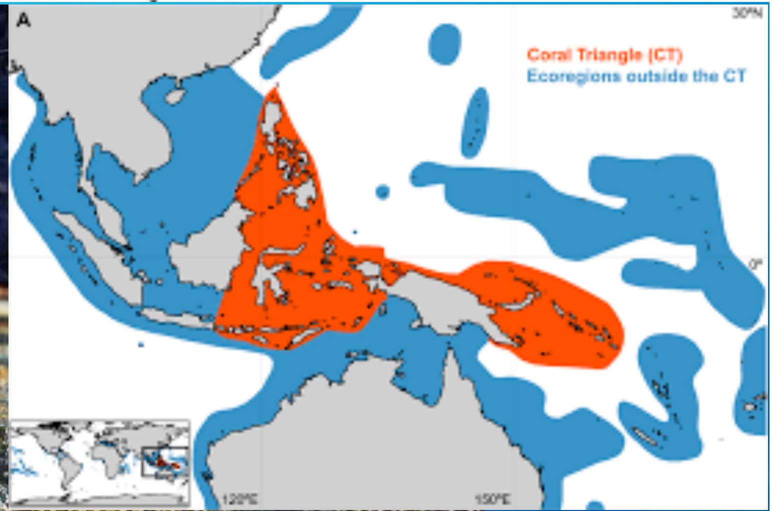
Anthony et al., 2015

Management

Example	D: Influence drivers and/or activities	E: Reduce stressors	F: Support ecosystem resilience	G: Support social-economic resilience
Great Barrier Reef	Influence national emissions policies through education and awareness-raising around climate change and linkages between land use and run-off	Improve land-use management to reduce pollution in receiving waters; maintained fisheries management	Networks of no-take areas (spatial planning for connectivity and population viability of key species); control CoTS at local scales	Work with fishers and tourism operators to help build resilience in their industries

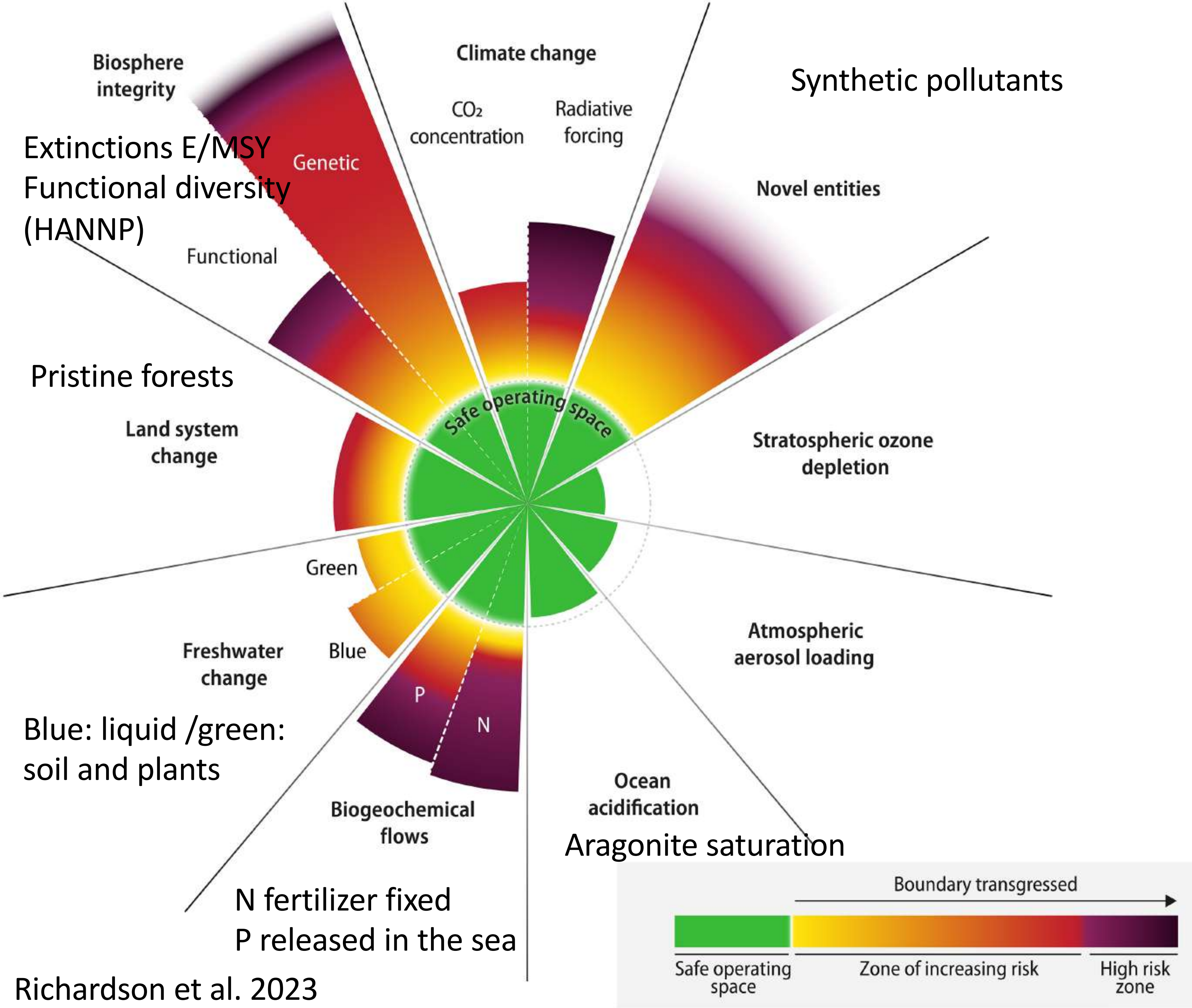
Management

Coral Triangle	Education of local communities and regional government bodies	Reduce fishing of herbivores; stop destructive fishing practices; reduce pollution	Networks of no-take areas (spatial planning for connectivity and population viability)	Capacity-building of local communities and regional government bodies, support alternative livelihoods



Management

Florida Reef System	Education and awareness-raising around climate change and linkages between land use and land run-off	Reduce nutrient and sediment loads; reduce fishing pressure; manage pressures from recreational use	Coral and reef habitat restoration in combination with networks of no-take areas	Work with local communities and the tourism industry to develop adaptation strategies including livelihood transitioning



Synthetic pollutants

Extinctions E/MSY
Functional diversity
(HANNP)

Pristine forests

Blue: liquid /green: soil and plants

Aragonite saturation

N fertilizer fixed
P released in the sea

Richardson et al. 2023

Final remarks

Complex systems are difficult to understand, and even more difficult to project. Previsions are largely uncertain.
Ecosystem can be assumed as chaotic systems, so their dynamics are extremely sensitive to initial conditions and unpredictable on the long run. There are too many variables… (Theory of chaos)

Could we manage to predict trajectories of ecosystems? Or it could be easier to reduce our pressure?