RESILIENCE: ECOLOGICAL AND SOCIO-SPATIAL MODELS EVOLVE WHILE UNDERSTANDING THE EQUILIBRIUM

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Abstract. The paper attempts to review the main models used in systems ecology, and applied to urban and territorial development, in tight connection with the developing understanding of equilibrium and stability. Initially, resilience was perceived as a component of stability (along with resistance, persistence, and variability), and later as a self-standing concept. As the understanding of equilibrium moves from homeostasis to homeoerhesis and practically to the carrying capacity, and stability finds different interpretations, ranging from constancy to dynamic equilibrium, the dynamics of ecological systems is modeled using adaptive instead of succession cycles. The new model is currently applied to other sciences, and also adapted to the man-dominated systems, including the urban ones. In this case, the understanding of resilience is even more divided among specialists, with particular interpretations resulting from partial or sectoral viewpoints. The analysis shows that more research is not a promising solution, but conceptual refinement is required instead.

Key words: resilience, stability, persistence, systemic ecology, urban development, adaptive cycles, equilibrium, thermodynamics.

1. Historical context

During the 1970's, the evolution of systemic ecology can be characterized by the studies dedicated to understanding the relationship between stability and diversity in the general context of biogeochemical cycles (Petrişor, 2008). Although almost 50 years had passed since this period, the interest of ecologists in these topics is still vivid and debates are continuing (Grimm *et al*., 1992).

2. Towards an integrated approach to stability

The moment of the 1970's coincided with the beginning of the environmental crisis, but also with the "zero growth" strategy proposed by the Club of Rome (Petrişor, 2011b, 2016). The two determined the ecologists to understand that, due to the globalization of irreversible impacts, stability can no longer be understood in a steady manner, as an intact state (Petrişor, 2011a). The new model is also the fruit of the progress made by systemic ecology in understanding the ecological equilibrium integrating the principles of thermodynamics, biogeochemical cycles, the relationships of a system with the sub-systems composing it and the hierarchically superior system, and diversity (Petrişor and Petrişor, 2014; Petrişor *et al*., 2016).

More precisely, ecologists understood that ecological systems have an anti-entropic dynamic (Corning and Cline, 2000). Using the radiating solar energy, systems tend to increase the complexity of their structure in order to achieve more stability (Petrişor, 2008, 2011b, 2016) using two mechanisms: maximizing the density of entering energy (by increasing the number of plant species, or replacing species based on their performance) and maximizing the use of energy (by diversifying and interconnecting food webs, increasing the complexity of all trophy levels, modifying the structure, or increasing the number of niches occupied by a single population) (Vădineanu, 1998). However, diversity cannot increase endlessly; its limit is imposed by the stability of relationships between species (Tomescu and Savu, 2002; Mougi and Kondoh, 2012). When this threshold is passed, the excess of diversity has a destabilizing effect.

3. Understanding stability and equilibrium

The interpretation of stability suffered numerous transformations. The concept of 'resilience' is part of the model proposed by Harrison (1979). The model is mathematically derived based on the potential action of a stressor and ultimately aimed at providing specific measurable indicators of stability. The four indicators are (1) resistance (range of fluctuations determined by a stressor), (2) resilience (speed of returning to the equilibrium state), (3) persistence (duration of maintaining the regular values of state variables during the action of a stressor), and (4) variability (frequency of changes during the action of stressors). Later on, Grimm *et al*. (1992) elaborate on the model, finding three sides of stability: (1) constancy (the system does not change) or resistance (the system does not change despite the action of a stressor), (2) resilience (the system returns to the original state after the action of a stressor), and (3) persistence (the system persists through time).

The understanding of stability is correlated to understanding the equilibrium. Studies carried out by Ludwig von Bertalanffy and Ilya Prigogine in the 1970's showed that, unlike mechanical systems which are characterized by static equilibrium (described by an unique state of equilibrium and resulting into the classification of equilibrium as unstable, if the system cannot return to the state of equilibrium once it has quitted it, stable, if the system returns always to the state of equilibrium, and indifferent, if the system is always in equilibrium), ecological systems are characterized by dynamic equilibrium. In thermodynamic terms, this is described by a multitude of states of equilibrium, basins of equilibrium, attractors etc. (Heylighen, 2001).

However, Holling (1973) starts from the previous model, according to which resilience is a component (or measure) of stability, and shows situations when the two may be in opposition. In his view, resilience and stability are two different properties of the system; resilience measures the ability of systems to absorb changes of state variables and command factors and still persist, or simply the capacity to buffer change (Folke *et al*., 2002). Hence, resilience measures the persistence, while stability characterizes the return of a system to its state of equilibrium.

4. The model of succession cycles

Equilibrium was modeled at the population level using a mathematical model of the predator-prey system consisting of first-order, non-linear, differential equations by Lotka (1910) and Volterra (1926), and later improved by other ecologists, including Holling (1959). The model shows that when environmental conditions are favorable the prey population starts increasing. After a while, the predator population increases too, reducing the prey population. Therefore, the model consists of two cycles, with a certain lag between them.

The first ecosystem-level model of equilibrium, still used nowadays, introduces the concept of succession cycles. If all variables controlling the dynamic of a system are represented (Fig. 2), and the 'normal' thresholds are figured, they define a multi-dimensional domain of stability. This corresponds, in thermodynamic terms, to replacing a unique steady state of equilibrium with a basin of equilibrium. Therefore, the adaptive capacity does no longer mean homeostasis (return to the state of equilibrium), but homoerhesis (evolution within the domain of stability) (Jantsch and Waddington, 1976). Within this domain, the system evolves and changes gradually through secondary succession. Command factors can reposition the system on a different evolutionary trajectory through primary succession. This process is determined by cataclysmic events which totally destroy the living (biotic) component of the system (Petrişor, 2008, 2011b, 2016).

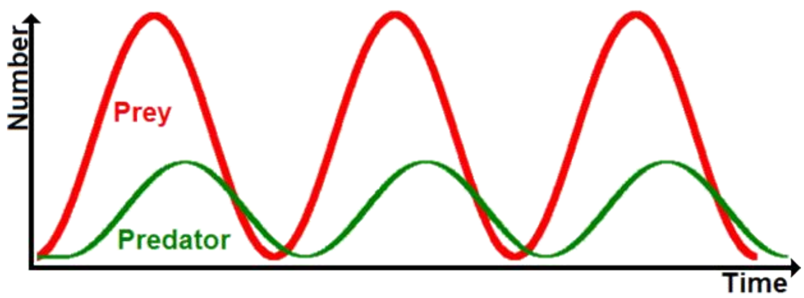

Fig. 1. The model of population equilibrium using Lotka-Volterra equations.

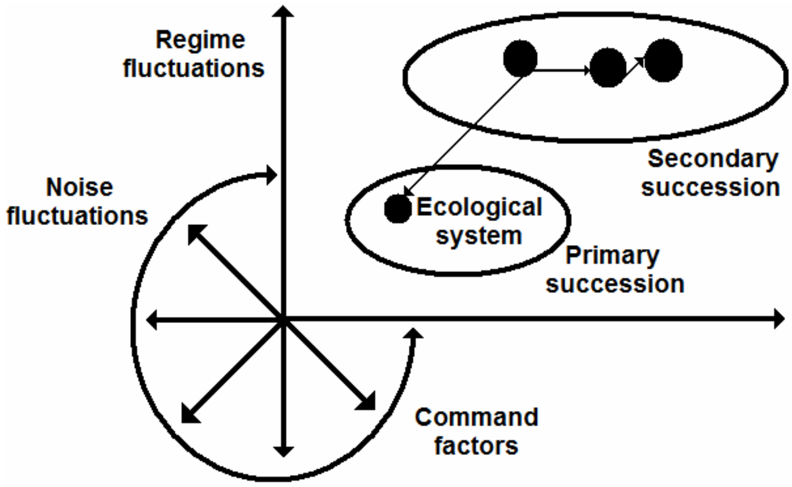

Fig. 2. The model of succession cycles. Within the domain of stability determined by the "normal" thresholds of state variables, the system evolves through secondary succession. Command factors determine, via primary succession, a new evolutionary trajectory (Petrişor, 2008, 2011b, 2016).

In this model, the equilibrium can be measured using the concept of "carrying capacity". If the system functions normally, it generates the primary yield (Tegos and Onkov, 2015, which can be used by a well-determined human community, with an assumed unchanged lifestyle and linear dynamic (Petrişor, 2007, 2008). In terms of ecosystem services, this is equivalent to a constant rate of the provision service (Pawlewicz, 2015). Therefore, the carrying capacity represents the dynamic ability of the environment to provide, under equilibrium conditions, the resources required by a well defined human population, absorbing its positive impacts and eliminating the negative ones (Negrei, 1999).

5. The model of adaptive cycles

Later on, Gunderson and Holling (2001) and Holling (2004) proposed a new model, known as "adaptive cycles" or panarchy (Fig. 3). In this model, the evolution of a system is described by a cycle consisting of four phases, termed entrepreneurial exploitation (r), organizational consolidation (K), creative destruction (Ω), and re- or de-structuring (α). Furthermore, the behavior of a system is interdependent of the behavior of sub-systems and integrating systems; small and fast cycles can affect larger and slower ones (revolt), or large and slow ones can control renewal of smaller and faster ones (memory). Resilience is another dimension of the adaptive cycle, measuring the efficiency of control and constancy and predictability of behavior in phases r and K, and adaptability, chaotic behavior and health of ecosystem in phases α and ω (Gotts, 2007).

Since Holling proposed a general theory, applicable to socio-ecological complexes and not only to biological systems (Chelleri, 2012), the new model was used by many disciplines, including landscape ecology (Moritz *et al.*, 2011), psychology, social and economic sciences (Chelleri, 2012), industry (Ashton, 2009), agriculture (Matthews and Selman, 2006), management (Mintzberg, 2009; Hahn *et al.*, 2010; Hubbard and Paquet, 2011), rural development (Salvia and Quaranta, 2015) or urban development (Ernston *et al.*, 2010). Furthermore, accounting for the influence of spatial variability on resilience and vice-versa, Cumming (2011) defined the 'spatial resilience'.

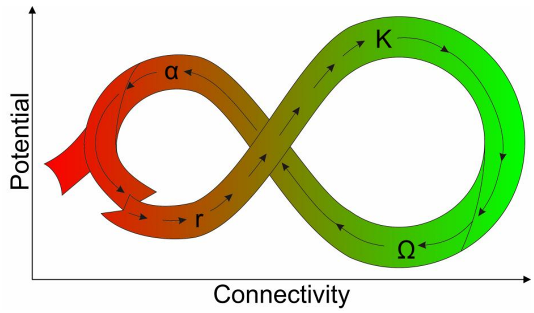

Fig. 3a. The adaptive cycle: r – entrepreneurial exploitation, K – organizational consolidation, Ω - creative destruction, and α – re- or de-structuring (Holling, 2004, modified).

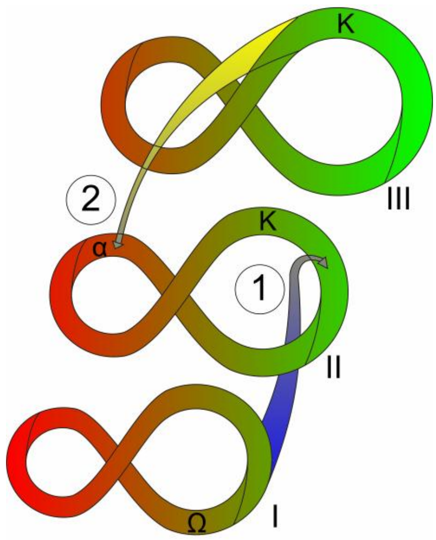

Fig. 3b. Interconnected adaptive cycles: 1 – revolt of small and fast cycles entering the re- or de-structuring phase; 2 – memory or transfer of adaptive potential from large and slow cycles; I – sub-systems with fast cycles; II – systems; III – integrating systems with slow cycles (Holling, 2004, modified).

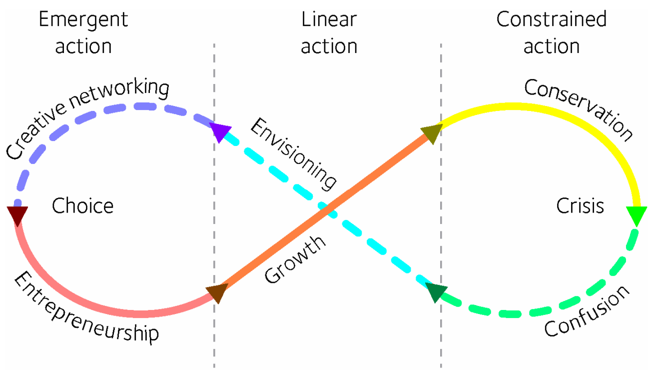

Fig. 4. Adaptive cycle in the dynamics of cities (Schlappa and Neill, 2013).

6. Adaptive cycles of socio-spatial systems

After analyzing the outputs of the URBACT projects developed in the previous period, Schlappa and Neill (2013) propose a version of Holling's adaptive cycle for the urban systems (Fig. 4), in fact a version of the model proposed initially by Mintzberg *et al.* (2009) adapted to cities. The full line refers to conventional performance, representing the base of current economic development policies, and the dotted line symbolizes the learning phase characterized by uncertainties and tensions between the current state and development alternatives. Declining cities face constraints, confusion and crises; options are limited and oriented mainly to conserving strategic abilities. The exit consists of redefining the purpose of development (Şerban, 2014). Phases have unequal durations, varying from one case to another. Moreover, the cycle is multi-dimensional, in accordance with the pillars and dimensions of development (Schlappa and Neill, 2013).

Schlappa and Neil's model replaced the previous proposal of Ianoş *et al.*, 2011, which was also attempting to adapt Holling's adaptive cycle to urban dynamics, while recognizing that the return to a previous state does bring back the historical city, but a "renewed" or "reinvented" version of it, qualitatively different. The output was a spiral model (Fig. 5). The first stage is the transformation of natural systems into rural settlements through the concentration of population due to the existence of resources or advantages of the geographic location. The former rural settlement turns, through creative destruction, into an urban one. Maturity is reached by the means of urban development. Inner and outer (environmental) constraints result into a permanent reconfiguration of the city. When the city can no longer adapt to the changes, de-structuring occurs. New structures, emerging during the process, determine the optimal insertion of the city in its environment. On the other hand, de-structuring can lead to new systems. Generally, the external factors are responsible for the reorganization or de-structuring of cities (Ye *et al.*, 2015); the dominant trend is anti-entropic and aimed at increasing the complexity.

Along with the evolution of the conceptual models of urban dynamics, urban resilience was continuously redefined. Some authors understand it in the very narrow sense of adapting to climate changes (Chelleri, 2012) and other risks (Peptenatu *et al.*, 2011, 2012) or recovering after natural disasters (Campanella, 2006), while others see it as a reconciliation between natural and socio-economic components (Ahern, 2012). Chelleri (2012) distinguishes two understandings of resilience: (1) ability of a system to return to the original state, and (2) ability of a system to retain the ability of returning to the original state, and advises managers for prudence in asking for measurements before actually knowing what is being measured (similar to the recommendation phrased by Klimovský *et al.*, 2016 in relationship to the 'smart city').

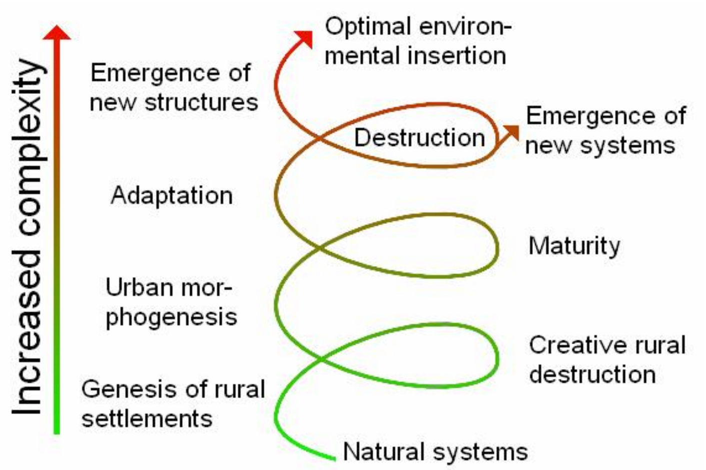

Fig. 5. Adaptive cycle in the dynamics of cities (Schlappa and Neill, 2013)

7. Conclusion

This study aimed to look at the evolution of key concepts and models used in ecology in general and in reference to urban systems in particular for modeling their dynamic. Although the concept of resilience is used extensively, its understanding appears to be an endless saga. In this particular case, probably a conceptual refinement would ensure a better progress than more research attempting to measure it. Such measurements can have deleterious effects if city managers use them for development without understanding what is actually measured.

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Received: 5 March 2016 • **Revised**: 18 May 2016 • **Accepted**: 19 May 2016