What Is Resilience? A Short Introduction

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Chapter 1

WHAT IS RESILIENCE? A SHORT INTRODUCTION

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Abstract Over the last three decades, resilience has become the most widely discussed stability concept in ecology and more recently also in socio-ecology. Influenced by physics, resilience often refers to the property of a system that its state variables return to their equilibrium values after a small disturbance. The Resilience Alliance, an international multidisciplinary network of ecologists and social scientists, promotes a different notion of resilience, which is focussed on the ability of a system to absorb changes and still maintain its essential functional relationships. In this chapter, we review the development of the concept of resilience in ecology. We provide a verbal definition, discuss examples, and list the main challenges of the resilience approach. These challenges set the stage for the original view of resilience explored in this book, resilience based on viability theory.

1. Introduction

Agent-based complex systems such as economies, ecosystems, or societies, consist of autonomous agents such as organisms, humans, companies, or institutions that pursue their own objectives and interact with each other and their environment (Grimm et al., 2005). Fundamental questions about such systems address their stability properties: How long will these systems exist? How much do their characteristic features vary over time? Are they sensitive to disturbances? If so, will they recover to their original state, and if so, why, from what set of states, and how fast? These questions are so important because the mere existence of agent-based complex systems is, in contrast to many systems studied in physics or chemistry, not granted but intriguing, calling for an explanation (Jax et al., 1998). The building blocks of these systems – organisms or human actors – do not have a blueprint of the entire system in mind and behave accordingly, but follow their own objectives. Nevertheless, system-level properties emerge which allow the identification of the systems and their behaviours over time. Tropical forests, for example, can be self-similar over thousands of years and reliably provide functions and services that are important for us. Systems can, however, also collapse and lose their identity and functions. For example, a stock market can crash, or a savanna can turn into a scrubland due to overgrazing, rendering it useless as rangeland (Scheffer et al., 2009).

Understanding stability properties is thus not only of scientific interest but is also a prerequisite for successful management of agent-based complex systems. For example, how can ecosystems be used in a sustainable way without impairing their stability properties and therefore their potential to provide services also in the future? How should economies be regulated to prevent crashes? How should large companies organize their workflow so that it is not only efficient but also robust to disturbances?

Of all scientific domains dealing with agent-based complex systems, ecology seems to be the one where stability properties have been discussed and explored most intensively. Models have played a central role in the development of and debate surrounding stability concepts in ecology. Other disciplines have been so far less influenced by modelling, such as political science, or are dominated by equilibrium-centred approaches, such as economics, so that questions of why and how long systems exist have lower priority.

We will therefore in this chapter review stability concepts in ecology. In particular, we will focus on resilience, a concept that has recently been promoted by the Resilience Alliance, an international multidisciplinary network to improve the sustainable management of socio-ecological systems (Folke, 2006; Brand, 2005; for an overview of the use of the concept of resilience in socio-ecology, see Janssen et al. 2006, Janssen 2007, Walker et al. 2006). First we will give an overview of definitions and terms used in ecology. Then, we will focus on two different notions of resilience, 'engineering' and 'ecological' resilience and describe further central concepts promoted by the Resilience Alliance.

Although this chapter is based on approaches and examples from ecology and socio-ecology, it nevertheless addresses stability concepts and resilience in general, as emergent properties of agent-based complex systems. The purpose of this chapter is to introduce important stability concepts, provide verbal definitions and examples, and serve as a guide to the relevant literature. Chapter 2 will provide more specific mathematical definitions of resilience.

2. Stability Concepts in Ecology

In a literature review, Grimm and Wissel (1997) evaluated 163 definitions of 70 different stability terms from ecology, but even at that time more definitions and terms certainly existed. In the meantime, many new definitions have been added, in particular definitions of 'resilience' (Brand and Jax, 2007).

Grimm and Wissel (1997) found that despite this terminological diversity, only three fundamentally different stability properties exist: constancy, resilience, and persistence (Table 1.1). All existing definitions of stability properties can be mapped to one of these basic properties or to a combination of them. Grimm and Wissel (1997) concluded that it would not be appropriate to equate just one of these properties with 'stability'. Rather, 'stability' is a multi-layered concept that includes the three basic 'stability properties' as specific aspects. Three further concepts are important enough to be considered essential stability properties, but are related to the basic properties: resistance (an interpretation of constancy), elasticity, and domain of attraction (quantitative aspects of resilience). If there are only so few basic stability properties, why does this huge diversity of terms and definitions exist? Grimm and Wissel (1997) discuss three possible reasons.

First, the term 'stability' is ambiguous by itself and cannot be narrowed down to one of the properties in Table 1.1. 'Stability' is a concept comprising the different aspects listed in Table 1.1. Many researchers therefore add an adjective to 'stability', for example 'species deletion stability' (Pimm, 1980, p. 142), to make the term more specific. Alternatively, they may use a narrower definition, for example equating 'stability' with 'resilience' as defined in Table 1.1, or they might simply invent a new term such as 'amplitude' (Connell and Sousa, 1983, p. 790).

Second, the fascination with 'stability' reflects the desire of ecology for powerful concepts: “Stability belongs to the expressions (as information and energy) of which, sometimes, a global explanatory power is expected and which is supposed to make tedious attention to detail more or less superfluous.” (Schwegler, 1985 p. 263; translated from German).

Third, stability concepts can, with the exception of 'persistence', not be applied to entire systems but only to specific state variables characterizing these systems, for example total biomass, number of species, fixation of CO_2, or spatial patterns. Moreover, statements about stability properties also depend on the specific type of disturbance considered, on the temporal and spatial scales involved, and on how, precisely, the reference state or dynamics is defined. The diversity of stability terms and definitions may thus reflect the many different ways in which ecosystems can be characterized and disturbed. Despite the profusion of terms in the ecological stability discussion, which can be confusing

Stability	Concept definition	Comment
Constancy	Staying essentially unchanged	Often, the inverse property 'variability' is considered
Resilience	Returning to the reference state (or dynamics) after a temporary disturbance	In theoretical ecology, this property often simply was referred to as 'stability'
Persistence	Persistence through time of an ecological system	This concept refers to entire systems, whereas the other concepts refer to one or more specific state variables
Resistance	Staying essentially unchanged despite the presence of disturbances	This is an interpretation of 'constancy'
Elasticity	Speed of return to the reference state (or dynamics)	This has often been referred to as 'resilience'
Domain of attraction	The whole of states from which the reference state (or dynamics) can be reached after a temporary disturbance	Related to 'persistence' since the 'domain' defines the states a system can achieve without losing its identity

Table 1.1: Six basic stability concepts, identified in a literature review in ecology (after Grimm and Wissel, 1997).

and irritating, two concepts play a dominant role in ecology: engineering and ecological resilience.

3. Engineeering Resilience

'Engineering resilience' is the same as 'elasticity' as defined in Table 1.1: "Rate and speed of return to preexisting conditions after disturbance" (Holling and Gunderson, 2002). The qualifier 'engineering' was added to distinguish this notion of resilience from the more holistic notion of Holling (1973) (see next section). But why 'engineering'? Because it can easily be calculated from simple dynamical models representing communities of interacting populations (Otto and Day, 2007). Prototypes of such models are Lotka-Volterra predator-prey or competitive systems. These models are expressed as nonlinear ordinary differential equations where the state variables are the time-dependent densities of the species considered (Wissel, 1989).

Calculating elasticity, and checking for resilience, is straightforward using linear stability analysis: calculate equilibrium densities; apply infinitesimally small displacements, or disturbances, from the equilibrium; use Taylor expansions to obtain a set of linear equations describing the dynamics of the displacements; calculate the eigenvalues of the matrix of coefficients of the linearized set of equations. If the real part of the dominant eigenvalue is smaller than zero, the disturbed system will return to its equilibrium (e.g., Otto and Day, 2007). Thus, the sign of the eigenvalue's real part indicates whether the system is resilient, and the inverse of its absolute value is a measure of its elasticity, or engineering resilience. However, the inverse of the eigenvalue indicates the time the system will need to return to equilibrium. A system might therefore be resilient in principle, but return so slowly that on time scales of practical relevance it is not.

For the 'domain of attraction', which is the second aspect of resilience as defined in Table 1.1, no similarly straightforward approach to calculate this property exists. Therefore, theoretical ecology had a much stronger focus on equilibria and return times than on the domain of attraction.

Theoretical ecologists were intrigued by being able to 'calculate' the 'stability' (as they usually called it) of ecological communities, which for the first time facilitated the quantitative study of one of the most important questions of ecology: the relationship between the diversity (and complexity) of a community and its stability (May, 1974). Linear stability analysis and the concept of 'engineering resilience' were therefore dominating approaches in theoretical ecology in the 1980s and a large part of the 1990s.

However, many ecologists felt that these approaches reflected a quite narrow notion of the stability properties of ecosystems (Holling and Gunderson, 2002). Specifically, the engineering resilience perspective does not allow the study of entire systems and how their internal organization and mechanisms promote persistence despite disturbances which could cause ecosystems to lose their characteristic features and functions. These researchers often referred to the highly influential review of Holling (1973) which suggested a more holistic definition.

4. Ecological Resilience

Holling's definition is verbal and qualitative, not mathematical and quantitative: "resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. In this definition resilience is the property of the system and persistence or probability of extinction is the result." (Holling, 1973, p. 17). He also suggested two measures of resilience: "Since resilience is concerned with probabilities of extinction, firstly, the overall area of the domain of attraction will in part determine whether chance shifts in state variables will move trajectories outside the domain. Secondly, the height of the lowest point of the basin of attraction (...) above equilibrium will be a measure of how much the forces have to be changed before all trajectories move to extinction of one or more of the state variables." (p. 20). This definition, which later was slightly modified and sometimes termed 'ecological' or 'ecosystem's resilience' (Holling and Gunderson, 2002; Brand, 2005; Brand and Jax, 2007), is, like 'stability', a term comprising several stability properties (sensu Table 1.1) simultaneously: persistence, resistance, resilience, and domain of attraction. Though Holling's review is widely cited, it has not been adopted by theoretical ecologists and modellers, because there is no simple way to quantify ecological resilience. Nevertheless, in the middle of the 1990s, a group of ecologists and social scientists founded the Resilience Alliance (`www.resalliance.org`). The Resilience Alliance has the declared aim to promote and develop Holling's notion of ecological resilience and related concepts because they are considered essential for solving vital socio-ecological problems and for fostering sustainability. The resilience definition currently preferred by the Resilience Alliance was formulated by Walker et al. (2004): "Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks." The three main differences between ecological and engineering resilience are: (1) A shift in focus from equilibria to domains of attraction, often also called 'regimes', where a certain characteristic network, or regime, of processes controls the system's properties and functions. This is important because ecosystems usually are not in equilibrium but can change within relatively wide margins, without losing their identity. Savannas, for example, are driven by rainfall events. After a couple of years with higher rainfall, tree density can increase and tree distribution can become clustered (Jeltsch et al., 1999). However, trees and grasses still coexist, as required by the definition of savannas (Jeltsch et al., 2000). (2) A shift in focus from numerical values of state variables to 'relationships', i.e. to the internal organization of ecosystems which gives rise to their properties. (3) A shift in focus from the ability to recover after disturbance (engineering resilience) to the ability to 'absorb' the effect of disturbances, i.e. not to change essentially in the first place. Mechanisms are believed to be in place which buffer the effect of disturbances, as in the case of savannas. The most important implication of this is that this buffering ability can be lost, leading to an abrupt regime shift.

5. Regime Shifts

If environmental conditions change too much, for example due to climate change, human impact, or both, ecosystems can suddenly change to another regime which might no longer provide services essential for human well-being. This is in analogy to chemical buffers, which have only a certain capacity for buffering pH values.

A classical example involves shallow lakes (Scheffer and Carpenter, 2003), which can tolerate increasing input of phosphorus only up to a certain tipping point where lakes turn from a clear to a turbid state. Figure 1-1 shows another example from semiarid savannas (Jeltsch et al., 1997): if the density of livestock exceeds a certain threshold, grass cover is reduced so much that the inter-

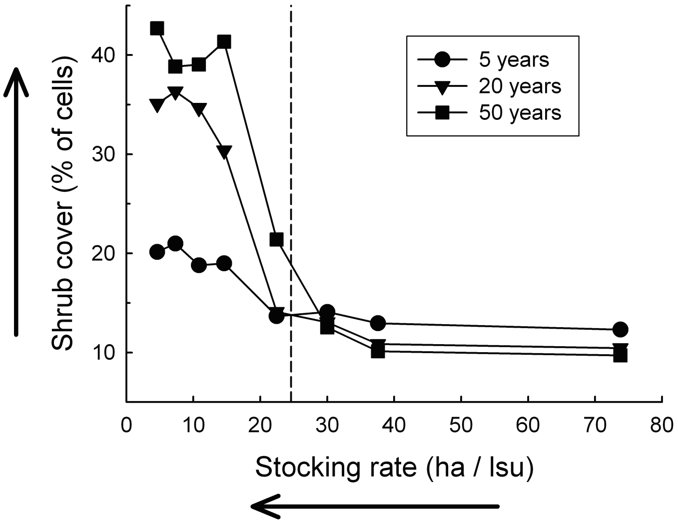

Figure 1.1: Regime shift in a semiarid savanna, as predicted by a simulation model. If livestock density increases (i.e., stocking rate, measured as hectare per livestock unit [lsu], decreases) beyond a certain threshold, shrub cover increases abruptly, making the savanna unsuitable as rangeland. The change in shrub cover is not very marked after only five years of overgrazing. The dashed vertical line gives the estimated stocking capacity of the site, which was estimated empirically and independently of the model. (Redrawn after Jeltsch et al., 1997)

nal organization of savannas, which includes interaction between grass cover, fires, and tree density (Calabrese et al., 2010), is disrupted. As a consequence, woody cover is no longer controlled by fire and increases abruptly, leading to a state of this ecosystem that no longer can be used for livestock grazing. This new regime, sometimes also called an 'alternative state', is also resilient so that the loss of ecosystem function caused by the regime shift is irreversible, at least on time scales relevant to humans. Such transitions occur in savannas worldwide and are an alarming example of the unsustainable management of natural resources.

Regime shifts have been demonstrated for several ecosystems, in particular shallow lakes, savannas, and coral reefs. The Resilience Alliance maintains on their website a database of observed regime shifts. However, the question of whether all ecosystems show abrupt changes and are characterized by alternative states is still open (Schroeder et al., 2005). Nevertheless, regime shifts are the most important element of the resilience approach fostered by the Resilience Alliance. They make us focus on the risk of losing ecosystem functions that are vital to human well-being. Consequently, management should not be concerned about equilibria and some kind of 'balance of nature', but should instead focus on the key mechanisms that allow a system to persist, and on the fact that these mechanisms have only a certain capacity, which can be reduced by environmental change and human impact.

6. Adaptive Cycle and Panarchy

The conceptual framework of the Resilience Alliance includes two further main concepts: adaptive cycles and panarchy. Adaptive cycles are an attempt to provide the generic mechanism underlying resilience. Ecosystems are believed to be resilient because they are able to 'adapt' to changes and new conditions. Resilience is believed to be based on cyclic changes of two properties: potential and connectedness: "Potential sets limits to what is possible – it determines the number of the alternative options for the future. Connectedness determines the degree to which a system can control its own destiny (...). Resilience determines how vulnerable the system is to unexpected disturbances and surprises that can exceed or break that control" (Holling and Gunderson, 2002, p. 51).

Connectedness is assumed to increase over time, leading to high internal control and limited potential to cope with disturbances. Naturally, such over-connected systems crash into a release period, where it has the potential to reorganize, thereby coping with disturbances. This development is believed to be cyclic. Resilience is also assumed to change at the local scale in a cyclic way. When connectedness is low, resilience is high because the system can vary over a wide range of states and respond to disturbance in many different ways. When connectedness, however, is high, ecosystem resilience is low because the system is more tightly organized and has fewer options for responding to disturbances. Interestingly, engineering resilience can be high at the same time as ecosystem resilience is high, i.e. effects of not too extreme disturbances quickly disappear (e.g. Holling, 2001).

Because of its very general nature, the concept of the adaptive cycle should be considered a metaphor (Carpenter et al., 2001) or thinking tool rather than a testable scientific theory. This metaphor certainly contains important elements of what drives agent-based complex systems. For example, succession of different plant communities on a certain site includes many elements of the adaptive cycle. In particular, the so-called climax community, which could be a mature, old-growth forest, could be considered over-connected and prone to crashing following disturbances such as fire or pest outbreaks. However, succession and, similarly, adaptive cycles apply to smaller spatial units, not the entire ecosystem.

In the concept of 'panarchy', adaptive cycles on different temporal and spatial scales are coupled in a nested hierarchy (Holling and Gunderson, 2002). Ecological and socio-ecological systems are thus assumed to be driven by 'cross-scale interactions' (Walker et al., 2004). As a result of these interactions, the characteristic control, or regime, of such systems emerges (Holling et al., 2002): "The complexity of adaptive systems can be traced to interactions among three to five sets of variables, each operating at a qualitatively distinct speed and scale." (Brand, 2005).

7. Challenges of the Resilience Approach

The Resilience Alliance has been extremely prolific, producing hundreds of publications (Janssen et al., 2006; Janssen, 2007) and a large number of books, and keeping a well-maintained website that contains databases, references, and material for education and policy makers. These activities have had a tremendous impact on how ecologists and social scientists think about socio-ecological systems, their stability properties, and sustainable management.

Nevertheless, proceeding from metaphors and thinking tools to operational concepts is challenging. Three main challenges are:

- *Separating normative from descriptive definitions of resilience.* This point has been raised by Brand and Jax (2007). They are concerned about the trend to mix descriptive definitions, which refer to how system are, with normative definitions, which refer to how systems should be. For example, Folke (2006) defines resilience as "The underlying capacity of an ecosystem to maintain desired ecosystem services in the face of a fluctuating environment and human use." (p. 14). Normative definitions have their place, for example in facilitating "communication across disciplines and between science and practice" (Brand and Jax, 2007), but for operationalizing the concept of resilience clear descriptive definitions are needed.

- *Gaining mechanistic understanding.* The observations on which the resilience approach builds are certainly essential and contain information about how agent-based complex systems are organized. For example, a central idea underlying the concept of panarchy is that such systems are usually controlled by a small number of, say, three to five variables. But why is this so? Understanding of the generative mechanisms (Lawson, 1989) is key to putting concepts into practice and to successful management. For example, Thulke and Grimm (2010) show how computational models helped to devise successful strategies for controlling wildlife diseases.

- *Reconciling engineering and ecological resilience.* The defining feature of engineering resilience is that a mathematical protocol exists to calculate, for models formulated as differential equations and for small disturbances, whether or not a system returns to equilibrium and how fast return will be. Ecosystem resilience is more focussed on the domain of attraction and regime shifts. Mathematical approaches for dealing with these aspects of resilience exist (Anderies et al. 2002) but are less general and powerful than linear stability analysis. Their limitations will be discussed in the next chapter.

8. Summary and Conclusions

Stability is a multi-layered concept comprising the three elements: constancy, (engineering) resilience, and persistence (Table 1.1). For a long time, theoretical ecology focussed on one specific aspect of stability: whether or not a certain state variable returns to its reference value after a temporary disturbance. Linear stability analysis allowed to quantify this 'engineering' notion of resilience but its ecological relevance remained unclear. In contrast, the concept of 'ecological resilience', which is promoted by the Resilience Alliance, is by definition multi-layered and comprises the aspects of persistence, resistance, resilience, and domain of attraction (Table 1.1). This certainly is an achievement, because it allowed to shift the focus from equilibria to the functioning of ecosystems and the key question under what conditions agent-based complex systems lose their ability to cope with disturbances and environmental changes, which leads to regime shifts.

So far, however, the concept of ecological engineering has not been operationalized: it remains unclear how to quantify resilience and identify the mechanisms underlying resilience. In this book, the main approach to achieve operationalization of ecological resilience is: simplify and aggregate simulation models so that key mechanisms of resilience are easier to identify, and, if possible, apply viability theory and a related new concept of resilience (Martin, 2004, Chapter 3). The approach studied in this book – viability theory – can be seen as an attempt to overcome some of the challenges of the resilience approach. A major aim of this book is augmenting the approach of engineering resilience, without losing its mathematical background, and linking it with a variety of complex dynamics defined by individual interactions.

In general, it will be important to clearly separate between *analytical* and *synthetic aspects* of resilience. Analytical stability concepts like constancy, resistance, and engineering resilience focus on single state variables and their dynamics. They are diagnostic tools for exploring how well different state variables capture the organization of a system, how different disturbances, reference states, and observation at different scales and hierarchical levels help understanding the functioning of agent-based complex systems. In contrast, synthetic concepts, such as persistence and ecological resilience, aim at explaining, in a holistic way, the existence and functioning of agent-based complex systems. They refer to the phenomenon we want to understand, explain, and take into account in managing such systems: their ability to cope with disturbance and change, and the limits of this ability.

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