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D1.1 Analysis of resilience in manmade and natural systems

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## RECORD OF REVISIONS

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ABSTRACT

This document is deliverable D 1.1 “Analysis of resilience in manmade and natural systems”, which is part of WP1, with 9.5 person-months involved in its completion. The following report delivery date is T0+10, which corresponds to the 1st of March, 2013. The document is a review of the way the term ‘resilience’ is used as a concept within a selection of different systems, as well as what may characterise and drive resilience, so as to inform application of the term in the Resilience2050 project. It specifically considers the use of ‘resilience’ in ecological, socio-ecological and socio-economic systems, as comparisons for the way the term has developed in the context of Air Traffic Management (ATM) socio-technical systems.
1. INTRODUCTION

This review aims to provide an overview of the way the term ‘resilience’ is used as a concept within a selection of different systems, so as to inform a rigorous operational definition of the term, and how it may be applied, within the context of Air Traffic Management. This in turn will underpin the project ‘New design principles fostering safety, agility and resilience for Air Traffic Management (Resilience2050.eu)’.

The review examines the concept of resilience in different systems in order to 1) reflect on the ways in which the term is used in different contexts, and 2) determine whether there are commonalities between the use of the term, so that this may help with deliverables 1.2 and 1.3, which aim to determine whether elements of the concept as applied to different systems could be applied to the focus of this project (Air Traffic Management), and to establish a precise definition of resilience for ATM, as the starting point for further investigation of resilience as applied to ATM.

The intention is not to review all systems exhaustively, but to consider the use of the definition in its original context (ecology) and then consider how it has been applied to different social system contexts, starting first with broad socio-ecological systems, and then more defined socio-economic and socio-technical systems, with the latter focusing specifically on air transportation management to be of most direct use. For each system reviewed, the system is defined, relevant disturbances considered, key elements of resilience examined, useful metrics reviewed (or the ways in which resilience is assessed, e.g. indicators) and finally some consideration is given to the ways in which resilience may be strengthened or improved. The review is organised as follows:

Section 2: This provides definitions of the key terms used throughout the review. As several different systems covering varying academic disciplines are being investigated, terms may not be familiar to all readers, or similar terms may be used in different ways. This section aims to help remove any confusion for an interdisciplinary readership.

Section 3: This section reviews the history of the resilience concept as applied to systems, from its origins in ecological systems to its more recent use throughout a range of broadly social systems. It considers the ways the term has been defined, and the implications that its use may have for different systems.

Section 4: This covers the use of the ‘resilience’ within an ecological context, from its initial use in the early 1970s to its more recent incarnation as ‘ecological resilience’.

Section 5: This covers socio-ecological systems – a broad area, but specifically this section considers how the incorporation of social components within a system changes some aspects of resilience, including adaptive capacity and the potential for transformation.

Section 6: Moving to a more narrow focus on the social aspects, this section considers the way resilience has recently been applied to economic or regional systems, highlighting the sorts of things such applications have focused on and the potential for a more complete understanding of ‘resilience’ in an economic sense to emerge.

Section 7: This section examines how resilience could apply within the context of air transportation management as an example of a socio-technical system, highlighting in particular how key system properties and disturbances are conceived, as well as important models and metrics that may be applied to such specific systems.

Section 8: This section provides a broad overview of the way ‘resilience’ has been used, summarising in particular some of the key commonalities in the usage and transition of the term through different
contexts, and what a study of system resilience would incorporate for any given system. To this end, the section ends with a simple ‘toolbox’ that may be followed for developing a working definition of resilience in a given system.

Section 9: References cited within the review.

It is intended that this review will lead to a robust, comprehensive and authoritative definition and application of ‘resilience’ within the air traffic management systems that will be investigated within this project.

1.1 Acronyms and Terminology

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<thead>
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<tr>
<td>ABM</td>
<td>Agent-Based Modelling</td>
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<td>ATC</td>
<td>Air Traffic Control</td>
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<td>ATM</td>
<td>Air Traffic Management</td>
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<td>CAS</td>
<td>Complex Adaptive Systems</td>
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<td>CODA</td>
<td>Central Office for Delay Analysis</td>
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<td>FRAM</td>
<td>Functional Resonance Assessment Method</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>GSHP</td>
<td>Generalised Stochastic Hybrid Process</td>
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<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>KPA</td>
<td>Key Performance Area</td>
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<tr>
<td>LTER</td>
<td>Long-Term Ecological Research</td>
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<tr>
<td>NEXTGEN</td>
<td>Next Generation Air Transportation System</td>
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<tr>
<td>NLR</td>
<td>Nationaal Lucht en Ruimtevaartlaboratorium (The National Aerospace Laboratory – The Netherlands)</td>
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<tr>
<td>NRM</td>
<td>Natural Resource Management</td>
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<td>PRA</td>
<td>Probabilistic Risk Analysis</td>
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<td>SA</td>
<td>Situation Awareness</td>
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<td>SARS</td>
<td>Severe Acute Respiratory Syndrome</td>
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<td>SDE</td>
<td>Stochastic Differential Equation</td>
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<tr>
<td>SES</td>
<td>Socio-Ecological System</td>
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<tr>
<td>SESAR</td>
<td>Single European Sky ATM Research Programme</td>
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2 Definitions of terminology

2.1 Adaptive capacity: The ability of a system to adapt to a changing environment (internally or externally) to avoid a change in state. It is therefore relatively synonymous with ecological resilience, but more specifically relates to a way of measuring resilience (i.e. quantifying capacity) and is usually applied to socio-ecological systems.

2.2 Adaptive cycle: The phases through which a system naturally progresses, characterised by a slow accumulation of resources followed by a rapid release of resources and system reorganisation – essentially representing a shift to another stable state. The four phases are: Exploitation (r), when a system is emerging and there is rapid utilisation of available resources; conservation (K) when some level of stability (even though dynamic) is established, and there is a general accumulation of resources; collapse or release (Ω), where the system is pushed to a new stable state by some external or internal disturbance (the threshold function), and so resources are once again released; and reorganisation (α), when a new system begins to form and potentially new components and processes originate, ready for the exploitation phase to begin. See Figure 4.1.

2.3 Complex system: A system of interacting components that in its entirety may display particular characteristics or behaviours that are not found or apparent in individual components or sub-systems.

2.4 Complex Adaptive System: Many systems are recognised as being Complex Adaptive Systems. A CAS is usually characterised by the existence of multiple interacting components (as for any system), non-linearity of pattern and process, the need for an external energy input to maintain the system (ultimately energy from the sun, but according to definition this may rather refer to, for example, sufficient external resources such as money or food), the capacity to self-organise (i.e. for the system to emerge without specific planning or design, at least in its entirety), and the capability to change or adapt in response to change (e.g. disturbance) originating within and beyond the system.

2.5 Disturbance: An event that is detrimental, or potentially detrimental, to one or more components or processes within a system. Usually characterised according to frequency of occurrence, severity of impact, and duration of effect. May have more specific meaning in certain system contexts, for example in ecological systems usually refers to something that leads to a loss of biomass within the system.

2.6 Ecological resilience: Ecological resilience is “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables” (Brand and Jax, 2007). This includes the capacity of the system to re-organise and maintain within the parameters that define its current state, rather than returning to a fixed or ‘equilibrium’ point.

2.7 Engineering resilience: Engineering resilience contains two aspects, which are resistance and recovery. Resistance is essentially the extent to which disturbance translates into an impact. If a disturbance occurs but the measured variables within the system (e.g. population, employment, frequency of flight take-off) do not change significantly, then the system can be considered to be resistant. Recovery is the speed at which a system returns to its point of displacement (e.g. how
rapidly populations, employment or flight frequencies return to the same levels found prior to disturbance). Engineering resilience therefore relates to more specifically to a return to a fixed or ‘equilibrium’ point (‘business as usual’) without a change in system organisation, and therefore differs from ecological resilience. This is often termed simply ‘resistance’ in many ecological or related studies, though the two types of ‘resilience’ are often conflated.

2.8 Equilibrium/non-equilibrium: Equilibrium is a property or characteristic reflecting balance in a system, attribute or measurement, such that deviation from the equilibrium may be considered notable, and usually with an assumption that the system, attribute or measurement will return to its equilibrium following displacement. A fixed equilibrium suggests an unchanging position, a dynamic equilibrium some deviation around an average position or value, but within defined limits. Non-equilibrium is a property or characteristic associated with fluctuations of systems, attributes or measurements, usually as responses to certain environmental factors or disturbances are differential. There is also no assumption that an equilibrium will be re-established following displacement, and so a given system may respond in an unpredictable way to environmental change.

2.9 Holarchy: Holons are entities within a hierarchy that are both wholes and parts – parts because they are elements of the hierarchy, but wholes because they also function independently within their own environment. Holons are distinguished by differences in the rates or frequencies of their characteristic processes. An example is an individual organism – it can interact with other organisms because both operate at the same space-time scales, but not with a biome as they are orders of magnitude different in scale.

2.10 Hysteresis: A change in stable state that results from changes in the variables or parameters that define a system, usually due to past disturbance or stress. Importantly, a shift in stable state cannot be easily reversed by removing or reversing the disturbance or stress, as the system itself has changed, and that particular aspect may be less important in the new system. This is a further characteristic of hysteresis.

2.11 Panarchy: The structure in which individual systems or subsystems are interlinked over space and timescales, with all systems going through adaptive cycles at their own space and timescales that are nevertheless influenced by those scales above and below. As an example, the ‘leaf’ system operates over very small space and timescales compared to the ‘forest’ or ‘biosphere’ system, but both are influenced by each other, even if weakly.

2.12 Perturbation: Often used as a synonym for disturbance or change, though Rykiel (1985) defines it specifically as the effect of a disturbance, i.e. the observable or measurable impact originating from a disturbance. A disturbance is the cause, while a perturbation is the effect within a system.

2.13 Resistance: The capacity of a system to prevent a disturbance having any measurable impact, for example maintaining economic performance despite a recession, or preventing the spread of an invasive species despite an initial invasion occurring. See also ‘Engineering resilience’.

2.14 Self-emergence/organisation: The emergence of a particular pattern or recognisable form of organisation resulting from a system’s properties operating naturally, rather than by intentional design.

2.15 Stability: The tendency of a system to remain at a relatively fixed point, as determined by key variables or characteristics of the system. Very few systems remain completely fixed, and usually
'Stability' is somewhat dynamic, positioned within distinct boundaries (e.g. population numbers, growth rates or community types).

2.16 Stable domains: Also termed 'domains of attraction'. This is a series of variables or characteristics that together define a particular 'form' or 'type' of a system. Given sufficient disturbance, a system will change the key structures and processes that drive and characterise the system, and so the system will move to a new 'stable domain'. Once in this stable domain, a system requires another further significant disturbance or change in stress to push it over another threshold and into another stable domain – i.e. the domain is stable without further disturbance.

2.17 Stress: Often synonymous with disturbance, but may refer to a slowly changing variable that influences a system, so that a distinction may be drawn between disturbance (rapid change) and stress (slow change). Examples might be a forest fire (disturbance) vs. the loss of soil nutrients (stress) in an ecosystem, or a sudden blocking of trade (disturbance) vs. a gradual decline in demand (stress) for an economic system. Again, may have specific meanings in certain contexts, such as a surfeit or deficit of an environmental variable in an ecosystem (e.g. water, light) that reduces biomass production.

2.18 System: A network of interacting components linked by processes. Most systems are discrete (i.e. forming a 'whole' or 'entity') but nested within larger systems (i.e. in a hierarchy or holarchy), and their boundaries are defined according to particular aspects or characteristics under scrutiny, or out of practicality. Particular definitions vary across multiple domains of research.

2.19 System of systems: A group of systems that utilise their resources and capacities to create a new system with greater functionality and improved performance, which goes beyond the simple aggregation of the individual systems.

2.20 Transformation: A fundamental reorganisation of a socio-ecological system ('regime change') that results in a new stable state and level of resilience/adaptive capacity.

2.21 Transition: An intentional incremental change within a socio-ecological system, as some members modify aspects of a system to increase resilience or adaptive capacity. This is essentially changing the current configuration of the system to alter resilience.

2.22 Threshold: A point (however defined, e.g. qualitatively or quantitatively) beyond which a system may be considered to have moved into a new stable state or domain.

2.23 Vulnerability: The incapacity of a system to cope with disturbances and still maintain its stable state. Generally utilised to mean the opposite of resilience. Essentially, as resilience decreases, vulnerability increases.
3 The development and evolution of the resilience concept for systems

3.1 The origins of resilience

The term ‘resilience’ first appears in English in either the 16th or 17th centuries, though its etymology is unclear. The term stems either from the Latin resilientia ‘fact of avoiding’ or from the Latin resiliens, to ‘leap back’ (Oxford English Dictionary, 2012). The term was initially applied to substances or materials, and incorporates the capacity for a substance to return to an original state after the cessation of a deforming stress (e.g. Hoffman, 1948). Even in 1948, Hoffman (1948) felt it necessary to propose ‘a generalized concept of resilience’ as the term applied to material substances, as it was clear that the term meant ‘different things to different persons’ (p. 141). It was recognised that substances responded differentially in both type and extent of resilience, with the key parameters being 1) response to an external stressor (stress per unit strain and increase of strain per unit time) and 2) recovery from stress, usually measured in a decrease in stress per unit time combined with some measure of capacity to return to original state (e.g. a decrease in deformation). Substances could be broadly grouped according to whether they were 1) low response and high recovery (high resilience), 2) high response and high recovery (medium resilience), 3) low response and low recovery (medium resilience) and 4) high response and low recovery (low resilience). This simple interpretation of resilience reflects an intuitive understanding of resilience as the capacity to return to ‘normalcy’ (or to not fail), something that repeatedly emerges as the concept of resilience has been translated to different disciplines and contexts.

Strunz (2012) has suggested that the particular definitions and interpretations of resilience used across different disciplines can be considered to be ‘ambiguous’, in that they share a phonological structure, but beyond that have little in common with each other. They may perhaps more accurately be termed ‘polysemous’ (again following Strunz, 2012) in that the terms are similar but separable – in each case the ultimate return to normalcy in the face of stress is the result of resilience, though the different contexts are clear in each case. It is when the term resilience is applied to broadly different systems that the various interpretations of resilience and its associated concepts begin to meld together and create some confusion regarding what exactly is meant by ‘resilience’ for a given system. It is therefore important to understand the different ways in which resilience as a concept may be understood and articulated, so that it may be appropriately defined for any given system.

3.2 Resilience and systems

The application of the concept of resilience as applied to systems originated in the field of theoretical ecology, with Holling’s (1973) seminal publication ‘Resilience and stability of ecological systems’. The details of ecosystems and the application of the terms ‘stability’, ‘resistance’ and ‘resilience’ within an ecological context are discussed in Section 4. Essentially, initial studies drew a distinction between stability, which is the capacity of an ecosystem to return to a relatively ‘fixed’ point within its current state or stable domain, and resilience, which was a measure of the amount of disturbance a system could withstand before changing its state from one stable domain to another, and therefore reflected the persistence of key relationships that maintained the system in a particular state (Figure 3.1).
Figure 3.1 – The current ‘state’ of a system may be defined by key characteristics relating to structure and process (the ‘box’). The current configuration of the system is represented by the black dot. The dot may move around within the box and still be within the same system ‘state’. The resistance of the system is a measure of how fixed the dot in relation to disturbance, or how fast it return to its location after a disturbance (often termed ‘recovery’. The resilience is the capacity for the dot to move around in response to disturbance, but still stay within the box (i.e. the same stable state). In the diagram, a shift from A to B represents a change in system configuration, but not a change in system state. System states must be defined based on appropriate variables for each system under consideration.

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<tr>
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<tr>
<td>Psychology</td>
<td>The capacity for an individual either to cope with a stressful situation without showing any negative effect (to ‘resist’) the stress, or to return to a normal state of functioning following stress or trauma.</td>
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<td></td>
<td>There has also been some interpretation of resilience as the capacity to become better able to cope with stress following trauma, i.e. an improvement in psychological condition.</td>
</tr>
<tr>
<td>Systems and enterprises</td>
<td>The ability of organizational, hardware and software systems to mitigate the severity and likelihood of failures or losses, to adapt to changing conditions and to respond appropriately after the fact.</td>
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<td></td>
<td>The capacity of a system to tolerate disturbances while retaining its structure and function.</td>
</tr>
<tr>
<td>Business</td>
<td>The ability of an organization, resource or structure to sustain the impact of a business interruption and recover and resume its operations to continue to provide minimum services;</td>
</tr>
<tr>
<td></td>
<td>The maintenance of positive adjustment under challenging conditions such that the organization emerges from those conditions strengthened and more resourceful;</td>
</tr>
<tr>
<td></td>
<td>The ability of an organization (system) to keep, or recover quickly to, a stable state, allowing it to continue operations during and after a major...</td>
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mishap or in the presence of continuous significant stresses.

Organisation science

Factors influencing the structure and dynamics of organizations that successfully survive and develop in complex and turbulent environments. In order to construct a resilient organization, the numerous parts or units composing its complex structure should be organized in two intermingled and integrated streams, which are referred to as the Performance system and Adaptation system respectively. The Performance system is in charge of pursuing excellent performances in the short term, which are of course essential for the organization to survive in the market. While in classical organizations a Performance system is static, within the new view to resilient organizations, the Adaptation system allows the Performance system to be dynamically created and be dissolved to respond to continuous changes in the environment. The management and coordination of this creation / dissolution process is performed by the Adaptation system. The Performance System forms the conservative part of the organization trying to preserve the current status, whereas the Adaptation system is the reactive or even the pro-active part to anticipate new market trends. Although both systems have to work together and have to be integrated in the whole organization, each one of them should be characterized by a different set of architectures, skills and culture.

Table 3.1: Examples of definitions of resilience from different disciplines that are not explicitly focused on in this review. Taken from information found in Argyris and Schon (1996), Stace (1996), Tugade et al. (2004) and Henry et al. 2012.

As with many ecological concepts, the use of the term ‘resilience’ was subsequently applied to different systems, in particular socio-ecological, socio-economic and socio-technical systems, with some transformation of meaning (Table 3.1). In some cases this may be because of a misunderstanding of ecological systems and the context within which the original systems resilience concept was applied, but in others this has been an intentional revision of the concept to make it more applicable to the system in question. Repeated use of the term in an imprecise way has led to some confusion in its interpretation from the very beginning. Even in 1977, a paper discussing the application of computer science to address human-environment issues refers to Holling’s (1973) definition of resilience as the capacity to absorb perturbations and recover from them, obscuring the difference between resilience and stability. In many cases, a reversion to the more intuitive pre-system meaning of resilience (resilience of substance) has been the case, at least until recently.

The use of similar but subtly different terms related to resilience has understandably led to some confusion over how best resilience may be defined, measured and improved, even within a particular system. Importantly, the original ecological concept of resilience did not have associated value judgements but was simply a way of observing, quantifying and classifying system behaviour. It is with the transfer of concepts to ‘human systems’ (e.g. socio-ecological or socio-economic systems) that the term has take on important social meaning and responsibilities. Brand and Jax (2007) performed an extensive review of the literature and categorised ten broad interpretations of resilience that had proliferated. They group these into three classes, which are 1) descriptive (relatively objective), 2) hybrid (both descriptive and normative) and 3) normative (wherein resilience is considered a beneficial attribute of a system that should be pursued). The categories were (taken from Brand and Jax, 2007, p.3-4):

Descriptive:

1. Original-ecological: Measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.
2. Extended-ecological: The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour, AND The capacity of a system to experience shocks while retaining essentially the same function, structure and feedbacks.

3. Systemic-heuristic: Quantitative property that changes throughout ecosystem dynamics and occurs on each level of an ecosystem's hierarchy.

4. Operational: Resilience of what to what? AND The ability of the system to maintain its identity in the face of internal change and external shocks and disturbances.

5. Sociological: The ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change.

6. Ecological-economic: Transition probability between states as a function of the consumption and production activities of decision makers AND The ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently.

Hybrid:

7. Ecosystem-services-related: The underlying capacity of an ecosystem to maintain desired ecosystem services in the face of a fluctuating environment and human use.

8. Socio-ecological system: The capacity of a socio-ecological system to absorb recurrent disturbances... so as to retain essential structures, processes and feedbacks.

Normative:

9. Metaphoric: Flexibility over the long-term.

10. Sustainability-related: Maintenance of natural capital in the long run.

Several of these key definitions are explored throughout this review, in the context of different systems.

3.3 Key components of the resilience concept

Fundamentally, the following general points can be used in the context of resilience for systems: 1) resilience of a system refers to the capacity to maintain fundamental processes that characterise the system via a process of adaptation, rather than simple resistance, in the face of disturbance or stress; 2) all systems have some level of intrinsic resilience; 3) the definition and determination of resilience used will vary between systems and will depend on the spatial and temporal scales defined by the user; 4) the resilience may vary spatially and temporally, even within the same or comparable systems; 5) resilience is a quality of a system that can be measured in some way, but needs to be in the context of a particular form or forms of disturbance (or stress, depending on definition). Without disturbance, resilience would not be a relevant concept, and so in effect all forms of resilience are 'operational' (after Brand and Jax, 2007) in some way. Many individual studies only consider one form of disturbance in relation to system resilience – and even where multiple disturbance or stressor types are considered, covering all forms is difficult.

3.4 Transfer of the resilience concept to different disciplines

Resilience as a concept has grown substantially in popularity in recent decades. The concept began to transfer to other disciplines and contexts in the 1990s, probably in response to an increasing recognition of non-equilibrium and non-linearity in different systems, alongside the development of 'post-normal' science that acknowledges uncertainty and unpredictability in the framing and
addressing of scientific questions (Funtowicz and Ravetz, 1993; Francis and Goodman, 2010). An Ngram graph of the term ‘resilience’ can be seen in Figure 3.2, highlighting the growth of the term in published works. The most dramatic increase was from 1990-2005, after which usage has been increasing more slowly. ‘Resilience’ is particularly being used as a panacea for large-scale problems associated with great uncertainty, including climate change (e.g. Nelson et al. 2007; Vogel et al. 2007; Pelling, 2011), disaster adaptation and response (e.g. Adger et al., 2005; Vogel et al. 2007), and issues around health, risk and national security (Coaffee, 2008; Loring and Gerlach 2009). Strunz (2012) draws a distinction between what he terms polysemous resilience, wherein the term is precisely defined for each particular discipline or system that it is applied to (though of course there are similarities and obfuscations), and resilience thinking, wherein resilience terms are applied in a vague way across different contexts. Both the precise and the vague uses of the term have value. Precision is required for scientific validity, as it restricts the inclusion of wider concepts and interpretation that may confuse findings, ensures that limits to the terms used can be clearly stated, is necessary for empirical testability, and ensures transferability and comparison of results. Vagueness on the other hand may help to foster creativity in resilience thinking, may help with communication across disciplinary boundaries, and may be more widely understood by non-scientists within the post-normal ‘extended peer community’ (e.g. Strunz, 2012). In the ultimate context of ATM considered here, we assume that a precise definition within regards to the socio-technical system under consideration is the most important (see Deliverable 1.3), as the ultimate aim of ensuring the resilient functioning of ATM systems has significant health and economic implications, and it is important that resilience can be empirically measured. However, we wish to understand the other interpretations to allow some of the strengths of wider resilience thinking to be incorporated in the composition of ATM resilience. Consideration of these types of knowledge within the context of ATM systems will help to ensure system resilience, and therefore sustainability, to the middle of the 21st century.

Figure 3.2: A Google ngrams diagram highlighting the use of the term ‘resilience’ in published works found on Google from 1900 to the present day (October, 2012). Note rapid growth from 1970s and then exponential growth from mid 1980s

Regardless of the ways in which the term resilience, and those terms associated with it, has been used across the disciplines and in different contexts, it is now embedded in scientific, political and corporate language. In some cases this has involved literal translations of the Anglophone term resilience into other languages, in some cases with inappropriate contexts. Although there has been little work on this aspect, it has been clear from informal discussions that the term ‘resilience’ does not always have a literal translation in some languages, and as a result an alternative term is used, which is more similar to ‘resistance’ or ‘stability’. This can further confuse interpretations, especially between international partners.

Pavard et al. (2006) further consider definitions of resilience, robustness and regulation, most specifically in relation to socio-technical systems:
• A robust system is one which must be able to adapt its behaviour to unforeseen situations, such as a perturbation in the environment, or to internal dysfunctions in the organisation of the system.

• A resilient system generally aims to maintain a constant output value, a performance, a production, or a function, etc. without fundamentally questioning the internal structure of the system in charge of the regulation. In certain cases, the structure of the system may be intentionally modified. However, this modification is always undertaken within the context of a process where it is a control structure (i.e. the meta structure) which decides the organisational changes.

• From a systems theory point of view, the processes linked to robustness are very different from resilience since 1) they inevitably do not guarantee to maintain the function of the system’s components (new functions can emerge in the system) and 2) it is difficult to disassociate the system from its environment since the two entities can be so closely coupled.

There are three main categories of regulation:

• ‘Classical’ regulations have the objective of constantly maintaining certain behavioural variables of the system to one or more reference values. These regulations generally resort to ‘feedback’ type mechanisms which aim to ensure the stability of the system’s behaviour.

• On a scale of increasing complexity, next are those regulations which, by self-adaptation, modify the structure of the system itself.

• Finally, there is regulation by emergence and self organisation. In this case, the mechanisms that govern the system are no longer controlled by the stakeholders but result from decisions that are usually taken at a local level without any global vision of the situation.

3.5 Recent perspectives on resilience and its limitations

The general consensus amongst both scholars and policy makers is that resilience is a good thing, a desirable attribute to have in a system. There has however been recognition that there is often a fundamental conflict between the desire to achieve stability (constancy, or resistance) and resilience, which includes the capacity to change or adapt. Although stability of a system as a whole, or of the fundamental components, outputs or processes of a system may be achieved by adaptation, this inevitably will involve modifications to some components or processes, which creates tensions in any system with human components. Such tensions depend greatly on the values placed on components and processes within the system. In an ecosystem for example, the replacement of one species of nitrogen-fixing plant with another, even with some loss of associated species, is unlikely to have a great effect on the structure and function of the system (e.g. biogeochemical cycling). The stability is maintained. However if the species are valued differently (the replacing species is an alien species for example, or harmful to human health), such adaptation becomes undesirable.

Likewise in a social system, where values are placed on all aspects of the system, even small changes may be undesirable. Pelling (2011) presents the example of Quintana Roo in Mexico, a rapidly urbanising coastal area that is important for tourism, but subject to hurricanes. In this socio-ecological system the residents of the tourist areas are mainly migrant workers who maintain little community cohesion or values, and are present only to make money. When a hurricane strikes, they accept losses to their residences (which they care little about) and return to their home towns and villages. This makes the system resistant to the disturbance – the people return and with some repairs, everything carries on. But the system is not truly resilient, in that no real adaptation is taking place. The government does not desire such adaptation, as it would mean finding ways to improve residences and infrastructure and build community cohesion, at great cost and effort. But without it, the system is probably unsustainable long-term, as repeated migration will not always be possible, and poor community cohesion may lead to increased development of social problems that may harm the tourist economy.
Furthermore, the building of resilience in one part of a system (e.g. via a form of adaptation) may compromise resilience elsewhere – for example where institutional capacity is focused on the response or adaptation to a particular form of disturbance or stress, and thereby reduces capacity to cope with other, less expected disturbances (Walker et al. 2006). It is important that actors within any given system do not assume that a resilient system is stable and unchanging, and that the tensions between a system that is resistant to disturbance and one that is resilient to disturbance are recognised.

There is also wider concern that the term can create unrealistic expectations – that a system that is considered to be resilient is therefore foolproof or ‘fail-safe’ when in fact no system is (Ahern, 2011). This has meant that some policy makers or organisations are shying away from using the term resilience as it may instil unrealistic expectations in people – either that a resilient system is in fact a resistant (stable, constant) system, or that a system considered to be resilient will have taken into account all potential disturbances and produced mechanisms for preventing or coping with them. In fact, those in favour of resilience generally wish to allow greater flexibility and adaptability, which involves change and learning, while other actors want to ensure the status quo and favour robustness or a simple decrease in internal or external system disturbances. This has also been accompanied by a fundamental assumption that the system and its outputs or objectives are appropriate and correct, so that the system’s persistence is desirable. In some cases the system may not be desirable (for example a corrupt political regime, or social system that denies environmental justice to many of its members), and so resilience may be perceived negatively in comparison to stability. In this sense, increasing resilience may prevent the full transformation of the system that is ultimately required.

### 3.6 Resilience and Air Traffic Management

We consider that resilience is important for ATM because this represents a complex socio-technical system that will be placed under increasing pressure in the coming decades with increased air traffic, growing demands and uncertain social and environmental stresses and disturbances. It is clear that for Air Traffic Management, a hybrid resilience concept is most appropriate – resilience is desired (normative) but should be described as objectively as possible. The key aspects are that not only should the system not change its fundamental state (‘stable domain’) but also the key parameters of the system should remain stable/resistant. This is implicit in the Complex World Position Paper (2012) definition of resilience, as follows:

‘Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions’ (p. 71). This definition is therefore considered appropriate for ATM systems.
4 Resilience in ecosystems

4.1 Defining an ecosystem

An ecological system, or ecosystem, was originally defined by Tansley (1935) as 'the whole system, including not only the organism-complex (species community) but also the whole complex of physical factors forming what we call the environment’. Though this original definition has been debated and redefined, including a focus on the nature of processes, interactions and flows, it may essentially be considered as the biotic and abiotic components found within a spatially delineated area, and is therefore scale independent (i.e. may be defined at any spatial scale). An ecosystem is characterised by 1) complex physical and biological structures that are nested in space and time scales, 2) self-organisation of pattern and process, 3) dynamic flows of matter, energy and information, 4) change in system structure/organisation and individual components over time (e.g. due to succession and evolution), and 5) non-linearity in patterns and processes (e.g. the existence of feedback loops and thresholds). Ecosystems differ from the other systems reviewed here in that they have no specific purpose (unless artificially constructed by humans, e.g. cropland, and are therefore part of socio-ecological systems) other than to reproduce their component parts (mainly biological and to some extent biogeomorphological aspects).

Early investigations into ecosystems acknowledged that they changed structure and characteristics over time, but assumed 1) relative stability of components (e.g. biological communities, populations) between time steps and 2) predictability of development (succession). The system was therefore seen to be deterministic. Although some of these assumptions were challenged, much ecological work was focused on quantification of populations, communities and physical characteristics (e.g. soils) and how ecosystems will return to their relative equilibrium (their stable state, or constancy) following disturbance. Stability was recognised as a fundamental property of an ecosystem and also a desirable attribute, as a 'fixed' system was somehow stronger and more reliable than one that changed frequently or behaved in an unpredictable way.

4.2 Ecosystems as complex adaptive systems

This perception of ecosystems as fixed or stable began to change with greater exploration of chaos and non-linearity in natural and social systems, and the recognition that such characteristics are very common in ecosystems, which are highly dynamic and unpredictable at multiple scales (Levin, 1998). These characteristics in turn have been closely linked with ideas of system resilience, as the underlying capacity of the system to be flexible and to change in response to its environment largely determines its resilience. Ecosystems are now explicitly recognised as complex adaptive systems (CAS) (Levin, 1998). A CAS may be characterised by the existence of multiple interacting components, non-linearity of pattern and process, the need for an external energy input to maintain the system, the capacity to self-organise, and the capability to change or adapt in response to change (e.g. disturbance) within and beyond the system. These characteristics are generally associated with resilience. The capacity to self-organise for example is essential in ensuring that key components are processes are found within the system, that they operate at appropriate scales, rates and orders of magnitude, and that they will be able to re-emerge if the system undergoes catastrophic disturbance – i.e. shifts to a new stable domain. The capacity to learn and adapt is reflected in plasticity of species behaviour, morphology and phenology, changes in populations and communities, and evolutionary processes at the largest scales.

4.3 Adaptive cycles in ecosystems

Ecosystems are considered to go through four ‘functions’ within what is termed the ‘adaptive cycle’. This has also been applied to other systems since its original conception for ecosystems. The four functions are exploitation (r), when a system is emerging and there is rapid utilisation of available resources (space, light, stored nutrients, seed banks etc); conservation (K) when some level of stability (even though dynamic) is established, and there is a general accumulation of resources
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D 1.1 Analysis of resilience in manmade and natural systems

...resilience in manmade and natural systems; collapse or release ($\Omega$), where the system is pushed to a new stable state by some external or internal disturbance (the threshold function), and so resources are released (space, light, nutrients, organic materials etc., e.g. due to disturbance that leads to mortality of organisms; and reorganisation ($\alpha$), when new organisms and processes arrive/occur, perhaps in novel combinations, and so the exploitation phase can begin. The first two stages are essentially the emergence and stabilisation of the system (and are more predictable), while the second two are the collapse and reorganisation into a new stable state (which is less predictable) (Figure 4.1). Exploitation and conservation are slow parts of the cycle (essentially relating to succession, the change in a system over time), while collapse and reorganisation are much more rapid (Holling, 2001). It is generally assumed that resilience is higher in the collapse and reorganisation phases, as networks are less rigid, while resilience is lower in the exploitation and conservation phases, where a particular ‘system state’ has emerged. Importantly, all ecosystems go through these cycles naturally (e.g. as the result of disturbances such as disease outbreaks through to climate change). Holling (2001) further notes that there are three fundamental components that influence the adaptive cycle within a system: 1) potential, or a measure of the range of future possibilities available. This may be simply termed the ‘wealth’ or ‘richness’ of an ecosystem and may relate to, for example, regional species pools or available energy; 2) controllability, or how connected system components and processes are and how rigid or flexible the structure is (essentially a measure of sensitivity); and 3) the adaptive capacity, or how easily a system may be able to adapt structures and processes to cope with a disturbance (the ‘ecological resilience’ of the system).

Figure 4.1: The adaptive cycle (see description). Taken from Holling (2001).

4.4 Disturbance in ecosystems

Unlike in some other systems, the terms ‘disturbance’ and ‘stress’ mean different things in an ecological context. Disturbance is an internal or external event that results in the loss of existing biomass within the system, for example organism damage or mortality. Examples include disease outbreak, wind-throw of trees, wildfires, landslides, flooding and so on. Disturbances may be...
categorised according to their frequency, severity and duration, and the capacity for ecosystems to be resilient to certain disturbances will depend upon these variables (Turner et al. 2001). For example, a long-lasting disease outbreak that causes illness and/or death of organisms may have low severity and frequency, but high duration. A hurricane or wildfire may have low frequency and duration but high severity, while high winds that topple trees may have low duration and severity, but high frequency. These all present different impacts to a given ecosystem (at a given point in time), and so it may respond in different ways, particularly when different disturbances are combined. As an example, Brooks and Chambers (2011) describe how the invasion of non-native grass species to deserts in the Great Basin of the USA may provide greater fuel for periodic fires, taking the fire regime outside of its usual frequency, duration and severity trends and thereby lowering the resilience of the system as a whole to fire disturbance – though different desert ecosystems will maintain different intrinsic resilience levels to begin with.

However, disturbances are fundamental to ecosystems and essentially represent a resource that is essential for their continued functioning. Intermediate levels of disturbance have long been shown to help prevent competitive dominance by a small number of species, allowing greater species diversity and potentially a better functioning of the system (Connell, 1978). Disturbance therefore actually helps to ensure the resilience of the system in many cases, as long as the level of disturbance is not too extreme, and therefore there may be something of a positive feedback between relatively short, frequent, non-severe disturbance and ecosystem resilience. It is increasingly recognised that ecosystem disturbances are stochastic and somewhat non-linear. This is not always the case in some other systems, where most or all forms of disturbance may be considered to be negative (though see Section 6 on socio-economic systems for another example of 'positive shocks').

Stress, in an ecological context, is considered to be a surfeit or a deficit of one or more environmental resources (e.g. water, nutrients) that limits the growth, survival or reproduction of an organism or organisms. Stress is normally relatively constant and associated with the nature of the ecosystem itself; for example deserts being characterised by water stress. An increase or a decrease in stress will also create a system response, but this is generally less crucial than disturbance as the relative fluctuations are smaller, and do not last as long. Most organisms within the ecosystem will be adapted to stresses found within the system, which essentially represents a form of 'ecological memory'. Within established parameters of stress, most ecosystems will therefore be resilient to fluctuations, though relatively rapid changes in stress (e.g. resulting from climate change) are likely to cause significant disruption. Stress may also act as a slowly changing variable that may generally push an ecosystem towards a change in stable state (Pahl-Wostl, 1995).

4.5 The emergence of ecosystem stability and resilience as concepts

Holling (1973), building on earlier work in the 1960s, was the first to propose that stability and resilience were two separate properties of ecosystem function. Stability was the ability of a system to return to equilibrium or constancy (the point of displacement) following a disturbance, while resilience was the capacity of an ecosystem to absorb disturbance while maintaining key structures and processes, and therefore persist in its current state. Examples of key structures and processes may include particular species or communities, seed banks, soil types, water availability, rates of nutrient cycling, species reproduction and dispersal etc. The importance of this distinction lies in the idea of a change from one stable state to another, and the understanding that thresholds exist that, once crossed, will cause a change in system state. Importantly, the thresholds are not symmetrical, in that once crossed, a change from the new stable state may require once again a substantial level of disturbance as the system has re-organised and structures and processes may not function in the same way (a pattern termed 'hysteresis' (Figure 4.2).

A good example of this is lakes, subjected to disturbance (or stress) in the form of increased addition of nutrients (cultural eutrophication – a ‘slow variable’ change in contrast to rapid disturbance from e.g. a landslide). As nutrients are added and phytoplankton populations increase, oxygen within the water is consumed, creating a hypoxic (oxygen-reduced) environment. Sunlight is also blocked, restricting photosynthesis below the surface and changing (e.g.) the water temperature. These and
other effects change the food webs in the lakes, increasing mortality rates, lowering populations and changing community composition (e.g. Pahl-Wostl, 1995). As a result, the physical environment of the lake also changes, and a new stable state emerges (Figure 4.2). Once this threshold is passed, simply reducing the nutrient levels of the lake below the threshold will not return the system to its previous state, but very large reductions must be made as well as other interventions to achieve the original stable state.

As the properties of stability and resilience are different, ecosystems may be stable but not resilient, and resilient but not stable. As an early example, Watt (1968) found that populations of forest insects in Canada that periodically experienced extreme climatic conditions had widely fluctuating population numbers (low stability) but nevertheless persisted in the face of such disturbance (high resilience). Forest insect populations in less variable climatic regions exhibited more constant population numbers (high stability) but did not persist following climatic perturbations (low resilience). The relationship between stability and resilience will have emerged for a particular ecosystem based on the development (evolution) of the system within a particular disturbance/stress regime. Systems subjected to frequent (but not severe) disturbances are more likely to be resilient than those that are not.

**Figure 4.2: A hysteretic shift or change in stable state in a lake ecosystem.** An increase in nutrient levels (slow variable) leads to a growth in algae until algae levels are so high that oxygen is depleted and many species die off. The increase in decaying material at the bottom of the lake then leads to a build up of gas that causes sediment to float up, making the water more turbid. A rapid change in both physical environment and community results. This is a new stable state, as simply reducing the nutrient levels won’t allow the system to return to its original state – the nutrients have to be reduced dramatically to allow a change. Taken from Pahl-Wostl (1995).

### 4.6 Space and timescales in relation to resilience

Ecosystems are holarchies, and are therefore spatially-nested ‘systems within systems’ that act as both a whole and a part (e.g. Figure 4.3). Each holon within the holarchy maintains its own spatio-temporal scale of structure and process, and it can be important to understand the similarities and differences between the varying levels when trying to determine how stable or resilient the system may be. For example processes such as the decomposition of organic matter will vary diurnally according to (e.g.) local temperature and invertebrate or microbial activity, seasonally according to
organism phenology and changes in microclimate, and over decades and centuries as succession
takes place, and communities and the physical environment change (e.g. Turner et al., 2001).
Likewise, organism activity will vary across a range of space and time scales, as will population
dynamics and (at a higher level) community composition and dynamics. The appropriate holarchic
level must therefore be recognised if resilience is to be measured – for example a study that focuses
on short-term population dynamics is not measuring the resilience of the system as a whole but only
one part of it. A true understanding of ecosystem resilience would probably require studies of long-
term patterns and processes, perhaps only recently made possible with long-term datasets from Long
Term Ecological Research (LTER) sites. Regardless, the holarchical nature of ecosystems has made
descrribing and quantifying their resilience problematic and often applicable only on a limited case-by-
case basis.

Much of our understanding of resilience in relation to ecosystems depends upon the ways in which
the ecosystem, the stable state, and the measure of resilience are defined and delineated. The
holarchical nature of ecosystems makes this particularly important, as a focus on one particular level
of the system will produce very different perceptions of whether the system is behaving in a stable or
resilient way. Likewise, the temporal point at which the system is defined will prove a constraint in
investigations. A system defined by a typical ecological community will be less resilient than one
defined by broad vegetation type (e.g. temperate forest), for example. This makes an explicit
statement of the spatio-temporal boundaries of the particular system under scrutiny essential for any
study into resilience, particularly if any form of quantification of resilience is to take place. The early
examples given above for Canadian forests (Watt, 1968) have used insect populations as their
indicator of stability and resilience, but this does not necessarily say anything about the wider system
or the key processes that are driving the system. These limitations are discussed further in Section
4.9 on ecosystem resilience metrics.

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**Figure 4.3: Holons are entities within a hierarchy that are both wholes and parts – parts
because they are elements of the hierarchy, but wholes because they also function**
Holons are distinguished by differences in the rates or frequencies of their characteristic processes. For example, an individual organism can interact with other organisms because both operate at the same space-time scales, but not with a biome as they are orders of magnitude different in scale. The biome is background or context for the organism.

### 4.7 Engineering resilience vs. ecological resilience

Following the development and application of the resilience concept in varying ways within the ecological literature, and with increasing recognition of ecosystems as complex adaptive systems (Levin, 1998), Holling (1996) outlined two forms of resilience to clarify the different ways in which the term was being used ecologically. Engineering resilience contains two aspects, which are resistance and recovery. Resistance is essentially the extent to which disturbance translates into an impact. For example, an ecosystem that is subjected to a disease outbreak or species invasion but shows no changes in key variables such as number of species may be considered resistant to that particular form, severity, duration and frequency of disturbance. Recovery stems to some extent from Pimm’s (1984: 322) definition of ‘resilience’ as a measure of “how fast the [system] variables return towards their equilibrium following a perturbation”. Both aspects are simple measurements, and are most appropriate for systems that are still within a particular stable domain and have a single equilibrium state (Figure 4.4). Both of these aspects are frequently referred to as ‘resilience’ within the ecological literature, and relate to the ‘classic’ interpretation of ecosystems as balanced systems in equilibrium states, considered at relatively fine space and timescales. Rate of recovery is often termed resilience (e.g. Downing and Leibold, 2010) but it is not – in fact a disturbed ecosystem may never recover its pre-disturbance equilibrium, but as long as the key defining factors or characteristics persist, it is resilient.

![Distance displaced](image)

![Speed of recovery](image)

**Figure 4.4:** Engineering resilience is a measure of how far a system is displaced from its point of stability by a disturbance (resistance) as well as a measure of its rate of return to that point of stability (recovery).

In contrast, ecological resilience is “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables” (Brand and Jax, 2007). Gunderson and Holling (2002) expanded this into an ‘extended ecological definition’ wherein the system is ”The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control..."
behaviour, AND The capacity of a system to experience shocks while retaining essentially the same function, structure and feedbacks” (see Brand and Jax, 2007).

The extended ecological definition may be further broken down into three characteristics and four aspects. The three characteristics are: 1) the amount of change a system can undergo and still retain the same controls on structure and processes; 2) the degree to which the system is capable of self organization and 3) the extent to which the system expresses capacity for learning and adaptation (Brand and Jax, 2007).

The four aspects are (see Figure 4.5):

1. Latitude: This is a measure of the maximum amount a system can be altered (‘moved from equilibrium’) before changing state, and is usually depicted as the ‘width’ of a stable domain.

2. Resistance: This is a measure of how easy it is to change the system, and is effectively how easily or effectively disturbances are converted into measureable impacts within the system.

3. Precariousness: This is a measure of how close a system is to a threshold at which it may change its state, and/or a measure of its current trajectory of change (i.e. whether it is heading towards a threshold or not).

4. Panarchy (cross-scale relations): This is a measure of how changes at one scale of the system may influence system structure and function (and therefore its state) at other spatial scales. An example would be the introduction of non-native species at a local scale that change fire disturbance regimes throughout the ecosystem, or seral changes leading to shading of a small waterbody, which is turn experiences a change in community composition.

In all cases, measurement of these aspects of an ecosystem will depend on the operational definition of the system and the disturbances under consideration – this is considered in more detail in section 4.9.

An appreciation of how these factors interact with disturbance and stress highlights that ecosystem resilience is not merely about resistance to change and conservation of existing structures (Folke 2006) but also about a capacity to re-organize in the face of change, thereby retaining the function, structure, identity and feedbacks characteristic of a particular stable state (see Walker et al., 2004; Folke 2006). Therefore flexibility or adaptability of the system and its components is crucial.
Figure 4.5: An illustration of how the aspects latitude, resistance and precariousness relate to basins of attraction (stable states). Resistance may broadly be considered to be basin depth (how hard it is for a disturbance to push a system out of the basin), latitude is basin width (how far a disturbance has to push a system to move it into another state), and precariousness is how close the system is to a threshold.

4.8 Drivers of ecosystem resilience

Establishing the key drivers of ecosystem resilience is difficult, particularly as many may be interlinked, but they may broadly be considered to be: 1) species richness within a defined area, 2) redundancy of functional role of components (particularly species) within the ecosystem, and 3) connectivity and circuitry of linkages between system components. All of these properties have developed naturally over time with the ‘evolution’ of a given natural ecosystem, and it has been suggested that ecosystems evolve to their most resilient state possible within their particular environmental envelope (Cropp and Gabric, 2002). This is one reason why anthropogenic disturbance in particular is detrimental to system resilience, as it changes the environment and disturbance regime that the system has evolved within.

1. Species richness within a defined area. It is reasonably well established that more diverse ecosystems, i.e. those with greater numbers of species and greater evenness of species populations, are generally more resilient to disturbances (Downing and Leibold, 2010; McClanahan et al. 2012), though in some cases resilience is again confused with recovery from disturbance (i.e. stability). This is closely linked to the idea of redundancy (see below) and essentially suggests that the larger the pool of species that exists, the greater the chance that key structures and processes that are fundamental to a stable state may persist if one or more species is lost, as another may take its place (e.g. Sundstrom et al. 2012). This is more than simple redundancy however – many species within an ecosystem will occupy slightly different niches (with many remaining unoccupied), and this heterogeneity of potential response is important in allowing the system to cope with different types, frequencies, durations and severities of disturbance (Elmqvist et al. 2003). This was also observed by Elton (1958), who noted that simple communities are more easily invaded by alien species than complex ones. This is not always supported by empirical evidence however, and it is possible that other factors that drive species richness (e.g. productivity or resource abundance) may instead relate more closely to system resistance and resilience. Diversity also relates to productivity, which may represent capacity to recover (i.e. replace lost biomass) following disturbance (Brooks and Chambers, 2011).

As an example, Seddon et al. (2011) have recently shown that diverse mangrove ecosystems in the past displayed the capacity to respond to sea level rise as some species can display rapid growth in increasingly saline conditions. As a consequence, they rapidly accrete sediment and raise their canopy level, ensuring persistence of that particular stable state. However, this process also led to a gradual erosion of species and mangrove patches, weakening the resilience of the system overall. As a result, subsequent climatic changes that resulted in a ‘drying out’ of the coastal area and a drop in sea level rapidly caused a change in stable state from mangrove to microbial mats. The combination of disturbances therefore led to collapse of the stable state, in part because of a reduction in diversity.

2. Redundancy (as described above) mainly relates to key functional roles of organisms within the ecosystem (e.g. pollinators, decomposers etc.). Ecosystems with more species will generally have species that perform broadly similar roles, but the essential aspect of redundancy is that replacement of functional role is present at some level, even if the system is not particularly diverse. Absence of redundancy can dramatically reduce resilience. The classic community ecology study of Paine (1966) that examined the effect of removal of the only predator within a simple tidal pool ecosystem demonstrates that the loss of an important functional role without replacement can rapidly lead to a change in stable state. In this case, the presence of the starfish *Pisaster ochraceus*, which predated on all invertebrates within the tidal pool ecosystem, ensured that all species populations were kept in
balance, and so all species persisted; those species that were competitively superior and had higher rates of reproduction were also eaten more frequently by the starfish. Consequently the species, and its process of 'compensatory mortality' helped to ensure persistence of the stable state (as defined by ecological community composition). These are often referred to as keystone species, and are those that underpin a particular stable state and help to guarantee resilience.

In the same way, the presence of generalist species helps to ensure adaptive capacity in the face of disturbance. Generalist species are those that have the capacity to tolerate a wide range of environmental conditions and resources (the available niche), either because they are naturally 'robust' or resistant, or have flexibility of physiology, phenology or behaviour that enables them to respond to changing or variable conditions. This is essentially phenotypic plasticity, and in part is maintained by a high level of genetic variability within a species or population. This is an important cross-scale aspect of resilience – adaptive capacity of individual organisms relates to the adaptive capacity of the wider community and ecosystem.

3. Connectivity of a system can be in the form of processes, such as predation, photosynthesis, competition etc. (as illustrated in a food web, for example), or spatial connectivity that allows processes to occur (and is a fundamental aspect of spatial ecology or landscape ecology), such as ensuring that populations within a metapopulation can interact, that habitat required for reproduction is accessible by organisms, or that predator and prey species can be found within the same spatial area. As with all systems, connectivity between components is important in ensuring that the system functions well. Many attempts to improve ecosystem resilience have focused on increasing functional and/or spatial connectivity (Bengtsson et al. 2003; Fischer and Lindenmayer, 2007; Cumming, 2011).

A well-connected ecosystem (both functionally and spatially) is most likely to be resilient. In particular circuitry, or the ability for processes or species movements to occur if one or more functional or spatial linkages are lost, is very important for maintaining resilience. This is particularly important for connectivity between different broad types of components rather than individual species. Circuitry would exist in a functional sense if a predator species had multiple prey species to consume, so that if one became unavailable, it could utilise others. Although one linkage in the food web has disappeared, others exist that allow the same processes to persist. This has been suggested for food webs in general, and applies not just to interactions, but also (for example) to flows of nutrients (Reynolds, 1998). Generally, greater numbers of species within a food web will increase resilience, though interaction strength between individual species may also be key, with multiple weak interactions (or at least heterogeneity of interaction strengths) better than fewer strong interactions (which may be destabilizing) (McCann, 2000). There is some evidence that the length of food chains may be important however (i.e. the number of levels involved). For example, Carpenter et al. (1992) determined that longer food chains lead to lower resilience, probably due to the significant impact of a relatively small number of top-level predators. Dunne et al. (2002) have noted that there are thresholds of node loss at which a food web will collapse, and therefore a change in stable state occurs. Their primary findings were that the loss of connections within the food webs (rather than simply number of species) was the key factor that brought about a change in state, as well as the relative importance of the different species. In other words, removing those species (which may be considered keystone species in this context) that maintained multiple and/or important connections pushed the community towards a threshold more rapidly (increased the system’s precariousness).

As noted above, resilience must be placed in the context of the disturbances a system is subjected to. Brand and Jax (2007) have noted that environmental (external) disturbance is much more likely to cause a shift in state that internal disturbance (e.g. competition), partly because the system has evolved to accommodate the majority of internal disturbances. The main risks to ecosystems come when the disturbance regime is taken outside of its natural range. Konstantinov (2011) for example show that pine forests in Russia were resilient to periodic wildfires that removed individual stands of trees, as a range of species at different life stages (e.g. seeding) remained to replace those lost patches. Therefore, the fundamental components and processes that defined the system as a lowland pine forest persisted over time, demonstrating resilience. However, a combination of timber harvesting (focused on large mature trees) and burning made the fire regimes too frequent and
severe, so that large areas were burned and many individuals of reproductive age were removed. As a result, the system became more homogeneous and less resilient to disturbance – the capacity to reseed burned areas was reduced. Eventually this disturbance, if maintained, would cause the ecosystem to shift to a new stable domain. In this context, and for this particular disturbance, heterogeneity of population structure of key species is therefore the defining characteristic of ecosystem resilience.

4.9 Resilience metrics in ecosystems

Much consideration of resilience remains at a conceptual or descriptive level, and in many cases relies on somewhat subjective assessments of how resilient a system is or how it may or may not be changing in relation to disturbance. Fundamentally, any kind of measurement of resilience requires an operational definition, i.e. a statement of what variables are considered to represent a stable state/domain, and what ‘disturbance’ may consist of, including quantifiable parameters such as frequency, duration and severity. This may then allow appropriate metrics to measure resilience to be determined. Often these are related to ideal states, reference ecosystems or past ecosystem states. It is difficult to give a broad overview of metrics as these vary according to system, scale and individual cases. Many studies rely on modelling to determine the likely outcomes of disturbances.

At the most basic levels, a binary approach can be adopted. This is where a system (defined by key variables) is compared before and after a disturbance. If the variables persist and therefore satisfy the criteria for the system’s stable state, then the system is resilient to that disturbance (Pimm, 1984; Derissen et al., 2011; Strunz, 2012). Such observations have limited value, of course.

A more common approach to measuring resilience is to attempt to quantify the different aspects of resilience noted above, in particular latitude, resistance and precariousness. Alongside this, studies often attempt to measure stability or engineering resilience, in the form of rates of recovery (i.e. change over time, or time required to reach a certain proportion of recovery, e.g. 80%; Pimm, 1984). The same indicators tend to be used throughout studies of ecosystem resilience, though of course much depends on the way in which the system is defined. The foci tend to be on either absence/presence of populations, processes (e.g. nutrient cycling, seed dispersal) or species (particularly keystone species or functional species/groups), or on measurements such as species richness/diversity, population fluctuations, models of population persistence over time, rates of change, or heterogeneity of structure or process.

Latitude has been measured in varying ways. Leuteritz and Ekbia (2008) simply considered that the species richness of the system (for arid ecosystems) was a suitable measure of the capacity for change without a shift in stable state (partly due to an assumed link between richness and redundancy), and assigned broad qualities of latitude based on general species richness levels. Dunne et al. (2002) focusing more explicitly on food webs, determined that it was number of connections (species interactions), rather than number of species, that was the most significant metric for determining the latitude and therefore resilience of the community.

Resistance is often measured as negative feedbacks leading to reduced process rates resulting from disturbances, or rates of propagation of a disturbance. For example, Brooks and Chambers (2011) determined resistance based on factors that limited the rate or extent of spread of invasive species within an ecosystem. Those ecosystems that had lower rates of invasive establishment and spread were considered to be more resistant. Vinebrooke et al. (2003) determined that lower trophic levels (primary producers) in lakes were more resistant to acidification than other trophic levels, with the key metric of biomass production (productivity) being maintained at a relatively stable level by the replacement of species as they were lost due to acidification. Despite losses of species richness of up to 80%, primary producer biomass was maintained. Other trophic levels were not resistant however, and displayed notable changes in composition, so that the disturbance was reducing the overall resilience of the system despite some aspects remaining resistant.
Precariousness: Several studies have investigated precariousness without naming it as such; for example, Dunne et al.’s (2002) work on food webs and thresholds of collapse is essentially a measure of both the latitude and precariousness of different food web systems. Many studies evaluating precariousness have focused on population persistence under varying scenarios, for example habitat fragmentation and loss of connectivity (Opdam and Wascher, 2004; Fischer and Lindenmayer, 2007), but other studies have looked at, for example, heterogeneity of habitat structure as a measure of a system moving to a less resilient state (Konstantinov 2011).

McClanahan et al. (2012) measured precariousness in coral reef ecosystems using indicators such as 1) the presence of stress-resistant species, and 2) a broad range of temperature variability (which essentially represents a form of frequent disturbance), as this helped to ensure a wide range of species present and therefore functional redundancy. Ecosystems that had fewer stress-resistant species and reduced temperature variability were considered to be more precarious. Likewise, Seddon et al. (2011) demonstrated that the decrease in species diversity that occurs as a result of increasing salinity is essentially a more towards precariousness – as demonstrated by the change in stable state when the climate changed further.

Heyder et al. (2011) use a proposed ‘generic ecosystem stability index’ to predict probability of ecosystem state changes under different disturbance scenarios, which is essentially a measure of system precariousness. System state is based on measures including 1) changes in vegetation structure related to plant functional types, 2) relative change in biogeochemical stocks and fluxes, 3) absolute change based on global mean values for the ecosystems, 4) changes in relative magnitudes of key biogeochemical exchange fluxes with respect to each other, as a measure of changes in balance between fluxes, 5) change in state in relation to the range of natural variability e.g. over interannual cycles.

Cross-scale measurements related to panarchy have also been measured in some studies, for example to determine similarities of key variables at differing spatio-temporal scales. Sundstrom et al. (2012) investigated this for bird species body mass in grasslands, considering particular ‘groupings’ or ‘aggregations’ of body mass, which is thought to broadly reflect niche partitioning (similar sized birds occupy similar habitats or niches). They measured 1) overall number of functional groups, 2) number of functional groups within an aggregation, and, 3) the redundancy of functional groups across aggregations. The assumption was that a diversity of species and functional groups both within and between aggregations was supportive of resilience – this pattern was observed and remained after modelling the loss of threatened species. They determined that loss of threatened species at varying scales lowered resilience, but not as much as anticipated due to high functional redundancy. Measurement of this metric at varying scales may therefore indicate the resilience of the system more holistically, as well as identifying appropriate scales for management or building resilience.

Recovery and stability: Metrics to measure these related aspects of resilience include high rates of species recolonisation or regrowth after disturbance, and the presence/absence of key factors necessary, e.g. suitable substrate for re-growth (Seddon et al. 2011) or the presence of a suitable seed bank.

Despite the particular aspect of resilience being measured, the same broad types of metric are applied. They usually focus on one or more aspects of the biological components of the ecosystem, for example species presence/absence, diversity, or connectivity/interactions. Sometimes a key process is measured, for example population growth or other dynamics, or productivity (production of biomass). In all cases the metrics are heavily context-dependent, and a true understanding of the resilience of an ecosystem would probably be possible only with an ecosystem metabolism approach that utilised a universal unit, such as solar emergy; a techniques that remains in its infancy (e.g. Zhang et al., 2009; Jiang and Chen, 2011).

4.10 Ecosystem management and resilience
In the absence of human influence, the study of resilience for ecosystems represents an interesting observation of the ways in which the natural environment functions. However, it is when human agency influences ecosystems that and understanding of resilience becomes more important. As a dominant species with the intention and technological capacity to modify ecosystems at large spatial scales, humans can change all aspects of resilience, including latitude, resistance, precariousness, and so on. This can be both detrimental and potentially beneficial. The historical trend of human influence has been the reduction of broader ecosystem resilience to increase the stability of one or more particular aspects of the system. In effect, we have often taken an ecosystem outside of its usual disturbance regimes, either by increasing or decreasing one or more forms of disturbance. This inevitably leads to degradation of one or more aspects of the ecosystem.

The history of natural resource management has generally been one of reducing natural variability to maximise the output of one particular aspect of an ecosystem. For example, an agricultural ecosystem generally aims to maximise biomass production (yield) and its predictability by reducing species diversity (by planting one crop), genetic diversity (usually planting one variety or genotype) and environmental heterogeneity (e.g. ensuring consistent and desired levels of water, nutrients and soil types) (Holling and Meffe, 1996). This reduces all of the factors listed in Section 4.8 above: diversity, redundancy and connectivity. The illusion of stability is favoured over the realities of an unpredictable nature and we have traded resilience for short-term stability. The danger then comes with the social aspects of such modified ecosystems then being based around maintaining the stability rather than the system itself. Some components (monitoring, research etc.) are lost. As resilience declines, vulnerability to disturbance increases. When an event happens it therefore becomes more catastrophic than it should be. An example would be disease outbreak or species invasions in monocultures; what is usually a relatively trivial disturbance that would affect only some individuals or populations within a wider community can have a more dramatic impact and bring about a full change in community composition (e.g. Dukes, 2002). This may be considered to be a natural process, and is the system trying to re-obtain its resilience – but in a way that is undesirable to human use.

4.11 Building ecological resilience

There is a large literature on ecological restoration and improvement within ecosystems, and in many cases the indirect intention of such efforts is to increase resilience. This is reflected in the more recent focus on many studies on attempting to replace not just lost species, and thereby attempting to recreate a stable state that may not be able to exist anymore, but rather to ensure a complex food web and a wide functional diversity within the biological community (e.g. Rosenzweig, 2003). This increases redundancy and connectivity in particular, and is likely to increase latitude and resistance, and reduce precariousness. It is increasingly acknowledged that returning a system to a previous stable state is particular difficult due to the challenges of hysteresis, and the focus is more on improving the resilience of the current system (Ahern, 2011). This can be problematic where particular values are associated with an ecosystem state. As an example, urban ecosystems are often cited as systems that can be manipulated to increase resilience in the face of environmental change (e.g. climate change), as they do not have a pre-existing state that people value and so the operational definition of these systems is more flexible (Francis and Lorimer, 2011; Kattwinkel et al. 2011). In contrast, the focus for an endangered system (e.g. rainforest) would be more on preservation of the existing state (and its resilience drivers, such as biodiversity and connectivity) rather than trying to ‘improve’ the resilience. Objectively, it does not matter if an ecosystem shifts to another stable domain. This is essentially inevitable with sufficient time, and the same fundamental processes re-emerge due to self-organisational properties found in all ecosystems (Levin, 1998). The main problems arise when humans need the system to exist in a particular state (i.e. the state represents important societal values). There has been little quantification of the success of ecosystem improvements in operationally defined resilience terms, however, and indeed there has been some observation that restoration or improvement attempts may be unsuccessful because the degraded system is in a very different stable state that is not well understood (Suding et al. 2004).

4.12 A final definition of resilience in an ecological context
Ecological resilience may ultimately be regarded as the ability of an ecosystem (as defined by user) to persist in a particular stable domain (as defined by user) by maintaining the key structures and processes that characterise that stable domain. This persistence is maintained by the (adaptive) capacity of the system to re-organise in the face of disturbance while maintaining the key structures and processes. It is usually measured as the amount of disturbance needed to move the system from one stable domain to another (i.e. across a threshold or tipping point), and such measurements are usually based on metrics such as species presence/absence, diversity, number and type of connectivity/interactions, or fundamental processes or traits such as population change or biomass production. The particularly complex structure and nature of ecosystems (as holarchies) and the fact that they operate at multiple spatio-temporal scales (from the individual actions of organisms to the scale of evolutionary processes) means that research into ecological resilience has been limited, though the underlying concepts seem valid. Instead, much work has focused on ‘engineering resilience’ or ‘resistance’ to a fixed point within a stable domain. Importantly, it does not matter to the ecosystem whether the stable domains shift, and indeed this is inevitable. This only becomes important in socio-ecological systems, which are considered in the next section.
5 Resilience in socio-ecological systems

5.1 Defining a socio-ecological system

At its simplest, a socio-ecological system (SES) may be considered as interactions between a defined set of people and their natural and human-made resources or environment (see Gooch and Warburton, 2009). As noted in Section 4, any social system becomes a socio-ecological system if broadened sufficiently in scale to include the physical environment of which it is a part, and so the separation of social and ecological aspects of any SES is somewhat misleading. Walker et al. (2006) note that SES are more than humans positioned within an ecological system, or ecosystems positioned within human systems, but a particular type of system wherein both aspects need to be considered together.

Usually a SES may be considered a complex adaptive system (CAS) as for an ecosystem, and has the following characteristics (see Redman et al. 2004):

1. A combination of biophysical and social components that interact in a relatively consistent manner.
2. A series of spatial, temporal and organisational scales found within the system – this may or not be organised as a hierarchy or holarchy (as for an ecosystem).
3. A series of critical resources that are regulated by ecological and social components and processes (e.g. water use).
4. Dynamism and complexity, with evidence of adaptive cycles.

SES experience adaptive cycles in the same way as ecosystems (see Section 4.3). Holling (2001) notes that the accumulation of resources in the conservation phase (K) in an SES will include economic, social, and cultural capital, as well as resources such as skills, knowledge, trust and innovation. Walker et al. (2006) highlight some further important differences between ecosystems and SES, particularly in relation to the reorganisation phase (α). In SES, this phase may be particularly reliant on social capital such as institutions and institutional memory, trust in and between components, social networks, financial resources and so on, which add extra layers of complexity beyond that of simple ecological re-organisation. Likewise, it is perhaps more common for a SES to reorganise without a release of resources (Ω), such as in the event of an election that puts new social and political components and processes in place. In some cases it is also possible for a conservation phase (K) to not be reached, such as when an emergent economy is disturbed sufficiently that it collapses. Crucially, most SES are found within a conservation phase, and it is generally desirable to keep them in that phase – therefore much work on resilience looks at the resilience of this phase and how it may be improved.

Overall, a SES is fundamentally similar to an ecosystem in that both maintain high levels of complexity, dynamism, organisation, and natural or intrinsic resilience. Like ecosystems, SES may be self-organised or ‘emergent’ rather than planned, and may have no specific ‘purpose’ other than the continuance of resource use to maintain the social components of the system. As its most basic level this is persistence of the system, but may also include the growth or refinement of the system (for example). However, the capacity of humans to design, plan and influence at least part of such systems means that they can be guided in particular directions, which is an important departure from a purely natural ecosystem. Essentially, the purpose of the system depends on the way in which a given system is defined. Almost all studies have looked only at a few aspects of SES, as they remain highly complex. In this, they are also very similar to ecosystems.

5.2 Resilience in the context of socio-ecological systems

In general, most studies of resilience in SES focus on how economic or social activities lower ecosystem resilience, which is turn feeds back into the social or economic components and may make the system either less resilient or force a change in state. An example would be the intensive use of soil in a farming system so that it becomes unproductive and can no longer be farmed. When the
ecosystem resilience is reduced, the adaptive capacity of the social components is tested. If sufficient, the system may be maintained, but if not it will shift stable state (Walker et al. 2006).

Resilience may therefore be regarded as a hybrid concept for SES (see Brand and Jax 2007), in that it is has both descriptive and normative aspects. While resilience can be measured using various metrics, from both social and ecological perspectives, it is generally recognised that resilience is something to be preserved, desired, aspired to and constructed where it is lacking in SES. This viewpoint is relatively recent, and has emerged within the last 10-15 years (e.g. Milestad and Darnhofer, 2003; Collier et al. 2009). There has consequently been something of a transition from ‘resistance’ to ‘resilience’ in the ways in which SES have been conceived and managed, particularly in relation to long-term sustainability, which is generally recognised as being tied into resilience principles (Cumming, 2011; Pierce et al. 2011). In many cases, resilience has been used as a metaphor or concept to help with the overall understanding of a system and its dynamics rather than something to be specifically measured (Carpenter et al. 2001). It is still common for many studies to look at the simple capacity for self-repair within a SES (more a measure of resistance) rather than more sophisticated self-organisation that allows the system to be maintained (Apa et al. 2012).

Importantly, there are virtually no studies that have investigated SES in their totality, in the same way as for ecosystems. The systems are too broad and complex for meaningful data to be collected across the board for such systems, and as a result there is again the requirement for an operational definition, or a specific clarification of what aspects of the system are being considered for resilience, and what disturbance they are being considered against (Carpenter et al. 2001). Consequently studies have focused on one or more specific aspects of SES, usually with some investigation of how one or more cultural, economic or political aspects of such systems may be related to biophysical or broadly environmental factors (Milestad and Darnhofer, 2003; King and Salem, 2012). Most commonly this has related to some form of natural resource management (how a community is maintained by, or maintains, the natural resources that sustain it) or disaster management (how a community may respond to natural disasters) (Collier et al. 2009; Pelling, 2011). The essential premise for most SES resilience studies is that the system is more-or-less desirable in its current stable state, and so it is of interest how that stable state can persist, even in altered form, following some form of environmental stress or disturbance. Some studies have more recently taken this further to consider whether a change in SES state is required to ensure a new, more resilient state in the face of ongoing disturbances or stress (e.g. Pelling, 2011; Marshall et al. 2012).

To continue to conceptualise SES following ecological analogies, the social aspects of the system may be considered a further stable domain that sits within that of the ecosystem itself. Consequently there is a ‘social resistance’ and ‘social latitude’ found within SES, as well as a current level of precariousness, as for an ecosystem (Figure 5.1). It is possible for the SES to move outside of the social stable domain, and for the system to move to a new state, without the underlying ecosystem changing substantially. A SES that is reliant on a specific resource for example, such as a particular crop, may be forced to move to another stable state simply because of, for example, a change in market forces or climate that makes the current organisation around that crop untenable (Ostergard et al. 2009; Eakin et al. 2012). Though few studies have examined SES in these terms, they are useful concepts to help explain SES resilience.
5.3 Disturbance and stress in socio-ecological systems

There has been little detailed consideration of what differences might exist between ‘disturbance’ and ‘stress’ in SES, and the two terms are frequently used interchangeably (e.g. Chuku and Okoye 2009). Drawing on analogies found in ecological systems however, it would be more accurate to define stress as a ‘slow variable’ that changes over time, and which may nevertheless lead to a change in system state. An example might be the gradual erosion of soil within an agricultural SES that limits productivity, or gradual changes in economic factors that erode demand for a product or output. Changes in slow variables may be less easy to detect or evaluate within a SES. Disturbance may be considered a fast variable, the sort of event that causes significant disruption and potentially rapid changes within the system over a relatively short temporal scale, such as a natural disaster (landslide, fire, flood etc.) or an economic shock.

Many studies have focused on disturbance rather than stress – there is abundant work on how a rapid change to the natural environment, or the economic, social or political environment (e.g. stock market crash, revolution or insurgency, disease outbreak) may disrupt a system (e.g. Gunderson, 2010; Eakin et al. 2012). This is mainly considered in relation to how environmental disruptions create feedbacks to the social components and processes, and thereby cause them to work ineffectively. There is however little focus on the gradual erosion of resilience via the slow variables, despite this arguably being the more relevant consideration as such factors are hard to determine and may be more difficult to recover or replace. This has led to a ‘catastrophe’ model of resilience thinking and evaluation rather than a ‘chronic’ model as applied to most SES, which may be an inappropriate focus in some cases (Pelling, 2011). Of course, the gradual increase of stress within a SES may also alter the characteristics of the disturbances experienced, for example the construction of buildings on slopes increasing stress on soils and thereby exacerbating the frequency or severity landslide events or impacts (Petley, 2010).

5.4 Space and timescales in socio-ecological systems
Investigations of resilience in SES inevitably need to focus on a particular space and timescale to achieve an operational definition. However, panarchy, or cross-scale relationships, is present in SES as within any other complex adaptive system. Carpenter et al. (2001) note in particular that both disturbances and resilience will vary with the space and timescale under consideration, and that a SES may be resilient at one scale but not at another. It is a fundamental property of many SES that resilience is obtained at one temporal or spatial scale at the expense of another. Agricultural systems are a good example: technological developments (such as the addition of fertilisers or pesticides) may allow an agricultural SES to persist (i.e. maintaining crop yields, economic viability and human populations/communities over time in a similar 'state') in the short term, and are part of the adaptive capacity of the SES. However, over a longer term this may compromise the ability of the soil to remain fertile and lead to soil erosion etc., meaning that the system has reached a threshold over which it will tip, and change state – the system resilience (based on measures of crop yield, economics and human populations) is lost, unless adaptive capacity exists to further manage the soil to replace lost fertility (e.g. Hartemink, 1997).

This also applies at spatial scales, with resilience of a SES being bought at the expense of degradation elsewhere. This is found in poor-resource areas, which may import e.g., water and food from elsewhere, and in particular for urban ecosystems, which remain in their stable state at an unsustainable point far from equilibrium precisely because of huge external inputs from elsewhere – the 'ecological footprint' that can extend for many kilometres (Folke et al. 1997). This means that many systems may in fact not be intrinsically resilient as a result, but may only appear so in defined boundaries of space and time. Carpenter et al. (2001) note that many current SES exist due to a legacy of resource importation from around the world, as a particular region subsidises itself from elsewhere. This is reflected in the imperial histories that have been the consistent story of human civilisation. The only examples where this has not been the case are where SES become isolated, in which case resilience is often lost over the longer term, essentially as predicted by the adaptive cycle (see Section 4.3). As an example, the Easter Island culture clearly did not have sufficient resilience to cope with the environmental stress associated with long-term deforestation of the island followed by the disturbance created by European colonisation and spread of disease. Despite some adaptive capacity in the ways in which the environment was managed, the SES consequently shifted to a stable state where the culture could not persist (Hunt and Lipo, 2009). Crucially, while ecosystems can change state without being destroyed, this is not the case for SES, as societal breakdown or population extinction can occur (Carpenter et al. 2001; Hunt and Lipo, 2009).

Consequently, although it is important to define space and timescale under consideration for a SES, it can be a mistake to assume that spatial and temporal boundaries selected are appropriate to fully explain system resilience. Wallace et al. (2007) demonstrate how those sectors of New York that maintain poor socio-economic characteristics operate in similar ways to more affluent areas in their response to disturbances such as fires etc., contrary to expectations. This is because the individual sectors are part of a larger system, and the whole system should be considered rather than individual components or sub-systems due to fundamental linkages that mean that resources are in effect shared between sub-systems. In this case, fire response efforts put in place in one area deprive resources from other areas, while containment in one area facilitates a better response elsewhere, and so on. As a result, any operationally-defined system should be considered in the context of its place within the broader holarchy (see Section 4.6), as well as the level of heterogeneity within the wider system. This further highlights the importance of getting the spatial and temporal scale correct for an effective operational definition.

Nevertheless, different elements of a SES may be more resilient than others, and much depends on definitions and metrics applied. For example the cultural components of a SES may be resilient despite changes in environment or politics. This has been described as 'multi-resilience' by Apa et al. (2012), though this term is somewhat vague and not always helpful. It is perhaps useful as an acknowledgement that different 'types' of resilience exist. For example a system can be maintained by high natural resilience, for example in the natural resources available to a community, despite the social aspects (income, education etc.) being weaker.
5.5 Key elements of resilience in socio-ecological systems

Carpenter et al. (2001) note three aspects of resilience that relate to SES: 1) Factors that determine ecological resilience in the same way as for ecosystems (see Section 4) and therefore allow the system to naturally persist in a given stable state; 2) Endogenous (internally-driven) self-organisation, in particular ecosystem components that have co-evolved and are therefore fundamentally linked, along with social networks that allow innovative problem-solving; and 3) Evolution of novelty, which may be natural selection leading to speciation of biota, as well as social institutions that facilitate innovation and experimentation. All three are important for overall resilience of a SES.

Crucially, a SES differs from an ecological system in that the social components of the system may intentionally change the system, including the ways in which resilience is maintained or not. Adaptability or ‘adaptive capacity’ may be considered the capacity of individuals or groups within a SES to intentionally manage resilience (whether explicitly recognising the concept or not) so that it can avoid change into an undesirable state, or can move towards a more desirable state (for example after a catastrophic shift) (Walker et al. 2006). Alongside the natural resources or capital available within the SES, important social factors that influence adaptive capacity include:

1) Effective leadership. This is the capacity for strong guidance and direction to be given towards adaptation, and should be dynamic and responsive. It is also recognised that multiple leadership (i.e. leadership from several individuals or components but towards a single or similar aim) is more effective than a single dominant leader within the system (Walker et al. 2006). In some ways important components such as leaders or leader organisations may act in similar ways to keystone species in ecological systems, having a greater impact on the system than may be anticipated for their size, number or position within the system.

2) Social networks. These allow for multiple flows of information between components and allow greater flexibility of response and also redundancy, as several components may be able to act on information. This is analogous to a resilient ecosystem having a complex foodweb into which redundancy is incorporated, or a complex community that facilitates more rapid speciation and the creation of new information.

3) Trust. Information and resource (e.g. money) exchange between social components can only occur when sufficient trust exists within the system. A lack of trust can therefore limit adaptive capacity (Walker et al. 2006). This aspect is entirely social and may act to ensure persistence or reliability of connections within the system.

In some cases however, specific changes away from a stable state are desired by social components of the SES: a SES may be particularly desirable for some members of the system when in a particular state, but not for others (e.g. Pelling, 2011; see Section 3.5). Consequently, instead of maintaining resilience within a system, transformation is required. Transformation or transformability is an extension of adaptive capacity, and is essentially the capacity to create an entirely new system if it becomes necessary, for example due to ecological degradation or due to an undesirable social aspect such as a lack of environmental justice or political instability (Walker et al. 2006). Transformation may require substantial interventions, which may be driven by social, political or environmental changes (Gooch and Warburton, 2009).

Fundamentally, a SES is most likely to be resilient, adaptable and transformative when:

1. The system does not rely on a few key environmental resources but can draw from a wide range of resources, or is based in a generally resilient ecosystem (as detailed in Section 4). This essentially allows for redundancy of components or processes that may allow the system to persist. As an example, The Fako community in Cameroon displayed adaptive capacity following the eruption of Mount Cameroon by farming banana/plantain crops rather than tuber crops, as the acid rain following the eruption weakened the suitability of the soil for the stable tuber crops (Apa et al. 2012). Although this did not result in the same quality of output (food production), and therefore the system may
have ultimately moved to a more precarious position, the stable state remained the same and the system persisted. Such responses do of course also require sufficient adaptive capacity (e.g. knowledge, technology) to effectively utilise the natural resources available.

2. The social components of the system are characterised by relatively high levels of socioeconomic status that allows flexibility of response to stress and disturbance, such as higher levels of income, education, social mobility, and access to technology. These allow greater opportunities for repair and response, but also greater capacity for understanding and innovation that may fundamentally increase system adaptability and transformability.

3. The cultural context is one that encourages a range of resource use and allows openness and variety, as this also increases flexibility of response and preparation for future stress and disturbance. Cultures that lack this may have reduced resilience and increased vulnerability to stress and disturbance. Apa et al. (2012) for example show that the culture of Fako community groups following the eruption of Mount Cameroon was restrictive, being based around particular social castes and chiefdoms, and this prevented the cultural freedom required to allow relocation of habitation, new architectural design, disaster education, or other responsive efforts. Campbell and Butler (2010) have suggested that socio-ecological systems involving salmon harvesting in North America have historically been most resilient when a range of resource utilisation was combined with beliefs and social institutions that encouraged restrictions or regulation of harvesting, such as strict limits on fishing times or locations. These cultural norms would have prevented the collapse of salmon populations during periods of natural disturbance, and therefore ensured the resilience of the SES until more recent times, when the regional cultures changed.

4. A system that maintains political flexibility and therefore supports changes and innovation. Although a more repressive political regime may be able to respond effectively to stress or disturbances, particularly by enforcing a desired response (e.g. Walker et al. 2006), adaptive capacity and particularly transformability is likely to be more limited in such systems, though there has been limited investigation of this (Folke et al. 2010).

5.6 Metrics for socio-ecological systems

As with many social studies, investigations of resilience in SES have tended to use resilience as a metaphor for a system that has the capacity to change while maintaining a defined function or output, but have not used direct empirical measurements to inform the resilience (Pelling, 2011; Apa et al. 2012). Instead, they have speculated on how different processes may increase or decrease the capacity for a system to cope with particular forms of disturbance, and have used the ‘resilience’ concept to effectively ‘map’ the key components and processes within a system that allow fast response or recovery. In some cases these have been used to position a system at a certain point on the adaptive cycle, and Dearing (2008) utilised measures of land use change and soil erosion to establish movement through adaptive cycles within socio-ecological landscapes in Yunnan, China over the last 3000 years. With some exceptions, investigations have mainly been qualitative and have often focused on quite narrow interpretations of resilience.

As an example, Gooch and Warburton (2009) examined resilience from the context of natural resource management (NRM) groups in Australia, with group persistence and longevity being the key characteristics of a desirable stable state. They considered the three system properties of resilience, adaptability and transformability (see above). Based on interviews and questionnaires, they determined that resilience was linked to the presence of volunteers within the NRM system, as well as heterogeneity of individuals and their knowledge and experience. These volunteers in turn relied on governmental funding and strong communication between themselves and other components of the system; the lack of both funding and communication was perceived to reduce resilience of the NRM system overall. Adaptive capacity was found to relate to opportunities for exchange of information so that lessons can be learnt and both failures and best practice shared, alongside ongoing development of new skills and an understanding of the system and its uncertainties. This was considered to be facilitated with large networks and effective communication channels. This is fundamental to all SES...
but may be lacking in some cases. Transformation involves a willingness on the part of individuals and organisations to adapt and take risks and form collective partnerships, particularly in how resources might be used. This also includes the ability to experiment and openness of communication.

Although these aspects are often not measured in any real sense, it is possible to determine some key trends that link to resilience. In particular, the existence of fundamental components and processes (supply of money, communication networks), as well as the strength and connectivity of linkages between components, determine resilience. As for other systems, the incorporation of redundancy (so that if a particular component of the system exposes itself to risks it will not cause the system to fail) and again the level of connectivity, with larger networks allowing information and momentum for change to be harnessed, emerge as important aspects of resilience. Gooch and Warburton (2009) found that constancy of processes was found to be key – primarily funding, as sporadic funding was harmful as capacity to maintain the system was lost each time funding declined or stopped. As with the presence of keystone species in ecosystems, the presence and persistence of leader figures were found to be central to reliance and represent key components of the system – the main threat to these figures is burnout, i.e. too much work being allocated to particular individuals. Such figures represent important ‘source components’ for the flow of resources through the system. It remains unclear whether aspects such as interaction strength are beneficial or detrimental in SES, and this is likely to vary from case to case; for example, while some strong interactions are likely to be crucial for system persistence, there have also been observations that they may ‘lock’ a system in a rigid structure that reduces flexibility and thereby lowers adaptive capacity (Pelling, 2011). The general principles for resilience and adaptability within SES can be consistently demonstrated (see Section 5.5), but meaningful measurements can be difficult to obtain.

For those SES that are characterised by a particular product or output, quantification is much more feasible, and baselines can be established against which resilience or its related aspects may be measured (e.g. Carpenter et al. 2001; Milman and Short, 2008). Ideally, these would quantify the risks and uncertainty found within the system (its vulnerability), the adaptive capacity of the system, and the system structure, including linkages between components (Milman and Short, 2008). For example Carpenter et al. 2001 examined wool production in a grazed rangeland ecosystem, using vegetation cover as the key indicator of change, contrasting the abundance/biomass of grass with woody shrub species. Key metrics were shrub:wood ratios (mass per area) with the key metric being the difference in grass root biomass production between a desirable system of primarily grass abundance with some woody shrubs, to one dominated by woody shrubs alone (“distance between stable point and unstable threshold in units of grass root biomass (mass/area)”, p.177, as a form of latitude). This metric reflects further changes in fire frequency that are important for maintaining the grass state, and the absence of which leads to further impacts that lower resilience (e.g. loss of diversity, invasion by non-native species). They also determined that social factors such as property rights were crucial, as leaseholder conditions limited economic activities that could be performed in the rangelands, limiting adaptive capacity; as well as market conditions that encouraged alternative uses where possible (such that wool production via sheep grazing was not the only profitable exercise). The best studies of SES resilience measure both natural and social indicators. Natural indicators are essentially the same as for ecosystems, though it may be easier to model the adaptive cycle as social parameters may help to define the system and disturbances in question. Social indicators are usually the persistence of certain components or processes, or outputs.

Walker et al. (2006) suggest a ‘rule of hand’, wherein the fundamental properties that control resilience can usually be determined by measuring no more than five variables for a given system (i.e. a defined space and timescale). This is because human understanding tends to be limited to only a few different variables/dimensions within a system, and only a few variables will be dominant within a given system. However, determining appropriate indicators can be complicated. For example, Brooks et al. (2005) found that literacy rates were associated with reduced mortality following a disaster, and therefore used this as a metric for adaptive capacity of the SES, as it presumably reflects a socio-economic indicator for level of education or development, as well as the ability to access information following a disaster. De Lange et al. (2010) examine several indicators for socio-
economic systems and note that almost all use expert judgment, the input of stakeholders, and ranking and mapping of the results to create qualitative rather than quantitative outputs; where quantitative analysis is performed, it is mainly based on modelling efforts with many caveats. As a general point then, indicators for SES are very context-specific and may often be somewhat arbitrarily defined. A more easily quantifiable aspect of a SES is the economics of the system, and it is more common for studies to examine how disturbances to supply and demand may influence the economic resilience of the SES (e.g. Batabyal 2003). The ways in which resilience has been applied to economic systems, as a subset of a SES, is discussed in Section 6.

Overall, as for natural systems, key metrics are system or component persistence, key flows, number of connections, consistency of connections or flows, presence of important functional components (e.g. leader figures or species), heterogeneity and redundancy, emergence of novelty, and budgets of materials and fluxes (e.g. different forms of capital). Thus far, there has been little quantification of these aspects in a resilience context, and measurements are often not sophisticated or rigorous, being mainly qualitative assessments led by expert opinion (De Lange et al. 2010).

5.7 Building resilience in socio-ecological systems

Of the studies of SES focusing on resilience, most have been in the context of preventing loss of resilience, such as finding ways to use natural resources more efficiently and therefore make the system more sustainable in the short to medium term (Chuku and Okoye, 2009; Verhulst et al. 2011). Some studies have however investigated the ways in which resilience or adaptive capacity may be improved so that a system is more able to cope with future stresses or disturbances (Bloetscher et al. 2010). This has been most pronounced in the disasters management literature, with a pronounced move from disaster response to prevention-mitigation and increasing adaptive capacity (e.g. Pelling, 2011; McBean, 2012).

The building of resilience is most likely to be achieved by increasing those natural, societal, cultural and political aspects that support innovation and flexibility in decision-making and response, and therefore increase adaptive capacity. Perhaps the most useful measures for building resilience in SES is the ways in which the system may cope with changes in slow variables (stress), and thereby improve its resilience to change. Milman and Short (2008) propose an indicator for urban water provision, termed ‘Water Provision Resilience’, which may be applied to any SES within the context of sustainable water use. They improve on the usual indicator of ‘% of a population that has access to safe water’ to consider how resilience may be both maintained and increased over a 50-year timeframe. They obtained qualitative information on six aspects of water supply systems: supply, finances, infrastructure, service provision, water quality, and governance. A series of criteria relating to each aspect was developed, and points allocated on whether these criteria were met for a given system using both measurements (e.g. of water supply) and expert judgement. The resultant scores for the different aspects could then be used as indicators to demonstrate which aspects of the system need to be improved to allow the system to be both resilient and sustainable over the next 50 years. This is a simple way of categorising resilience rather than quantitatively measuring it, but can be a useful tool compared to complex modelling, and is perhaps more transferrable between different SES.

5.8 A final definition of resilience in a socio-ecological context

For socio-ecological systems, resilience is the capacity of both ecological and social components of the system to re-organise in the face of disturbance or stress, so as to persist in a given stable state. This is an extension of the resilience concept for ecosystems (see Section 4) but includes the acknowledgement that humans may shape adaptive capacity in specific ways, including entirely transforming the system if it is considered that it is no longer ‘fit for purpose’. Resilience in SES is generally considered a desirable trait, and therefore has a normative element in this context. The complexity of SES means that most investigations have focused on relatively narrowly defined systems, and have focused on qualitative rather than quantitative interpretations of what resilience is, comparing between ideals, other states and past states in their assessment of resilience. Key drivers of resilience in SES include redundancy, diversity, multiple connections/interactions, the presence of
key components, and the emergence of novelty and innovation, as for ecosystems. The central concepts therefore transfer across from ecosystem resilience, but have not always been well-explored in that context – many investigations are very system-specific, or use ‘resilience thinking’ approaches rather than operational definitions.

The review now moves to a focus on socio-economic and socio-technical systems, which may be considered subsets of SES but are generally easier to define in terms of their structure, relationships, and what resilience may mean for these systems, though resilience has only been considered for these systems relatively recently.
6 Resilience in socio-economic systems

6.1 Defining a socio-economic system

A socio-economic system, often referred to simply as an ‘economic’ or ‘regional’ system, is based around the flows of money and monetised resources (capital) between individuals and institutions, within a defined region. They are essentially subsets of socio-ecological systems, with a more explicit focus on the economic aspects of SES.

Economic systems are complex adaptive systems (see Section 4.2), though there has been little specific investigation of CAS in the economic context, with occasional exceptions (e.g. Holling, 2001; Tesfatsion, 2003). Importantly, they proceed through adaptive cycles in the same way as for other systems (Figure 4.3; Holling, 2001) with the distinct phases characterised by a build-up/release of economic capital in particular (Figure 6.1). Crucially, there is substantial desire to keep economic systems in the conservation phase (K) of the adaptive cycle to ensure continued accumulation of capital and wealth. The major difference between economic CAS and others is that, despite the presence of self-organisation and other key characteristics, economic systems are driven to a great extent by human action, and therefore contain specific elements of foresight and intentionality that aim to guide and predict the way the system functions and its dynamics (Holling, 2001). This may include, for example, particular forms of innovation, regulation, communication (e.g. using new forms of information technology), and may apply at a vast range of spatial and temporal scales.

The particular purpose of a given economic system can be difficult to determine, but may generally be considered to be: 1) persistence, or continuation of the system; 2) growth, i.e. an increase in output or productivity of the system, however this may be measured; and 3) wealth generation, or an increase in wealth for the different components of the system, though this may be differential (i.e. wealth generated more for some system components/sections than others).

![Phases of Adaptive Cycle](image)

**Figure 6.1:** the phases of the adaptive cycle in an economic system, illustrating the accumulation of capital at different stages in the cycle and how resilience is thought to change with the different phases. From Simmie and Martin (2010).

6.2 Resilience in the context of socio-economic systems

The concept of resilience has only recently been applied to economic systems, from 2002 onwards (Reggiani et al. 2002). In particular, the emergence of an ‘evolutionary perspective’ of economic
systems (Simmie and Martin, 2010) alongside the post-2008 global economic crisis and the difficulties that have been experienced in mitigating and rectifying the recession, has led to increased interest in the ways in which the concepts of resilience explored within Sections 4 and 5 may relate to economic systems (Martin, 2012). Where there has been a focus on resilience, it has been on the conservation phase of the adaptive cycle (K) or a relatively predictable business-as-usual situation, rather than on other phases.

Unlike in other systems, there has been some discussion in the economic literature as to whether economic systems have any form of resilience, or whether the concept is in fact helpful (e.g. Christopherson et al. 2010). This is alongside the usual considerations in relation to how resilience might best be measured or applied (Hudson, 2010; Martin, 2012). Perhaps most significantly, economic resilience is a contentious subject because researchers and analysts disagree on whether resilience is a positive or negative attribute of an economic system (e.g. Christopherson et al. 2010). Whereas resilience is not normative at all when considered for an ecological system, and may generally be considered normative for an SES, unless specific problems arise and some form of system transformation is required, for an economic system resilience may be considered a way of ‘excusing’ poor performance of a system, and instead a focus on stability or resistance to change is paramount (Martin, 2012).

Some of this conflict of interpretation may arise because of differences in the ways in which economic systems are conceived. As with ecology, early conceptualisations of the economic system have assumed a relative equilibrium, wherein a particular economic structure and its dynamics have been assumed to be reasonably consistent. This may be an equilibrium of state or may actually be (e.g.) a relatively stable growth trend. Many studies have defined resilience within this context, and have considered it as the capacity for a region to respond to and recover from a disturbance, usually measured in the context of its current growth trajectory (Foster, 2007; Hill et al. 2008). The focus is therefore much more similar to that of engineering resilience or resistance (see Section 4.7) – how a current growth trajectory may absorb a disturbance without changing, or how fast it may recover if displaced. This is not surprising given the history of assuming self-correcting forces in economics, whereby the system will return to its ‘natural’ conditions via market forces (Martin, 2012). From this perspective, as long as the measured aspect of the system (e.g. output, growth rate) returns either to its pre-disturbance point or to where it would have been had the disturbance not occurred, then it may be considered resistant. This is in line with the ‘plucking model’ of fluctuations (see Martin, 2012), which indicates that any form of impact should be temporary and that the system will recover over time (Figure 6.2).
More recently, resilience as applied to other systems is beginning to be considered for economic systems, such as how a system may reorganise its structure and stay within a defined state. In reality, the recovery of a system that is often defined in simplistic ‘resistance’ terms will probably involve some re-structuring and so in effect this may be considered resilience. Much depends on how the system is defined, e.g. using structure, growth rates, institutional arrangements and so on (Martin, 2012).

The ecological resilience concepts, where stable domains exist and systems may be pushed from one domain to another with sufficient disturbance, is now increasingly acknowledged for economic systems, and is mainly related to the concept of hysteresis. Structural change is therefore central to this. In the economic context, this is change in economic agents, composition of the economy (i.e. presence/absence or abundance of components), and a change in trajectory that becomes self-sustaining prior to a further disturbance. Consequently, instead of the ‘resistance’ shown by the plucking model, change to a new stable state may be characterised by a permanent reduction in (for example) output or employment, even if the rate of increase recovers (Figure 6.3a) or a decline in both (Figure 6.3b). These may occur when, for example, a recession is sufficient for a region’s industrial sector to be lost or damaged entirely, which then goes on to affect other sectors within the regional economy (e.g. outmigration, lack of investment), leading to a more stagnated economy, as often seen in neglected industrial regions (Martin, 2012). Uniquely, a disturbance may in fact prove to be beneficial for the normative aspects of the economic system, such as employment or output, and may also represent a beneficial move to another stable domain. This may occur when recovery returns to a higher than pre-disturbance state due to reformation of sector components, heavy investment, new technologies that increase productivity and so on (Figure 6.4). This new stable state may not be sustainable in the long term, however.
Figure 6.3: Negative impacts from disturbance that may lead to a shift in stable state. In (a) the growth rates recover, but the system maintains a generally lower output or employment (which is the metric used to define the system in this case). In (b), both output/employment are reduced, and the growth rate is also reduced. In both situations the system may be considered to have changed its state. From Martin (2012).

Figure 6.4: A beneficial change in stable state following a disturbance. In (a) the output/employment metric increases to a higher level and then maintains pre-shock growth rates. In (b) the output/employment metric increases both in absolute terms and in growth rate. From Martin (2012).

Martin (2012) considers that there are four ‘dimensions’ of resilience: resistance, recovery, re-orientation and renewal. Resistance is the same as for other systems – whether disturbances register in the system or not. Recovery is the speed and extent of a return to the pre-disturbance characteristics, however measured. These two together are essentially engineering resilience. Re-orientation is to what extent the structure changes, and how that may define the system characteristics. Renewal is whether the same growth path/trajectory occurs, regardless of whether
outputs etc. are the same. The two aspects are therefore linked to concepts of stable states and resilience. Re-orientation most relates to latitude – which components are important, which display adaptive capacity that allows them to cope with disturbances and so on. Usually more components and linkages means more resilience as adaptive capacity is greater – a diverse and heterogeneous economic structure means that different organisations or industries will respond different to disturbances, in the same way as species respond differentially to disturbances in ecosystems (Conroy, 1975; Martin, 2012). This may also incorporate an element of redundancy, in that the loss of an organisation or sector will not mean a large disruption to the system, as similar organisations will take on the functional capacity of the lost component. Renewal is perhaps most akin to ‘precariousness’ – how close the new situation is to changing the stable state. Too low a level of renewal and the stable state will have to change.

One key distinction between resistance and resilience in economic systems is that resistance is often considered to be related to the characteristics of the system, including structure, competition between organisations, workforce skills, entrepreneurialism, and economic governance arrangements, while resilience is related more to the political economy of a region, including the cultural and political systems that may help to shape responses and prepare for disturbances (Martin, 2012). This is a somewhat arbitrary distinction however, and the two are sure to overlap to a large extent.

6.3 Disturbance in socio-economic systems

Disturbances within an economic system are usually characterised in terms of ‘shocks’, which are external (e.g. social, technological, environmental) factors that have direct impact on specific economic variables used to define the economic system in question (e.g. output, employment). Examples might include sudden shifts in supply and demand, technological developments, some form of disaster or event that disrupts (e.g.) trade, currency fluctuations, changes in fuel costs and so on. These are the key disturbances in economic systems, and may ultimately be positive or negative. The key elements of the disturbances are (as for other systems) 1) severity, or the amount of change in the measured variable that the shock produces, 2) frequency, how often the shocks may occur, and whether they may have cumulative effects, and 3) duration, or how long the shock (e.g. a recession) is likely to continue for.

Economic shocks are linked to the concept of vulnerability of an economic system. Given the historical focus of the ‘resistance’ of economic systems rather than true resilience, there has been greater focus on vulnerability to shocks than many other aspects of the system. Vulnerability is often linked to 1) economic openness, which is a reliance on other regional economic systems and therefore means that disturbances elsewhere are more likely to impact the system, 2) a concentration of the economy on a narrow range of exports, which increases the risk of demand declining, and 3) a reliance on strategically important imports, which also increases the risk of a shock occurring if supply becomes limited (Briguglio et al. 2009). These observations on vulnerability tend to relate to negative shocks rather than positive, of course. Due to the ways in which economic systems are characterised and measured, e.g. based on output and rate of growth, fluctuations or deviation in output can be considered a sign of vulnerability, though in reality all systems fluctuate and this does not indicate a lack of resilience. Nevertheless, a higher level of resilience is more likely to ensure that fluctuations are not severe or do not lead to a change in stable state (however defined).

As a human system it is also acknowledged that disturbance, even those that push a system into a new stable state, may ultimately be desirable (‘creative destruction’) as outmoded structures or processes may be removed that allow greater output or productivity to follow. This relates to the adaptive cycle – everyone wants the system to remain at the initial growth phase (r) and conservation phase (K) rather than the breakdown and reorganisation phases, as they want to benefit from the accumulation of capital (see Figure 6.1).

6.4 Space and timescale in socio-economic systems
Economic systems are, often by necessity, defined based on geographical (regional) boundaries. Martin (2012, p.13-14) notes that ‘the [regions studied] are rarely functionally meaningful economic entities, but instead are often demarcated – for data collection, administrative or political reasons – along somewhat arbitrary lines’. This means that there are always limitations in measuring and interpreting the systems, as space and timescales considered are not always appropriate. Importantly, economic growth is discontinuous and growth in one area is likely to be at the relative expense of another area (e.g. as resources or investment are redistributed), or will involve the accumulation of capital that must be paid back in the future, so that (as with a more general SES), resilience is to some extent illusory and not indefinitely sustainable. No single economic system is self-contained, and there is increasing recognition that such systems exist within an ecological environment upon which they are dependent – the traditional view of economic systems as driven entirely by economics is being increasingly revised in the face of environmental changes and disturbances (e.g. climate change), a shift that relates back to initial suggestions of the need for an ‘economics of survival’ rather than mainstream models based on capital accumulation (e.g. Mueller, 2001; Hudson, 2010). Economic systems are therefore influenced by the wider SES they are a part of, and will also be internally discontinuous – different components within an economic system may be more vulnerable (i.e. less resistant and/or less resilient) than others. For example, it is widely accepted that industrial and manufacturing sectors within an economic system tend to be more vulnerable to recessionary shocks (Martin, 2012). This may translate into regional differences between economic systems, as they may be based more heavily around particular sectors or components. Martin (2012) found for example that the industry-based regions of the north of the UK proved less resistant to recessionary shocks than the more service and finance-based industries than the south, as once industrial capacity is lost (both financial and social capital, i.e. loss of money, outmigration, loss of investment, loss of industry) it is difficult to recover.

### 6.5 Key elements of resilience in socio-economic systems

As noted above, openness, export concentration and strategic imports have been linked to vulnerability, though consideration of resilience is less common. Briguglio et al. (2009) consider the ‘Singapore paradox’, where high GDP (as the key measured output) is maintained by an economy that should be very vulnerable to shocks. They are really considering resistance, as they examine features that allow the system to recover from negative shocks or exploit positive shocks, but key elements include 1) macroeconomic stability, 2) microeconomic market efficiency, 3) good governance and 4) social development. These are expanded in Table 6.1.

<table>
<thead>
<tr>
<th>‘Resilience’ component</th>
<th>Variable</th>
<th>Metric</th>
</tr>
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<tbody>
<tr>
<td>Macroeconomic stability</td>
<td>Fiscal deficit (-)</td>
<td>Ratio of fiscal deficit to GDP.</td>
</tr>
<tr>
<td></td>
<td>Inflation and unemployment (-)</td>
<td>Levels of unemployment and inflation, which may be combined to make an ‘economic discomfort index’.</td>
</tr>
<tr>
<td></td>
<td>External debt (-)</td>
<td>External debt to GDP ratio.</td>
</tr>
<tr>
<td>Microeconomic market efficiency</td>
<td>For all variables, few specific indicators exist – it is assumed that governmental interference is generally bad for resilience as defined. These variables together make up a ‘market efficiency index’. Indicators are mainly based on expert judgement and country/region ranking exercises.</td>
<td></td>
</tr>
</tbody>
</table>
Private firm dominance in the banking industry (+)

Foreign bank competition (+)

Credit supply to private sector (+)

Controls on interest rates (-)

Interference in labour market (-)

Bureaucratic control of business efficiency (-)

Good governance

For all variables, few specific indicators exist – it is assumed that most variables have a positive influence on resilience as defined. Indicators are mainly based on expert judgement and country/region ranking exercises.

Judicial independence (+)

Impartiality of courts (+)

Protection of intellectual property rights (+)

Military interference in the rule of law (-)

The political system and the integrity of the legal system (+)

Social development

Education (+) e.g. adult literacy rate or school enrolment ratios

Health (+) Life expectancy at birth

Table 6.1: A summary of components for a resilience index as proposed by Briguglio et al. (2009), with suggested metrics. In their definition, resilience is most liked to recovery and resistance of output rather than true system ‘resilience’. (+) and (-) relate to whether the variables are thought to be positively or negatively associated with resilience.

The resilience and adaptive capacity of regional economies is based around the ability of the components (industries, institutions, technologies etc.) to reconfigure and still maintain the desired characteristics that define the system (whether this is output, employment etc.). As noted above, a more diverse or heterogeneous system is most likely to have high adaptive capacity and resilience because the components will respond in different ways and incorporate redundancy, and this is effectively latitude as defined in the ecological and socio-ecological literature. Hudson (2010) has noted that a truly resilient economic system would maintain a diverse regional economy to lessen shocks and allow it to take advantage of opportunities, as well as being relatively closed (self-contained), as a more open system is more reliant on imports and exports to other regional economies, and therefore more likely to be influenced by shocks that affect those economies.

It has been suggested that relationship strength (in a similar way to ecosystems) may be key – economic systems that are bound by very strong interactions may be destabilised by disturbances because the impact resonates through the system (Conroy, 1975). Likewise, economic structures that are held in place by strong interactions may lack flexibility, which reduces their adaptive capacity and increases vulnerability. This has potentially been observed for the EU with its standardised currency, which has made the post-2008 global recession particularly problematic in Europe.
It has also been observed that differences are likely to exist between sectors, with for example manufacturing and construction more vulnerable than private service, and public service being least vulnerable. This is often considered to relate to adaptive capacity, with private and public service being more flexible in their operations than industry – they are less reliant on certain manufacturing resources or techniques, may not require large capital investment to upgrade technology, and so on. This also relates to the frequency and severity of shocks – the difficulty for industrial regions to recover and associated loss of capital as noted above means that once capital is reduced, the system becomes less resilient and able to cope with future shocks. The system is therefore made more precarious, or with sufficient disturbance will move to another stable state – though the distinction on when this happens is subjective and relates mainly to the perception of the person considering the system (Martin, 2012).

6.6 Metrics in socio-economic systems

Most studies of resilience in economic systems have focused on quantifiable measures such as employment, output (e.g. GDP), or wealth generation (accumulation of financial capital). Measures have tended to be either total amounts or rates (e.g. of output growth). Persistence of rates (e.g. growth) is not measured but is assumed to be indefinite. The question of whether a focus on growth is appropriate has been investigated to some extent. There is generally an interest in consistent dynamism (e.g. continued growth) rather than a fixed equilibrium condition. Most metrics become difficult to interpret when it comes to resilience however. While resistance is relatively easy to measure (e.g. change in employment or output during a recession), as is recovery (how quickly employment or output returns to ‘normal’ levels), determining when an economic system may be considered to have shifted to another stable state, and therefore conditions have changed indefinitely, is more difficult.
In Martin’s (2012) study of regions in the UK (Figure 6.5), it is clear that the different regions respond in different ways, and Martin (2012) interprets this as a shift in stable state, as growth trajectories do not return to normal. But this very much depends on how the system is defined and measured. Martin (2012) measures resistance by calculating the ratio of decline in employment or output in a given region compared to the entire country. His judgements on resilience are based around employment changes in different sectors within the regional economies – essentially a measure of structural change – and growth rates following recessions. He determined that a high sensitivity to shocks was linked to slower recovery (as per engineering resilience, or resistance). This is then assumed to relate to a change in stable state in those more sensitive regions, supported by the suggestion that regional sector components have changed (decline in industry with slow replacement in service sector in the north, compared to faster service growth in the south). This is a fair assessment, but the interpretation of sector change remains somewhat arbitrary, based around ‘scale’ of change (everything is the same after all, it is merely the abundance that alters). In this sense, perhaps the concept of a shift in state does become less relevant. In all cases, the appropriate metrics are tied closely to the key variables and scales used to define a given system.

6.7 Building resilience in socio-economic systems

The complexity and relative unpredictability of economic systems, particularly given their many connections to other region and ultimately global systems, makes building resilience a difficult task. Historically, the focus of ‘improving’ economic systems has been on trying to ensure stability or constancy of growth, or a return to growth levels prior to negative shocks (e.g. via investment or state intervention such as supporting financial institutions when they are in debt), rather than increasing adaptive capacity by ensuring survival of a range of different sectors or allowing re-training or innovation within the system that may increase diversity and functional redundancy (Hudson, 2010). There is substantial disagreement on the level of state intervention that is appropriate, or which timescales are best to focus on (Kitson et al. 2011). Intervention has mainly been aimed at addressing uneven economic development and the reduction of vulnerability, though such efforts have generally had limited success (Hudson, 2010). The acknowledgement of the reliance of economic systems on natural resources may be leading to a change in the way economic systems are managed, and resilience concepts and applications are likely to feature heavily in this in the coming years. Hudson (2010) considers that the follow elements are most important for developing a resilient regional economy:

1. Diversity of economic activities and institutions – this is essentially the same as increasing both redundancy and connectivity as in other systems.
2. Inclusion of the third (voluntary or charity) sector in economic models, alongside greater recognition of other forms of capital besides financial (including natural, physical, social and human capital), which is already taking place in some cases within the (mainly academic) field of ecological economics.
3. Greater recognition that flows of money, material and energy take place between economic systems and the wider SES of which they are a part – in part our poor understanding of economic systems may exist because these wider linkages are not explicitly recognised or investigated, yet clearly have important effects.
4. Internal closure – an economic system that is relatively self-contained and does not rely extensively on many other economic systems is more likely to be both resistant and resilient to shocks, particularly those that may originate elsewhere but propagate to the system under consideration. All systems will remain open to some extent of course, but managing this will help to increase resilience.
5. Expansion of learning capacity and innovation, particularly considering wider aspects of the system (e.g. the third sector and other forms of capital as noted above).

It is further recognised that such changes are dramatic and somewhat fundamental, and so ‘transformation’ (Pelling, 2011) of such systems may be required to notably increase resilience. This is still in very early stages of conceptualisation though: as Hudson (2010, p. 13) notes, ‘the extent to
which regional economies can be rendered more resilient and less vulnerable to the damaging effects of externally controlled or originating processes... remains an open question’.

6.8 Final definition of resilience in a socio-economic context

Resilience is not well-defined for economic systems, and remains a somewhat exploratory concept. Most studies have actually focused more on concepts of resistance. Economic systems are usually defined around persistence, productivity/output or capital accumulation. Diverse economies with many connections between components are more likely to be resilient, though full consideration of resilience has been limited by lack of consideration of the position of regional systems within wider systems, particularly with regard to the environment. The particular focus on outputs in many economic systems does mean that common metrics are easier to consider and apply between systems. Most considerations of resilience have emerged recently and depend very much on how a stable state might be defined for a given economic system, and are mainly associated with non-traditional models that call for a wider range of capitals etc. to be included.
7 Resilience in socio-technical systems

7.1 Defining a socio-technical system

A socio-technical system is one in which there are complex interactions between humans, machines and environmental aspects (Emery and Trist 1960). They are usually very specifically focused on certain outputs and often have safety or accuracy of output as a defining feature. Historically they have been treated as relatively closed, bounded systems but more recently, interaction of a socio-technical system with its environment has been identified as an essential ingredient (e.g. Badham et al. 2000) of an open socio-technical system. Typically, these interactions are bidirectional: in order to be able to fulfil its objective in an ever-changing context, an open socio-technical system adapts to the environment and at the same time it influences that environment with its actions. In safety science it is commonly recognized that the established safety engineering approach falls short in adequately handling the challenges posed by the design of safety critical socio-technical systems, especially if open. In order to make a maximum contribution to this review, the specific context of air transportation systems is focused on here, drawing in particular upon the Complex World Position Paper (2012) developed by some of the contributing authors.

7.2 Objective and purpose of air transportation systems

The air transportation system is a complex socio-technical system that is constantly influenced by internal and external events. Every day, several times each day, and at different locations, the operation of the system is perturbed by disturbances of different nature and impact. These disturbances may interact with each other, potentially creating a cascade of adverse events that may span over different spatial as well as time scales, ranging from affecting only one aircraft or a crew, up to a group of aircraft. In the current air transportation system interacting disturbances usually have a small impact on the overall performance of the system, e.g. some flights are rerouted, some passengers are rescheduled. Besides that, events occurring each day that do not fit within the pilot or controller trained procedures. Nevertheless most problems are adequately solved. Due to this kind of resilience of commercial air transportation operations, almost all these events pass without any discomfort for passengers.

In some exceptional cases, however, the resilience of the air transportation system falls short resulting in passenger discomfort. In some rare exceptional cases the discomfort is out of any proportion. There are two categories of such exceptional events: i) catastrophic accidents involving one or two aircraft; and ii) events that push the dynamics of the air transportation system far away from its point of operation and therefore dramatically affect the performance of the system. Examples of the latter are terror action causing closing down of air travel in a large area (e.g. 9/11 in 2001), a disease causing passengers to change their travel behaviour (e.g. SARS in 2003) or volcanic ashes blocking air travel in a large area (e.g. Iceland volcano in 2010). Examples of the former are fatal runway incursion (e.g. Linate runway collision in 2001), fatal mid-air collision (e.g. Ueberlingen mid-air in 2002), loss of control of an aircraft flying through a hazardous weather system (e.g. Air France crash in Atlantic Ocean in 2009).

The examples above show a wide variety of consequences stemming from an event that escapes from the resilience of commercial air transportation operations. At the same time, these examples show that rare exceptional events also have important commonalities: each of these events involves both economy and safety aspects. The 9/11, SARS and Volcano events happened as a result of precautionary safety measures (by authorities or by potential passengers) and implied large economic losses for airlines. The Linate, Ueberlingen and Air France crash accidents are examples of catastrophic outcomes in terms of passenger fatalities as well as hull losses. And because of the large economy and safety impacts, each of these rare exceptional events triggered in depth studies towards better understanding of why things happened and what can be learned from it for the further improvement of the air transportation system.
Learning from these rare exceptional events that happened because resilience failed to work has played a key role the evolution of the air transportation socio-technical system into the current one. However, these exceptional rare events have not been the only source of learning. An important complementary source of learning is formed by the many human operators that have daily experience in handling many situations that are not exactly covered by procedures. This means that human operators in the air transportation system have the possibility to learn from a much larger set of events, rather than only catastrophic events.

The learning from incidents and accidents, as well as the more process involved learning by human operators, has resulted in step by step improvements of the air transportation system. In practice this means that resilience of the current air transportation operation has largely evolved from learning experience by human operators, whereas the knowledge about rare unsafe events largely comes from safety analysis. This decoupled way of working has led to the extraordinary situation that commercial air transportation has become safer, but at the same time, system safety analysts have no objective approach in establishing which role resilience plays in realizing these high safety levels in combination with accommodating capacity, economy and environment requirements 24 hours a day and 365 days a year. Although we may have some qualitative understanding of resilience in the context of current air transportation, no quantitative results exist, and we are not able to assess whether system A is more resilient than system B.

Air Transportation has experienced an important and fast evolution in the last decades, with a constant growth in the number of flights, aircraft and airports. Also, the market itself has changed significantly: from being composed by a small number of national airlines, up to the recent appearance of many companies with new business models. In this context, the optimization of common airspace resources, along with more strict safety regulations, has reduced the flexibility of some actors, as well as their capacity to react to a changing environment, in turn, reducing the resilience of the system. Even the definition of the "normal" events of the air transportation socio-technical system, is not a trivial problem: and this is worsened by the evolving nature of air transportation – an event may be extremely rare today, but not so rare tomorrow.

This lack of objective insight regarding the embedding of resilience in the air transportation system makes it difficult for SESAR (http://www.sesarju.eu/) and NEXTGEN (http://www.faa.gov/nextgen/) to implement resilience systematically into the design of future air transportation system. Because resilience will remain crucial for the complex socio-technical air transportation system, the only way to escape from this restricted situation is that the role of resilience and how to design it is systematically investigated.

### 7.3 Resilience in the context of air transportation systems

Eurocontrol (2009) provided the following definition for resilience in air transportation: "Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions."

The scope of resilience in air transportation is large. In order to describe this in a systematic way, we explain the key dimensions, which are:

- Multiple key performance areas
- Multiple human operators
- Multiple stakeholders
- Multiple time-scales
- Multiple spatial layers
- Emergent behaviour
- Growing air traffic demands
7.3.1 Multiple key performance areas

As stated in ICAO Doc 9883, the Manual on the global performance of the Air Navigation System, the ATM system seeks to meet diverse expectations in terms of service delivery. For performance management purposes, it is considered that each of these expectations corresponds to a key performance area (KPA). The expectations for the 11 KPAs are described in Appendix D of ICAO Doc 9843, the ATM Global Operational Concept, and are repeated here:

- **Access and equity** - A global ATM system should provide an operating environment that ensures that all airspace users have right of access to the ATM resources needed to meet their specific operational requirements and that the shared use of airspace by different users can be achieved safely. The global ATM system should ensure equity for all users that have access to a given airspace or service. Generally, the first aircraft ready to use the ATM resources will receive priority, except where significant overall safety or system operational efficiency would accrue or national defence considerations or interests dictate that priority be determined on a different basis.

- **Capacity** - The global ATM system should exploit the inherent capacity to meet airspace user demands at peak times and locations while minimizing restrictions on traffic flow. To respond to future growth, capacity must increase, along with corresponding increases in efficiency, flexibility and predictability, while ensuring that there are no adverse impacts on safety and giving due consideration to the environment. The ATM system must be resilient to service disruption and the resulting temporary loss of capacity.

- **Cost-effectiveness** - The ATM system should be cost-effective, while balancing the varied interests of the ATM community. The cost of service to airspace users should always be considered when evaluating any proposal to improve ATM service quality or performance. ICAO policies and principles regarding user charges should be followed.

- **Efficiency** - Efficiency addresses the operational and economic cost-effectiveness of gate-to-gate flight operations from a single-flight perspective. In all phases of flight, airspace users want to depart and arrive at the times they select and fly the trajectory they determine to be optimum.

- **Environment** - The ATM system should contribute to the protection of the environment by considering noise, gaseous emissions and other environmental issues in the implementation and operation of the global ATM system.

- **Flexibility** - Flexibility addresses the ability of all airspace users to modify flight trajectories dynamically and adjust departure and arrival times, thereby permitting them to exploit operational opportunities as they occur.

- **Global interoperability** - The ATM system should be based on global standards and uniform principles to ensure the technical and operational interoperability of ATM systems and facilitate homogeneous and non-discriminatory global and regional traffic flows.

- **Participation by the ATM community** - The ATM community should have a continuous involvement in the planning, implementation and operation of the system to ensure that the evolution of the global ATM system meets the expectations of the community.

- **Predictability** - Predictability refers to the ability of airspace users and ATM service providers to provide consistent and dependable levels of performance. Predictability is essential to airspace users as they develop and operate their schedules.

- **Safety** - Safety is the highest priority in aviation, and ATM plays an important part in ensuring overall aviation safety. Uniform safety standards and risk and safety management practices should be applied systematically to the ATM system. In implementing elements of the global aviation system,
safety needs to be assessed against appropriate criteria and in accordance with appropriate and globally standardized safety management processes and practices.

- Security - Security refers to the protection against threats that stem from intentional acts (e.g. terrorism) or unintentional acts (e.g. human error, natural disaster) affecting aircraft, people or installations on the ground. Adequate security is a major expectation of the ATM community and of citizens. The ATM system should therefore contribute to security, and the ATM system, as well as ATM-related information, should be protected against security threats. Security risk management should balance the needs of the members of the ATM community that require access to the system, with the need to protect the ATM system. In the event of threats to aircraft or threats using aircraft, ATM shall provide the authorities responsible with appropriate assistance and information.

The examples of air transportation events provided in the previous section show that analysis of resilience involves KPAs such as capacity and safety, and that improving for one of the two may come at the cost of the other. This balancing aspect in the further improvement of the air transportation system also applies for the various other key performance areas in air transportation. For example for an aircraft landing under significant wind conditions, the safety preferred landing runway may differ from the noise preferred landing runway. In such situation safety and environment KPAs are competing with each other. Another example is increasing robustness in flight scheduling to avoid delays which may have a negative overall economic impact for airlines, but which may also have a positive effect for passengers because their chance to be on time is increased. Similar competing examples exist for the other KPAs; therefore resilience should be studied against a wide spectrum of KPAs in air transportation.

7.3.2 Multiple human operators

In air transportation, many interacting human operators like pilots, air traffic controllers and maintenance technicians, and technical systems, functioning in different organizations at a variety of locations, work at the sharp edge in assuring efficient and safe air transportation amidst various uncertainties and disturbances (e.g. delays, weather, system malfunctioning). Although procedures and regulations tend to specify and oversee sharp end working processes to a considerable extent, the flexibility of human operators appear to be essential for assuring efficient and safe operations in normal and rarer conditions (see FAA/Eurocontrol, 2011). Along this way human operators play an essential role in the resilience of the socio-technical air transportation system. A good understanding of this human-invoked resilience is essential for the design of more automated and adaptive future air transportation. In line with the advances in automation of future air transportation, the roles and responsibilities of humans will change. Nevertheless, it is expected that the flexibility of human operators will remain essential for resilient performance of future air transportation.

7.3.3 Multiple stakeholders

Another challenge is that the analysis of resilience in air transportation typically involves multiple stakeholders such as air navigation service providers, airlines, airports, aircraft manufacturers, repair stations, policy makers and regulatory bodies, passengers and people living or working in the vicinity of airports (Roelen, 2008). For example both the 9/11 terror event and the Iceland volcanic ashes event involved flight crews, air traffic controllers and passengers at the front level, and airlines and ATC centres plus several organizations at the management level. Similarly, the SARS event involved flight crews and passengers at the front level, and airlines and several organizations at the management level. The runway incursion event and the fatal mid-air collision involved flight crew and air traffic controllers at the front level, and airlines, ATC centres and some organizations at the management level. The Air France crash involved flight crew at the front level, and their airline, the aircraft manufacturer and safety oversight at the management level.

7.3.4 Multiple time scales
As is depicted in the air transportation resilience pyramid in Figure 1, one of the challenges of analyzing resilience in air transportation is that the relevant events extend along multiple time scales, which varies from normal activities which may happen many times per flight hour to acting upon potentially hazardous situations, which may happen once per thousand flight hours, to catastrophic accidents or large economic losses which may happen once in a billion flight hours. It is needed to better understand how interacting behaviour in the air transportation socio-technical system may influence resilience at various heights along the slope of the safety pyramid. The definition of the "normal" events of the air transportation socio-technical system is not a trivial problem, and this is worsened by the evolving nature of air transportation – an event may be extremely rare today, but not so rare tomorrow.

Figure 7.1 Air transportation resilience pyramid

7.3.5 Multiple spatial layers

The air transportation socio-technical system is composed of a plethora of different elements, which are located on different scales that hold interaction between them. These scales have both a spatial and a temporal dimension; for instance, a conflict resolution covers a time scale of seconds and a spatial scale of few Nautical Miles, while fleet planning may cover the whole European airspace along multiple days. While any external observer may easily perform the identification of these scales, it also has to be noticed that the elements of the air transportation socio-technical system are organized in more abstract layers, each one contributing to the dynamics of the system. They may include: airport capacity layer, airspace capacity layer, weather layer, etc.

7.3.6 Emergent behaviour

Due to the interactions between various human operators, technical systems and procedures, the air transportation socio-technical system exhibits emergent behaviour. Some examples are propagation through the network of some disturbances, as reactionary delays; impact on the performance of the
system of failures of elements that may seem independent (but which indirectly interact, and lead to important consequences); or, in a future context, the behaviour emerging from different agents making decisions in a collaborative environment. At the same time, one should be aware of the fact that current air transport also works thanks to the explicit use of emergent behaviour for the better. Examples of this are the various control loops that are working in current ATM, within each aircraft itself and also those formed by the interplay between the aircraft crew and each ATM centre on its path. And there is no doubt that the role of control loops will only increase for advanced ATM. Unfortunately intended positive emergent behaviour also may have undesired negative effects. Typically one even should expect that emergent behaviour that is not well understood will have the tendency to have negative effects. Only once emergent behaviour is well understood, it may be exploited for the better.

7.3.7 Growing air traffic demands

Air Transportation has experienced an important and fast evolution in the last decades, with a constant growth in the number of flights, aircraft and airports. Also, the market itself has changed significantly: from being composed by a small number of national airlines, up to the recent appearance of many companies with new business models. In this context, the optimization of common airspace resources, along with more strict safety regulations, has reduced the flexibility of some actors, as well as their capacity to react to a changing environment, in turn, reducing the resilience of the system (as noted in some other systems discussed in this review).

7.4 Disturbance in air transportation systems

As indicated above, resilience is important for the complex socio-technical ATM system, where large numbers of interacting human operators and technical systems, functioning in different organizations at a variety of locations, must control air traffic safely and efficiently in the context of uncertainty and disturbances (e.g. delays, weather, system malfunctioning). Disturbances in air transport can be identified from various perspectives. In particular, the KPAs (defined in Section 7.3) provide specific perspectives in which disturbances can be identified.

The KPA safety has a high priority in ATM and it is a focal point for a wide range of events and conditions in operations that may affect flight safety. Safety assessments of air transport operations take into account the wide variety of conditions, events and circumstances that may be encountered by all relevant entities and their interactions in the operation, most notably the human operators, technical systems and environmental conditions. In safety assessments, conditions, events or circumstances which may (somehow) induce an accident are indicated as hazards and these are identified as a basis for the assessment of the safety implications of existing or future air transport operations. An overview of hazards that have been collected in NLR’s ATM Hazard Database has been provided in Stroeve et al. (2011).

Delays are a considerable concern within air transport. The Central Office for Delay Analysis (CODA) of Eurocontrol provides delay statistics for European air transport (Eurocontrol, 2012). CODA receives delay data from airlines, which uses IATA delay codes. The IATA delay codes provide a wide range of causes for delays. These delay causes can be considered as disturbances from a delay perspective.

7.5 Modelling of resilience in socio-technical systems, with a focus on ATM

The analysis of resilience in the current and future socio-technical air transportation system is in need of modelling approaches which account for the various key dimensions identified in the previous section. Implicitly this means there will not be a silver bullet which addresses all dimensions. Instead multiple complementary approaches need to be explored.

The study of resilience from a complexity science perspective is quite recent. This means that it is not yet clear which techniques are most useful in modeling of resilience in air transportation. Part of the research is to identify which techniques are most useful. In view of this, the aim of this section is to
give a rather broad overview of complexity science techniques that are of potential use in the
modelling of resilience in current and future air transportation. Specific tools and techniques that may
be of value in this context are:

- **Static analysis.** The aim of static analysis is the identification of topological (i.e., structural) metrics
  of the graph that are of special significance for the resilience of the system. For the analysis of a
  multilayer resilience graph, most relevant are topological efficiency and clustering coefficient.
  Topological efficiency is defined as the harmonic mean of the lengths of the minimal paths connecting
  all pairs of nodes. The higher this value, the easier it is to move from one node to another node of
  the network; in other words, a high topological efficiency describes a system in which a perturbation
can easily propagate and affect different parts of it.

- **Out-of-equilibrium physics** (Van Vliet, 2008). Understanding the general characteristics of systems
  which exhibits behaviours close to criticality is crucial to design managing strategies to improve their
  performance. Several examples can be found in the literature, including the power transportation
  network (Carreras, 2004a; Carreras, 2004b), streets network inside a city (Jiang and Liu 2009) or
  more theoretical systems like sand piles. Nevertheless, little effort has been dedicated to applying this
  branch of physics to the ATM;

- **Complex Networks** (Boccaletti, 2006; Newman, 2003). This mathematical framework has been
  widely used in the last decade to understand the hidden topology of relations between elements of a
  large number of natural and man-made systems.

- **Applications range from networks of human personal relations, to yeast genes, through the Internet
  or relations between economical agents. Complex Networks can help in the understanding of relations
  between different agents of the ATM systems at several levels: from interactions between aircraft and
  safety, to networks of flights connecting different cities through different airlines;

- **Swam intelligence, natural and spatial computing** (Castro, 2006). In the coming years, ATM will go
  through important changes: the responsibility of many decisions will be decentralized to aircraft or
  airports; with this, there will be a need for more coordination and collective awareness. Such changes
  may lead to undesirable emerging behaviours, which should be predicted and managed to ensure the
  safety of the system;

- **Viability theory** (Aubin, 1991) has originally been developed to study dynamical systems which
  collapse or badly deteriorate if they leave a given subset of the state space. Therefore the objective is
  to keep the system in the part of the state space where it can survive, i.e. where it is viable. In
  follow-up research (Aubin et al., 2002) viability theory has been extended to hybrid dynamical
  systems. Recently (Martin et al., 2011) have explained that viability theory provides a natural
  mathematical framework for the modeling and analysis of resilience in complex systems.

- **Agent-based simulations and Multi-Agent Systems.** For the modelling and analysis of sociotechnical
  systems, it has become common practice to adopt an ABM simulation approach. Bonabeau (2002)
  captures the benefits of ABM over other modelling techniques in three statements: (i) ABM captures
  emergent phenomena; (ii) ABM provides a natural description of a system; and (iii) ABM is flexible. It
  is clear, however, that the ability of ABM simulation to deal with emergent phenomena is what drives
  the other benefits. In Burmeister (1997) it is further argued that multiple interacting agent models
  are suited to domains that are functionally or geographically distributed into autonomous subsystems,
  where the subsystems exist in a dynamic environment and interact more flexibly. This makes ABM
  simulation a logical choice for the evaluation of advanced ATM designs. For example, Shah et al.
  (2005) showed that ABM simulation offers the capability to integrate cognitive and technology models
  and description of their operating environment. Simulation of these individual models acting together
  can predict the results of transformations in procedures and technology. This emergent behaviour
typically cannot be foreseen and evaluated by examining the individual behaviour alone.
• Human performance modelling. In modelling a socio-technical system a key element is to capture human performance models have been developed; overviews and comparisons of these models are provided in Corker et al. (2005), Blom et al., (2005) and Foyle and Hooey (2008). Of these human performance modelling approaches, MIDAS has specifically adopted the agent based modelling (ABM) framework in order to include human directed situation awareness of the world. Within TOPAZ ABM has explicitly been embraced (Stroeve et al., 2003) in order to extend the human directed situation awareness (SA) model of Endsley (1995a) to a multi-agent SA propagation model. This model covers both human and technical agents. The motivation for developing this extension was twofold: 1) Endsley (1995b) showed that more than 60% of the causal factors underlying aircraft accidents involving major air carriers in USA involved problems with proper SA; and 2) our finding that many hazards identified through brainstorming with pilots and controllers could be properly modelled through such a multi-agent SA propagation model. The multi-agent SA model of (Stroeve et al., 2003) makes explicit that in a multi-agent system, SA propagates from one agent to another agent. This is comparable to Chinese whisper errors may sneak in without noticing by the participants, errors may sneak in the SA’s of agents in a multi agent system without noticing by the agents.

• Reachability analysis. In an ABM simulation, safety critical events can be defined as events where the joint state of the simulated agents involved hit a certain subset of their joint state space. In systems theory, the estimation of the probability of reaching a given subset of the state space within a given time period is known as a problem of probabilistic reachability analysis, e.g. (Kurzhanski and Varaija, 2002). Because of the huge dimensionality of a multi-agent model of a complex sociotechnical system, existing probabilistic reachability approaches, e.g. (Prandini and Hu, 2006), fall short. In safety-critical industries, e.g., nuclear, chemical, etc., reachability analysis is addressed by methods that are known as dynamical approaches towards probabilistic risk analysis (PRA). For an overview of these dynamical methods in PRA, see (Labeau and Swaminathan 2000). These dynamical PRA methods make explicit use of the fact that between two discrete events the dynamical evolution satisfies an ordinary differential equation. In the stochastic control theory these are known as piecewise deterministic Markov process (Davis, 1993; Bujorianu and Lygeros, 2003). For proper safety modelling of air traffic operations, however, it is often needed to incorporate Brownian motion in the piecewise deterministic Markov process models, e.g. to represent the effect of random wind disturbances on aircraft trajectories (Pola et al., 2003).

• Generalised Stochastic Hybrid Process (GSHP). The class of systems which incorporates Brownian motion within piecewise deterministic Markov processes, has been defined as a stochastic hybrid automaton (Bujorianu, 2004). Such automaton has a hybrid state consisting of two components: a continuous valued state component and a discrete valued state component. The continuous state evolves according to a stochastic differential equation (SDE) whose vector field and drift factor depend on both hybrid state components. Switching from one discrete state to another discrete state is governed by a probability law or occurs when the continuous state hits a pre-specified boundary. Whenever a switching occurs, the hybrid state is reset instantly to a new state according to a probability measure which depends itself on the past hybrid state. Complementary dynamic and stochastic effects are induced by the interaction between the hybrid state components. A key quality of a stochastic hybrid automaton is that it generates a process named generalised stochastic hybrid process (GSHP) which satisfies the strong Markov property (Bujorianu and Lygeros, 2006; Krystul et al., 2007).

• GSHP generating Petri Nets. For the modelling of accident risk of safety-critical operations in nuclear and chemical industries, the most advanced approaches use Petri nets as model specification formalism, and stochastic analysis and Monte Carlo simulation to evaluate the specified model (e.g. Labeau and Swaminathan, 2000). Since their introduction as a systematic way to specify large discrete event systems that one meets in computer science, Petri nets have shown their usefulness for many practical applications in different industries (e.g. David and Alla, 1994). Various types of Petri net modelling have also found their way into reliability and safety applications (e.g. Sadou and Demmou, 2009; Kleyner and Volovoi, 2009; Bouali et al., 2012; Ghazel, 2009).
Monte-Carlo simulations and Probabilistic Complex Networks. Uncertainty is present all the time in the Air Transportation System, both for external (for instance, weather) and internal causes (instruments precision, equipment failures...). Monte-Carlo simulations are the standard way to account for this uncertainty in simulating the behaviour of a system. Yet more approaches are available, like adapting Complex Networks theories to non-deterministic analysis;

Stochastic Differential Equations (Oksendal, 2003) and Hybrid SDEs (Krystul et al., 2007). SDEs are widely used in physics and finance to describe processes with a stochastic (that is, not deterministic) part; they have the form of a differential equation in which one or more of the terms are related to some form of stochasticity, for instance white noise;

Hybrid Petri Nets, High-level Hybrid Petri Nets and Hybrid Automata (Wieting, 1996; Allam and Alla 1996; David, 2001). Hybrid models allows to join a continuous part, describing some physical process with continuous flows, with a discrete logic and computational functioning;

Bisimilarity: This refers to formally proven transformations of one formalism to another one, e.g. (Van der Schaft, 2004). A bisimilarity transformation allows to combine the specific theory and tools available for both formalisms. For the different classes of stochastic hybrid systems bisimilarity relations have been developed by (Everdij and Blom, 2005; 2006; 2010). These bisimilarity relations are for example exploited in agent-based accident risk analysis (Blom et al., 2007).

An important part of resilience engineering is to assess how people at the sharp end of an operation, such as air crew or air traffic controllers deal, with their normal tasks and respond to disturbances in the system. It is essential to know if there any constraints that hamper how things are done, if there are there conflicts of interest, and if a good set of procedures is available which takes into account necessary operator creativity. Qualitative methods and models can be used to assess elements of system resilience in normal operations.

One such qualitative method is presented by Gomes et al (2009) who use Cognitive Task Analysis to assess how work is done in an offshore helicopter transportation system, thereby considering constraints or boundaries that shape work and reflecting about risk models that people use to support decision making under various types of pressures.

Furniss et al. (2011) provide a qualitative resilience markers framework which can be used to analyse resilience in small teams. It builds on a paper of Back et al (2008) which distinguishes different levels of granularity for considerations of resilience, viz. individual level, small team level, operational level, plant level, industry level. The resilience markers framework for small teams consists of three levels:

Markers level – This is the top level which generalizes across domains, and consists of a low number of markers, e.g. the marker "Maximising information extraction", or "recognising and responding to failure".

Strategy level – This level is more detailed than the markers level and reveals the mechanisms that are relevant for achieving resilience, e.g. “Creating an external cue” or “provision of feedback to enable error correction”.

Observation level – This level accounts for the observations of resilience. This actually happens in practice and can be specific for a certain domain, e.g. “A paper clip to bookmark a page in the procedure someone is following” or “admitting to following the wrong procedure”. The strategy level, which is the central part of the framework accounts for four factors which are important for analysing resilience (Furniss et al., 2011):

Resilient repertoire – This encompasses skills, strategies and competencies that comprise the responses to threats and vulnerabilities which are outside design-basis.
• Mode of operation – This is the way the system has organised itself. A mode of operation can refer to the style or structure that a system adheres to and can be useful for making available suitable resources.

• Resources and enabling conditions – hard and soft constraints that influence whether a strategy can be enacted

• Vulnerabilities and opportunities – Responding to vulnerabilities and opportunities is a central part of resilience when these reactions are outside design-basis.

Regarding potential strategies, Furniss et al. (2011) refer to Malakis and Kontogiannis (2008), who distinguish individual and joint cognitive strategies that are used by actors for local adaptations in support of resilience

• Individual cognitive strategies: recognition, managing uncertainty, planning, anticipation, managing workload

• Joint cognitive strategies: coordination, information exchange, error management, workload distribution management.

Another framework is presented by Bergström et al (2011). That framework considers generic competencies that are required for managing escalating situations. The framework consists of four elements:

• Information management – Use shared and explicit goals based on which the incoming data can be sorted, distributed and shared.

• Communication and Coordination processes – The organisation has to be able to balance between a predefined role structure and a flexible structure to respond to the dynamics of the escalation. For a more detailed discussion of coordination, see also (Klein et al. 2005)

• Decision making – Shared and explicit goals need to be used for decision making in a distributed decision-making environment

• Effect control – importance of constantly monitoring and updating the process by which the escalating situation is managed.

In 2007, Eurocontrol launched a project with the aim of understanding the relevance of Resilience Engineering to Air Traffic Management. Their white paper (Eurocontrol, 2009) provides an overview of the work that was carried out. It briefly presents one method, the Functional Resonance Assessment Method (FRAM). This method is elaborately presented in (Hollnagel, 2012). FRAM applications in ATM are amongst others an analysis of a mid-air collision (Rodrigues De Carvalho, 2011), the use of a Minimum Safe Altitude Warning system (Macchi et al, 2011) and the use of automated speed adjustments en route (Woltjer and Hollnagel, 2008). Also, the resilience engineering contribution to risk analysis in ATM is explored in (Herrera et al, 2010) in which FRAM is compared with traditional risk analysis methods.

7.6 Building resilience in air transportation systems

The above discussion provides a basis for exploring ways in which resilience could be expanded in air transport management, though there has been little research into this thus far. As for other systems, there is probably some relationship between resilience/adaptive capacity and characteristics such as connectivity between components, multiple weak interactions, redundancy of function, the presence of key organisations and processes and so on, but this remains unexplored. According to Hollnagel et al. (2011), building resilience into an organization requires the following four cornerstones:
- Knowing what to do, that is, how to respond to regular and irregular disruptions and disturbances either by implementing a prepared set of responses or by adjusting normal functioning. This is the ability to address the actual.

- Knowing what to look for, that is, how to monitor that which is or can become a threat in the near term. The monitoring must cover both that which happens in the environment and that which happens in the system itself, that is, its own performance. This is the ability to address the critical.

- Knowing what to expect, that is, how to anticipate developments, threats, and opportunities further into the future, such as potential changes, disruptions, pressures, and their consequences. This is the ability to address the potential.

- Knowing what has happened, that is, how to learn from experience, in particular how to learn the right lessons from the right experience – successes as well as failures. This is the ability to address the factual.

7.7 A final definition of resilience in an air transportation system context

Resilience is a concept only recently applied to air transportation management, but early concept explorations have included elements of both ‘engineering resilience’ (resistance and recovery) as well as ‘ecological resilience’ (re-organisation) as it may be broadly termed (Eurocontrol, 2009; Complex World Position Paper, 2012). This provides an innovative and useful way forward for the application of resilience in the ATM context. As a specific type of socio-technical system, it is easier to get a clear operational definition of what an air transportation system is and what it does, and therefore how resilience may relate to this. It is certainly a normative concept in this context, and is a desirable trait. Because the aims and outputs of the system are more clearly defined, it is also possible to use more established metrics and models, and to some extent to predict potential future change in the system. There has been little consideration at the current time of how resilience of such system may be improved, but hopefully some of the observations made in this review will help to further that intention.
8 A summary of key commonalities and differences between resilience concepts and applications in different systems

8.1 Introduction

Through exploring the ways in which the ‘resilience’ as a concept has been applied to varying systems, moving along a gradient from its original application to ecological systems, through socio-ecological, socio-economic and socio-technical systems, we have determined several key commonalities of resilience and its application that may be used to help shape the effective use of the term in Air Traffic Management.

8.2 General vs. specific usage

It is clear that in most cases the term ‘resilience’ has been used in a generic way in many publications, referring to an abstract capacity for a system, or one or more of its components, to recover from a disturbance or stress. What recovery actually means in terms of ‘return to a norm’ or ‘the ability to persist’ is often not clarified, and there is some confusion between the terms ‘resistance’ and ‘resilience’ or what is actually being measured in a given study. In reality, the ‘resistance’ of a system, or the ability to not display an impact and to return to a pre-disturbance condition, is a part of broader resilience as specifically conceived. The terms (and associated applications and measurements) have been more clearly defined for those disciplines in which the term has been used for some time (e.g. ecology, socio-ecological systems), as a requirement for clarity has emerged through differential use over time by different researchers, while disciplines that have incorporated the term more recently have yet to explore the most appropriate operational definitions. We may also predict the existence of a half-life of the term in a given discipline, as the popularity of the ‘resilience’ concept is considered to be waning in ecological systems, where it is beginning to be considered somewhat passé as it has been used for some time. In other contexts the concept is still emerging but this may decline more rapidly if the concept becomes ubiquitous or so generic as to be meaningless. The best remedy for this is precision of an operational definition in each particular study, so that the elements of resilience being tested are clear. As a given system becomes more narrowly defined (i.e. a regional economic system rather than a broad socio-ecological system), it should be easier to clarify exactly what elements of resilience are being examined.

The better use of the term has involved very specific definitions of what a system is and how it may be described, what disturbances are being considered, what metrics might be appropriate to demonstrate resilience to specific disturbances, and (in some cases) how factors relating to resilience may be improved. As we move from ecological systems to increasingly social systems, there comes a change in the normative values of the term, i.e. moving from a more objective way of determining how an ecosystem may respond to different forms of disturbance, and whether this will involve some change in its stable state and the fundamental properties that define the system, to a recognition that resilience is desirable and something that is to be (in general, with some exceptions) supported and improved in many social systems. This may sometimes create specific tensions, as some members of society may not wish for a system to be resilient, or the idea of a resilient system may create unrealistic expectations in the ways in which the system may respond to future disturbances. It should be noted that it is impossible to ensure resilience or resistance for a system against all disturbances.

8.3 Key resilience factors across systems

Throughout all of the systems examined, their adaptive capacity is closely linked to resilience. Although this term is usually used in a socio-ecological context, it is also relevant for all systems and is essentially the ‘other half’ of resistance – where resistance to a disturbance fails to keep the system
in a stable state, adaptive capacity allows flexibility of response to ensure that the stable state persists. Adaptive capacity is mainly linked to the system properties such as the number of components within the system, the redundancy of the different components (i.e. whether their role can be filled if the component is lost or compromised), the flexibility of components (i.e. whether can alter or adapt role or function as internal or external conditions change), the connectivity of components within the system (with more connected systems generally having greater adaptive capacity), the presence of ‘keystone’ components or linkages (which have an important functional role within the system that is either relatively unique or greater than the component might suggest), and the potential for the emergence of novelty or innovation, whether physical/biological/technological or social. In an ecological system these components will be both biotic and abiotic, e.g. species and nutrients, while in a social system people, organisations and so on feature more heavily – in economic or socio-technical systems for example, social components will comprise almost all of the system, though the systems are of course placed within a broader environmental context, whether acknowledged or not. These elements of resilience may all be considered important, but not all have explored for the systems considered here; often studies have focused only on a small subset. An example would be the reliance on output or employment in economic systems, and examinations of the ways in which shocks may impact growth trends, rather than a full analysis of the system.

8.4 Measures and metrics

Some of the key concepts in conceptualising resilience, including latitude (‘width’ of a stable state), resistance (‘depth’ of stable state) and precariousness (current system position within a stable state) have not translated beyond some ecological and socio-ecological systems. It is clear that some of these aspects have been measured for a wide range of systems, with for example estimates of proximity to thresholds or tipping points being made (as essentially a measure of precariousness). Usually measures of ‘resistance’ have been made, i.e. the extent to which an impact is observed within a system, or the rapidity of recovery of a key aspect of the system (e.g. output or biomass production). In all cases such measurements must be compared to either another (reference) system (whether elsewhere in the world or in time) or an idealised or desired system. All resilience analysis is therefore comparative in some sense, and mainly offers a tool for exploration and understanding of the system properties and dynamics rather than something tangible.

Generally, metrics to measure resilience are easier to determine for systems that have very specific objectives and quantifiable properties. At the ecosystem level, there are no broad metrics that should be measured, and these are defined for particular aspects of an ecosystem that are defined based on arbitrary space and timescales (e.g. an acidifying lake over a decade). Ecosystems use a mix of qualitative and quantitative analysis with some modelling to determine levels of resilience. In socio-ecological systems, most analysis is qualitative and relies on expert opinion and judgement rather than detailed quantification and modelling, though this may occur for some aspects, such as crop production or disaster response metrics. Economic systems are more quantitative and there are some established metrics or indicators that can be used to examine the systems (Section 7), but there remain some qualitative gaps in determining what a stable state might look like, or how measurements may inform this. Socio-technical systems have more specific measurements and metrics that can be made, as such systems are grounded in modelling and quantification of components and processes. Ideally, a coherent survey of resilience would involve:

- Measurements of number and role of components and processes, including the space and timescale over which they operate, from which elements of diversity or heterogeneity can be obtained
- The number and type of linkages between components, strength of linkages, and circuitry
- The number and type of keystone components, processes and linkages
- Measurements of capacity for components and processes to include novelty and innovation, including absolute capacity and rates of change
Different metrics may of course be used to obtain these measurements. These may in turn be used to determine the location of the system in the adaptive cycle, as well as within the latitude, resistance and precariousness concepts utilised in some resilience thinking.

Importantly, social systems also involve the need for transformation, which is the expressed conversion from one stable state to another. This is done either because the original stable state is undesirable, or because there is a desire to move towards another specific stable state. This requires normative judgements to be made, and requires a thorough understanding of the system, which may often be lacking. In particular, the importance of ‘power’ and adaptive capacity needs to be considered, i.e. who or what maintains power to effect change in a given system, and how important this may be for improving resilience (Hudson, 2010). Ideally these attributes should also be measured in any system with a social component.
9 References


Complex World Position Paper (2012) Deliverable 23.2 of the FP7 ComplexWorld Project led by Innaxis (project number E-01.01).

Connell JH (1978) Diversity in tropical rain forests and coral reefs – high diversity or trees and corals is maintained only in a non-equilibrium state. Science 199: 1302-1310.


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