Untangling ecological complexity: “ecological resilience” as a jigsaw piece.

LUCZAK Christophe [1, 2], ROLET Céline [2, 3], SPILMONT Nicolas [2, 3, 4], SEURONT Laurent [2, 5, 6]

[1] Université d’Artois, IUFM, Centre de Gravelines, 40 rue V. Hugo - BP 129, 59820 Gravelines, France
[2] CNRS, UMR 8187 LOG, Station Marine, 28 avenue Foch, BP80, F-62930 Wimereux, France
[3] Université Lille 1, Station Marine, Laboratoire d’Océanologie et de Géosciences – UMR 8187 LOG, 28 avenue Foch, BP80, F-62930 Wimereux, France
[4] Environmental Futures Centre and School of Environment, Griffith University, Gold Coast Campus, QLD 4222, Australia
[5] School of biological Sciences, Flinders University, Adelaide, SA5001, Australia
[6] South Australian Research and Development Institute, Aquatic Sciences, West Beach, SA5022, Australia

This work was partly supported by MACROFONE Project n°CC00010R-R8RA (FRB/Région Nord-Pas-de-Calais).

Even *a priori* « simple » sandy shores are Complex Adaptive Systems - (© C. Luczak)

SETTING THE SCENE

Marine ecosystems are complex adaptive systems (CAS) (Levin, 1999) in which macroscopic dynamics emerge from numerous nonlinear interactions over multiple spatial and temporal scales in a hierarchical structure. Complex interactions and feedbacks involves both abiotic and biotic processes over multiple spatial and temporal scales. Capturing the inherent complexity of marine systems remains a major challenge in ecosystem-based management plans. Often, the observed state of these dynamic systems under pressure will initially show little obvious change until a critical threshold is reached at which point a sudden shift to a contrasting dynamical regime takes place (Beaugrand *et al*., 2008). Hirota *et al* (2011) concluded that determining the resilience of complex systems to critical transitions remains one of the most challenging problems in environmental science today.

The resilience approach emphasizes non-linear dynamics, thresholds, uncertainty and surprise, how periods of gradual change interplay with periods of rapid change and how such dynamics interact across temporal and spatial scales. Thus resilience appears to be a good candidate to capture part of the ecological complexity simply, but not simpler.

INTERACTIVE INTERLUDE: WHAT’S YOUR DEFINITION OF RESILIENCE?

Before going any further, ask yourself what is your definition of resilience. We bet with a high probability of winning that your definition is very close to: “*resilience is the speed or time of return of an ecological system to equilibrium/or initial position following a disturbance*”. This is the widely used definition, but also the narrow one.

PROVIDING A DEFINITION OF RESILIENCE CONSISTENT WITH A « TANGLED BANK »

Part I: ENGINEERING RESILIENCE.

Darwin (1859) used the metaphor of a « tangled bank » to describe the complex interactions between species. A clear definition of resilience consistent with Complex Adaptive Systems is required and essential to go further.

Holling (1973), in his seminal paper, defined ecosystem resilience as the magnitude of disturbance that a system can experience before it shifts into a different state with different control on structure and function. However resilience is often defined as the speed or time of return of an ecological system to an equilibrium following a disturbance (see “interactive interlude” above). This latter definition, also outlined by Holling (1973) ignores the presence of alternatives (transients) states. An equilibrium-focused view is attractive to humans, but it fails to capture the behaviour of CAS. This equilibrium-centred view is indeed static and provides little insight into the transient behaviour of dissipative complex systems always far from any equilibrium (Frontier *et al*., 2008; Hastings, 2001). Even undisturbed ecosystems are likely to be continually in a transient state.

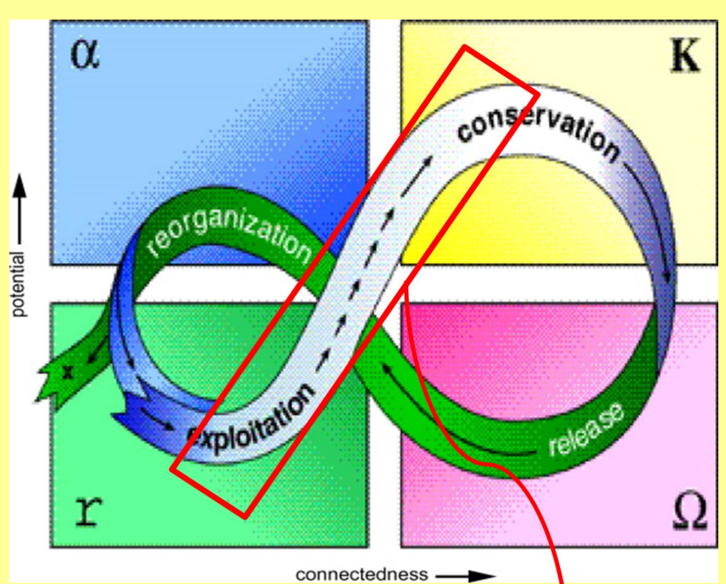
Holling (1996) explicitly contrasted the two definitions of resilience, which he described as ***engineering resilience*** and ***ecological resilience***. Engineering resilience focuses on equilibrium states and stability and is simply measured as the return time following a disturbance. He pointed out that engineering resilience is a less appropriate measure in ecosystem with multiple “stable state”. This definition based on return time implicitly assumes that there is only one equilibrium state. Scientists holding this view tend to apply theory (influenced by an engineering and applied mathematical tradition) to practice rather than to develop theory empirically as part of practices.

Part II: ECOLOGICAL RESILIENCE.

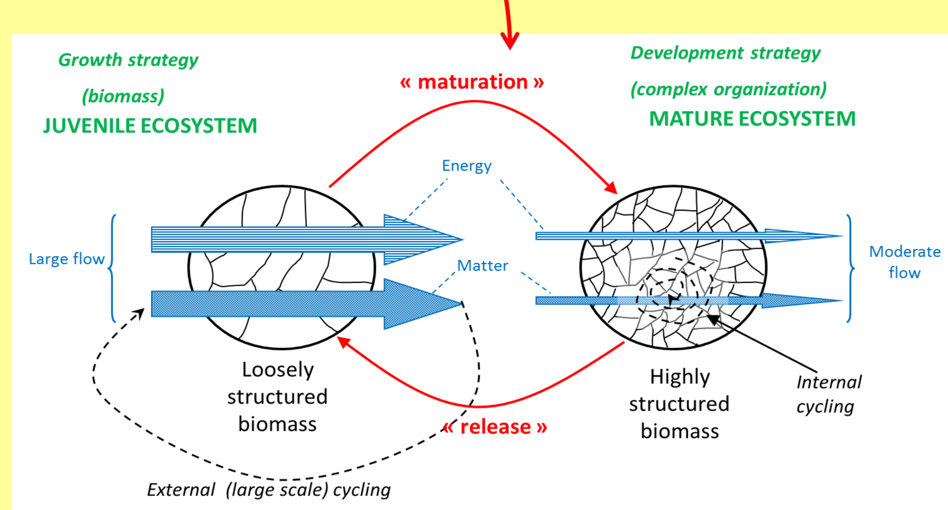
Ecological resilience is a concept that has advanced in relation to the development of complex adaptive systems with interactions across temporal and spatial scales. The strategy of ecosystem development exposed by Odum (1969) and extended by Frontier *et al* (2008) connected to the adaptive cycle proposed by Holling (1986) and the more recent concept of panarchy (Gunderson & Holling, 2002) are of great help to take fast/slow dynamics and cross scale interactions and interdependencies into account (Folke, 2006).

Spatial scale is of prime importance because what is “best” for a local community is generally not what will work best regionally or globally. In fact resilience at the level of the whole system may be achievable precisely through the lack of resilience at the level of the parts (e.g. species or local communities) that make up the system (Levin & Lubchenco, 2008). Resilience requires the presence of sufficient variability at the level of the system’s components to operate: without variation, there can be no adaptive response.

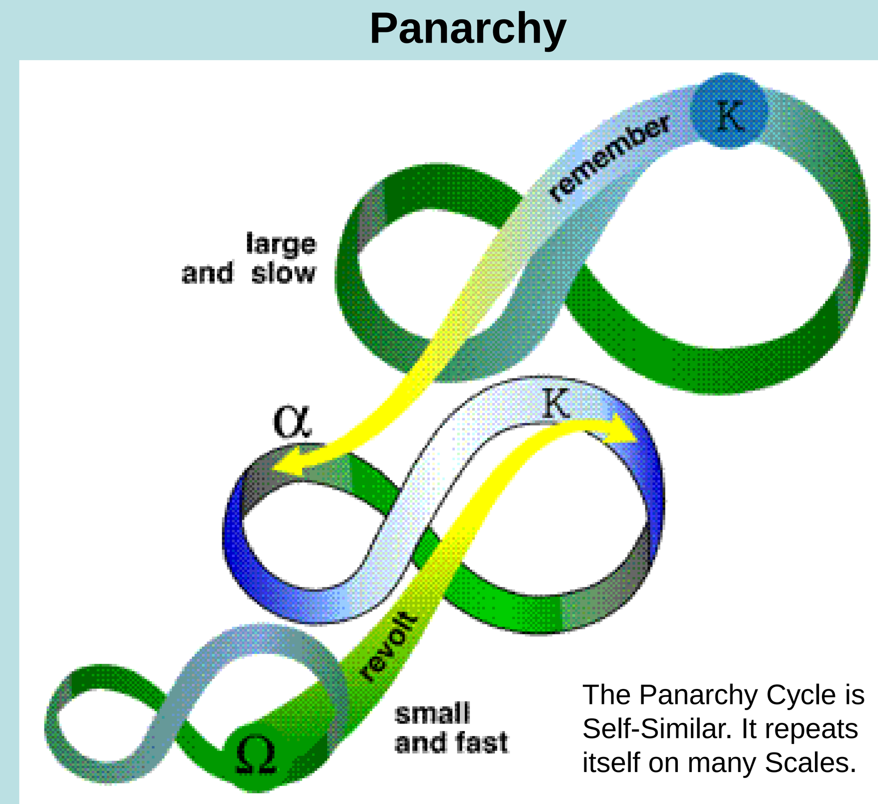
Folke et al. (2004) forwarded a refined definition of resilience that more explicitly recognizes within and cross-scale linkages and adaptability: “*resilience reflects the degree to which a complex adaptive system is capable of self-organization…and the degree to which the system can build and increase the capacity for learning and adaptation*”. This definition explicitly considers that self-organization (i.e. feedbacks) in ecosystems occurs at distinct targeted nested scales of space and time. This nested structure within ecosystems has been described as panarchy (Allen *et al*., 2010). Panarchy is a concept proposed by Gunderson & Holling (2002) to help explain the evolving nature of CAS. A panarchy is the hierarchical structure in which several CAS are interlinked via adaptive cycles in nested set of spatio-temporal scales. Panarchy created discontinuities in the organization of a CAS according e.g. to slow/fast processes as function of level (Allen & Holling, 2008).



Adaptive cycle (Holling, 1986) coupled to strategy of ecosystem development (Odum, 1969; Frontier *et al*., 2008)



Panarchy



The Panarchy Cycle is Self-Similar. It repeats itself on many Scales.

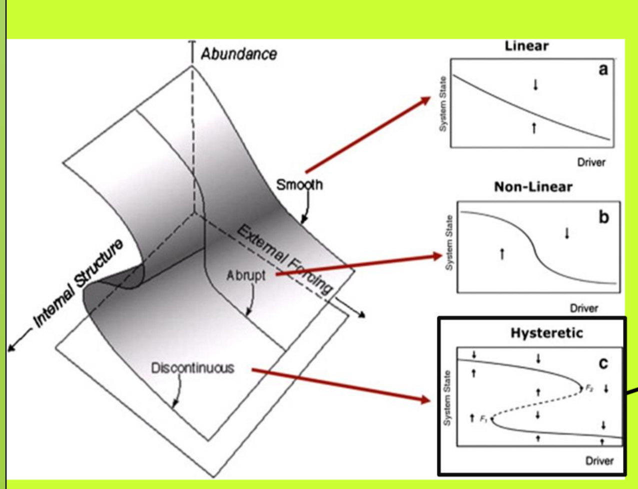
Part III: OPERATIONAL DEFINITION.

Here, we define **ecological resilience** as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same functions, structures, identity, and feedbacks (Walker *et al*., 2004). In short, this can be translated as the ability of an ecosystem to remain within bounds/limits of the attractor/adaptive landscape.

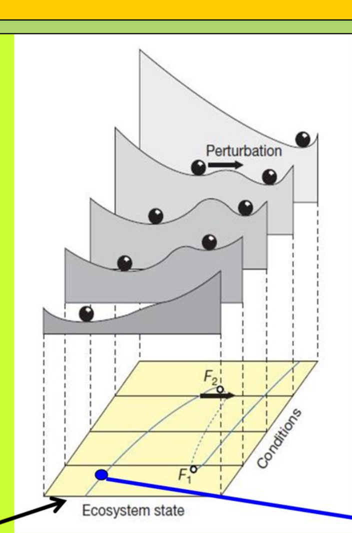
A challenge is to elaborate a tool to estimate resilience - i.e. to represent adaptive landscape - in particular in relation to the panarchy of cross-scale dynamics and interplay between a set of nested adaptive cycles.

BUILDING THE JIGSAW:
PERSPECTIVES TO DEVELOP A TOOL REPRESENTING *ECOLOGICAL RESILIENCE*

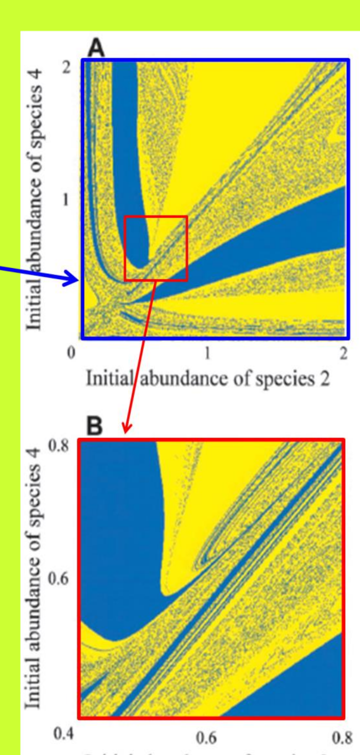
Complex systems have multiple attractors. This implies that a perturbation can bring the system over a threshold that marks the limit of the basin of attraction or adaptive landscape/domain, causing the system to be attracted to a contrasting state. Different regimes are usually metaphorically represented by a ball-and-cup diagram. This type of representation appears “simpler” given the observed complexity of ecosystems. Attractors cannot be only stable points or more complicated cycles of various kinds; this approach captures only part of reality. In communities of high biodiversity, the outcome of multispecies competition is fundamentally unpredictable: several alternative outcomes are observed and exhibited basins of attraction with an intermingled fractal geometry (Huisman & Weissing, 2001). Therefore it is unlikely that the structure of the ecosystem dynamic can be represented by a single value. An adaptive landscape with several basin of attraction seems more realistic.



Catastrophe manifold with two equilibrium states illustrating three types of regime shifts that are special cases along a continuum of internal ecosystem structure.



Hysteresis: ball-and-cup representation with 2 stable equilibria (modified from Scheffer, 2009)



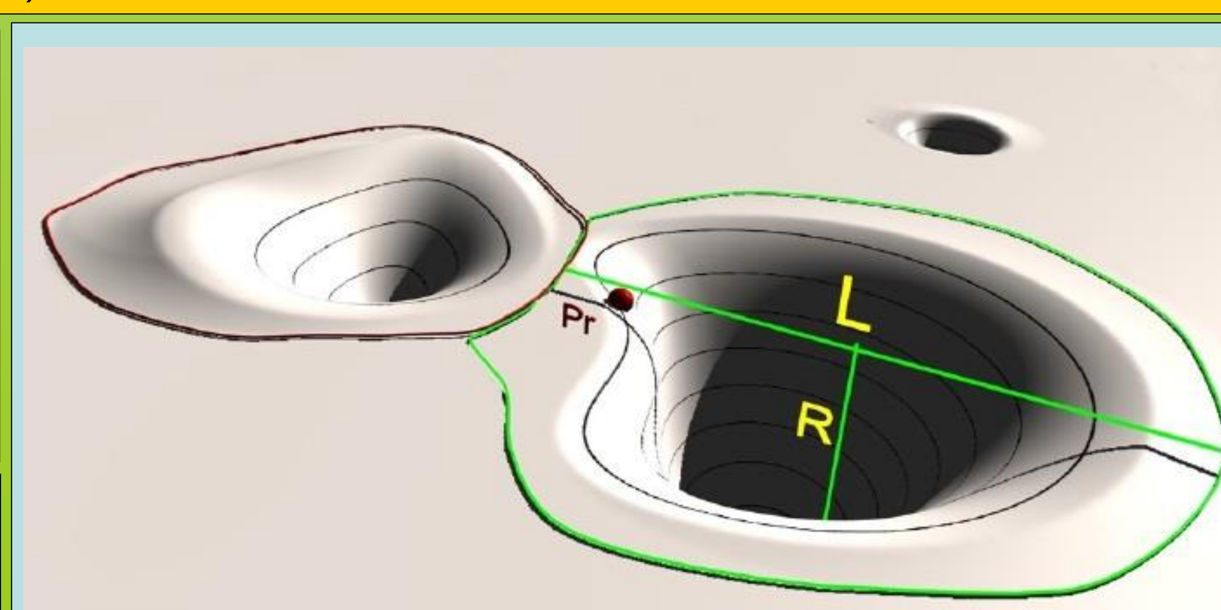
Fractal basin boundaries based on 5 species in competition.
Blue : species1-3 win; yellow: species 1, 4 & 5 win
(modified from Huisman & Weissing, 2001)

Ecological resilience can be measured by the size and properties of the adaptive landscape/domain which is a jigsaw piece of CAS. The nature of the attractor may change over time e.g. with the effect of external stochasticity. Sharp shifts observed in ecosystems are called regime shift and may have different causes (Scheffer, 2009). When they correspond to a shift between different adaptive landscapes, they are referred to as critical transitions (Scheffer, 2009).

Folke *et al* (2010) acknowledged that multiscale resilience is fundamental for understanding the interplay between persistence and change, adaptability and transformability. That means that the construction of this type of adaptive landscape requires particular knowledge of higher levels of the system studied, constituting its context and the interactions between levels (cross-scale transfer -panarchy). This knowledge is not within our reach. As in the case of chaos theory, it is however possible to reconstruct a landscape, with his / her attractor(s) using data from the system itself in the same philosophy as the reconstruction of the phase space of a dynamical system. It then becomes possible to study the topological properties of the resulting attractor representation in the phase space, phase space whose characteristics are close to the “theoretical” attractor (Bergé *et al*, 1988).

It cannot be ruled out the possibility for a CAS to be characterized by a multifractal dynamic, i.e. no attractor, no predictability and high dimensionality according to Seuront (2010).

Through adaptive landscape representation, ecological resilience appears to be a major jigsaw piece to capture part of CAS as simply as possible, but not simpler.



Three-dimensional adaptive landscape with three basins of attraction showing the current position of the system (red dot) and three aspects of resilience: **L** = latitude, **R** = resistance, **Pr** = precariousness (adapted from Walker *et al*. 2004).

REFERENCES

- Allen C. & Holling C.S., 2008. Discontinuities in ecosystems and other complex systems. Columbia Univ. Press,
- Allen C. et al, 2010
- Beaugrand et al., 2008, Ecol. Lett., 11, 1157-1168,
- Bergé P. et al, 1988. L’ordre dans le chaos. Hermann
- Darwin C., 1859.On the origin of species. Murray ed.
- Folke C. et al., 2004, Ann. Rev. Ecol. Evol. Syst., 35, 557-581,
- Folke C., 2006. Glob. Env. Change, 16, 253-267,
- Folke C. et al, 2010, Ecol. & Society, 15(4), art.20
- Frontier et al., 2008. Ecosystèmes. Dunod,
- Gunderson L.H. & Holling C.S., 2002. Panarchy. Island Press
- Hastings A., 2001. Ecol. Lett., 4, 215-220,
- Hirota M. et al, 2011, Science, 334, 232-235.
- Holling C.S., 1973. Ann. Rev. Ecol. Evol. Syst., 4, 1-23,
- Holling C.S., 1986.Resilience in ecosystems; local surprises and global change, p 292-317. In Clark W.C. & Munn R.E. eds. Cambridge Univ. Press
- Holling C.S., 1996, Engineering resilience versus ecological resilience. In Schulze P.C. ed., Nat. Aced. Press.
- Huisman J. & Weissing F.J., 2001. Am. Nat., 157(5), 488-494.
- Levin S., 1999, Fragile dominion. Perseus publishing.
- Levin S. & Lubchenco J., 2008. Bioscience, 58(1), 27-32.
- Odum E.P., 1969. Science, 164, 262-270.
- Scheffer M., 2009. Critical transitions in nature and society. Princeton
- Seuront L., 2010. Fractals and multifractals in ecology and aquatic sciences. CRC Press
- Walker B. et al., 2004, Ecol. & Society, 9(2), art5,