COMPLEX Final Scientific Report, Volume 2
Non-linearities and System-Flips

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With contributions from the COMPLEX Consortium

http://owsgip.itc.utwente.nl/projects/complex/

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4. Definitions

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Non-linearities

Most coupled socio-environmental systems (SES) exhibit nonlinear behaviour (Liu *et al.*, 2007). In general, this implies that small changes in independent variable(s) or in underlying micro behaviours may cause non-constant effects in a dependent variable or macro patterns and phenomena. In complex adaptive systems it is often the case that many interacting agents follow rules that produce complex nonlinear dynamics at macro-level (Axelrod, 1997). Yet, even when processes at micro level or within subsystems are rather straightforward and linear, the interactions and feedbacks between them may cause non-linear responses resulting in a change in the trajectory of the system (Walker, 2004). Cross-scale interactions and positive feedbacks among system elements, which lead to the emergence of nonlinear system responses, is a common feature of biological, physical and economic system (Peter *et al.*, 2004; Levin, 1999; Carpenter *et al.*, 2011). Thus, nonlinear effects and their macro scale impacts stem from local processes, which shift from one state to another (Arthur, 1999). A transition between alternate states often occurs when a threshold level of some control variables in a system is passed (Walker, 2004), making such thresholds a common form of non-linearity (Liu *et al.*, 2007).

Emergent nonlinear system behaviour is characterized by discontinuities (Liu *et al.*, 2007; Huggett, 2005), what makes it difficult to predict systems behaviour on various spatial and temporal scales (Peter *et al.*, 2004). In coupled SES certain positive feedbacks within or between subsystems may trigger nonlinear increases in economic costs (Chapin *et al.*, 2000).

Thresholds

Threshold is a critical value of independent variable where a system flips from one stable state to another (Muradian, 2001; Wiens *et al.*, 2002; Walker & Meyers, 2004; Bennett *et al.*, 2006; Kinzig *et al*, 2006). In resilience literature critical thresholds are called tipping point (Scheffer *et al.*, 2009). In mathematics thresholds are known as bifurcations (Andersen *et al.*, 2008). Bifurcation refers to a qualitative change in a steady state of an adaptive system at a faster time scale when a parameter on slower moving time scale goes through a critical value that causes the stable state on the fast time scale to become unstable (Brock, 2004). While mathematics studies bifurcations as changes to cyclic or irregular transitions, an analysis of SES focuses primarily on a transition between two steady states (Andersen *et al.*, 2008). As reviewed by (Hugget, 2005) a threshold can be seen as a (1) a bifurcation point, (2) a boundary in space and time, (3) a critical value of independent variable, (4) a single point or a zone – where a "relatively rapid change" between alternate regimes occurs.

Crossing a threshold results in an abrupt shift of complex system from one regime to another, and may cause a cascade of thresholds crossed. Empirical research suggests that the positions of critical thresholds and chances of crossing them in one domain or scale dynamically react on the changes in other domains and scales creating a phenomenon of a moving threshold (Kinzig *et al.*, 2006).

To some extent crossing a threshold may be used to identify a regime shift in SES. However, the data for identifying thresholds is often absent or incomplete (Huggett, 2005). Moreover, there might be a time lag between the system crossing a threshold and the reflection thereof in the domain-specific macro-measures of interest.

Irreversibility

While complex adaptive SES are perpetually out-of-equilibrium going through marginal or non-marginal changes, some of those changes in system's states may be irreversible. According to Folke (2004) irreversibility is a consequence of changes in variables with long turnover times and a loss of SES potential and interactions between system elements, which are able to help the system to renew and reorganize back in a desired state. A transition, which is not reversible, is called hysteresis (Scheffer *et al.*, 2009). As Brock *et al.*, (2004) define it: a hysteresis is a change in a system state, which requires more efforts to shift it back to the previous desirable state compared to the original forcing that triggered the regime shift. For example, if a system flip was caused by a slow-moving variable going "up" and crossing a critical value, it needs to be forced "down" to a level quite far below the original value, which initiated this critical transition, to be able to "recover" the old state (Brock *et al.*, 2004).

The three terms – non-linearity, thresholds and irreversibility – are closely related to the notion of resilience. "Resilience reflects the degree to which a complex adaptive system is capable of self-organization (versus lack of organization or organization forced by external factors) and the degree to which the system can build capacity for learning and adaptation." – a quote from (Adger *et al.*, 2005)