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FORUM

Effective management of ecological resilience – are we there yet?

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Summary

1. Ecological resilience is developing into a credible paradigm for policy development and environmental management for preserving natural capital in a rapidly changing world. However, resilience emerges from complex interactions, limiting the translation of theory into practice.

2. Main limitations include the following: (i) difficulty in quantification and detection of changes in ecological resilience, (ii) a lack of empirical evidence to support preventative or proactive management and (iii) difficulties in managing processes operating across socio-ecological systems that vary in space and time.

3. We highlight recent research with the potential to address these limitations including new and/or improved indicators of resilience and tools to assess scale as a driver of resilience.

4. *Synthesis and applications*. Effective resilience-based management must be adaptive in nature. To support this, we propose an operational model using resilience-based iterative management actions operating across scales.

Key-words: ecosystem, management, policy, preventative, research, resilience, society

Introduction

Environmental change threatens the complex ecological systems humanity relies upon at local, regional and global scales. To support a 'resource-efficient, green and competitive low-carbon economy' (European Environment Agency 2014), society must reduce pressures degrading ecosystems. To achieve this, managers must reduce pressures and/or manipulate components of ecosystems to achieve either no change (i.e. prevention of degradation) or change to a more desirable ecological state (i.e. restoration of degraded systems). Despite the need to redress the pressures of population growth and resource use (Carpenter *et al*. 2009), appropriate adaptation measures are difficult to achieve (Beddington 2009). For example, although reductions in sulphur dioxide and nitrous oxide emissions have been achieved, which has greatly reduced the input of 'acid rain' to freshwaters, ecological responses have been slow and region specific due to stabilizing feedback mechanisms (Battarbee *et al*. 2014).

The focus of policymakers is turning to enhancing the resilience of socio-ecological systems to safeguard them from environmental change (i.e. future proofing: Moss *et al*. 2013). This approach relies upon our ability to detect, quantify and manipulate ecological resilience. A recent assessment of resilience-enhancing measures, designed to address impacts of climate change across ecosystem types, has revealed limited confidence in this approach (Kareiva *et al*. 2008). We discuss factors limiting the manipulation of ecological resilience and draw on recent advances with the potential to address them. We present these advances within an operational model designed to bridge theory and practice.

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Barriers, successes and opportunities

Ecological resilience was defined by Holling (1973) and adapted by Walker *et al.* (2004) as 'the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity and feedbacks'. Evidence from a range of studies in terrestrial and aquatic ecosystems has shown that ecological change often occurs suddenly in response to pressures and management activities (Folke *et al.* 2004). As such, management must be conducted with a comprehensive understanding of underlying processes (Seastedt, Hobbs & Suding 2008). Shallow lakes continue to be an important test bed for practical resilience-based management (Batt *et al.* 2013), and we inevitably draw on evidence from these systems. For example, practical demonstrations of resilience-based management have been well documented in lakes where the disruption of stabilizing feedback mechanisms (e.g. through catchment management or the manipulation of food webs) can result in a rapid transfer of primary productivity from the plankton to the benthic macrophytes which supports a fundamental shift in ecological structure and function associated with turbid and clear water states, respectively (Scheffer 2009). However, in other ecosystems, the key processes and interactions responsible for resilience are, arguably, poorly understood leading to the consideration of measures that target population- or individual-level responses. For example, a range of measures have been proposed for climate change mitigation and adaption in terrestrial ecosystems. 'Assisted species migration' has been proposed to counteract climate change effects on key service provision in forests where intolerant species are replaced with tolerant ones (Kareiva *et al.* 2008). The effects of such 'species swapping' are contentious (Minteer & Collins 2010) and resilience-based 'managed evolution' has been proposed to consider intra- and interspecific diversity, as opposed to single species tolerances which builds on the need to consider ecological resilience across scales (Cavers & Cottrell 2014). Lessons from large-scale environmental management successes, for example measures to reduce the causes of 'acid rain' (Fowler *et al.* 1982), show that action at local and global scales must complement each other if wide-scale environmental management efforts are to be successful.

Scheffer (2009) and Carpenter *et al.* (2009) demonstrate the value of understanding interactions across scales and between socio-ecological systems as a basis for effective environmental management and, collectively, lay out a blueprint for translating theory into practice. However, this translation is limited by significant knowledge gaps including the following: (i) difficulties in detecting changes in resilience (Batt *et al.* 2013), (ii) a lack of evidence and agreement to support successful preventative management actions (Barrett *et al.* 2014) and (iii) the need to work across multiple geopolitical scales to achieve effective management (Servos *et al.* 2013).

We argue that the evidence is available with which these limitations can be addressed and propose an operational model with which resilience-based management can be used to develop a more adaptive approach (Fig. 1).

An operational model for resilience-based management

MODULE 1 DETECTING ECOLOGICAL SENSITIVITY TO PRESSURES

Our ability to detect the effects of environmental change on ecological processes is critical for effective management of ecological resilience (Audzijonyte *et al.* 2013). Our understanding of ecological process responses is generally underpinned by long-term case studies using simple chemical or biological (often single species or simple community) indicators (Russell *et al.* 2012) impacted by single pressures across limited scales (Allan *et al.* 2013). To address this, existing indicators are being scrutinized for use in 'resilience detection' and where necessary, novel indicators are being developed and validated towards use in routine monitoring programmes (Batt *et al.* 2013). Indicator development has been conducted using three approaches discussed below.

First, time-series approaches have helped quantify variation in the nature of ecological systems [i.e. demonstrating ecological resilience characteristics of an ecosystem (Angeler, Drakare & Johnson 2011)] including alternative ecosystem states (Angeler *et al.* 2013). In these studies, resilience has been inferred by quantifying interactions between ecological processes across temporal and spatial scales (Peterson, Allen & Holling 1998; Allen, Gunderson & Johnson 2005). Additionally, time-series analysis has been used to detect change in ecosystem state indicators (e.g. increased variance and autocorrelation) where, for example, slower and larger fluctuations in an indicator can precede a sudden regime shift (e.g. Ives *et al.* 2003; Batt *et al.* 2013) allowing potential 'early warning'. These studies demonstrate the use of existing indicators to detect changes in ecosystem resilience in response to pressures across multiple scales. The detection of subtle changes in the structure of ecological networks following perturbations shows promise as an early warning indicator of the loss of ecological stability that considers the timing of structural and functional degradation and recovery (Dakos & Bascompte 2014). These approaches can be applied to provide insight into scale-specific structure in a system (Allen *et al.* 2014; Nash *et al.* 2014). Most delineation of scale is arbitrary and subjective, and the development of objective methods to identify scale breaks and scale-specific structure is a critical need in ecology.

Secondly, researchers have developed indicators capable of predicting ecological resilience across multiple spatial scales without also having to consider temporal dynamics. Specifically, the discontinuity framework (Holling 1992)

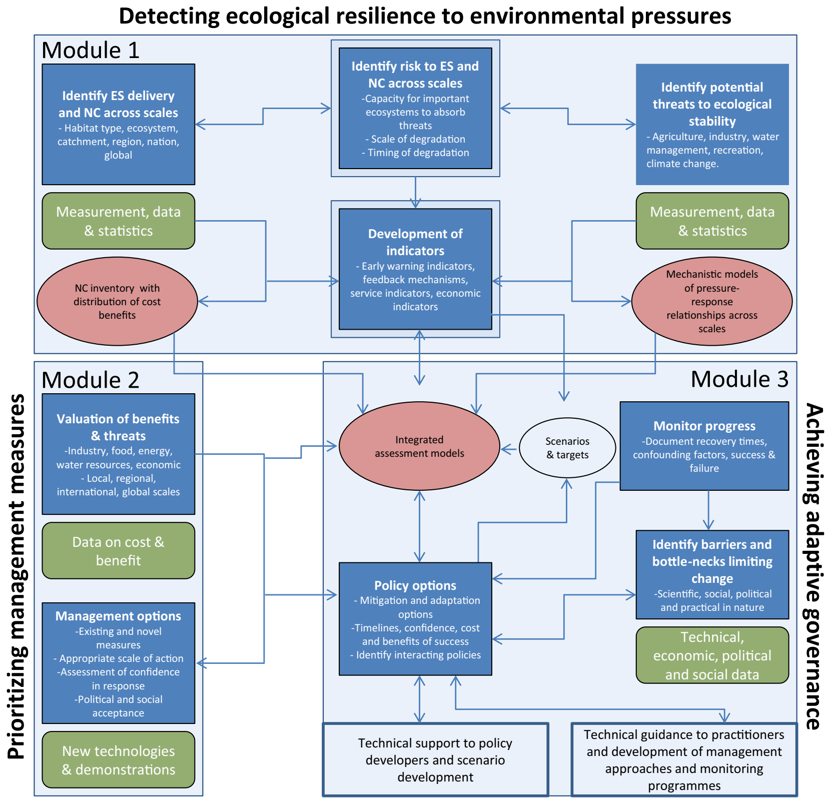

Fig. 1. Operational model showing potential for linkages between research areas that stand to improve the evidence base with which policy and practical management can be developed towards more effective management of ecological resilience. ES, ecosystem services; NC, natural capital. Blue boxes represent the major resilience-based research fields; green boxes represent the production of data and tools; pink boxes represent the development and use of models.

has been used to quantify resilience based on simple ecological metrics (e.g. animal body mass or plankton biomass) (Allen & Holling 2008). This framework can detect a loss of resilience across multiple scales (Allen *et al.* 2014) and may be useful when identifying transboundary management approaches.

Finally, in microbial and higher organisms, changes in the genetic and epigenetic composition of populations can be rapidly detected using next-generation sequencing methods (Stafford *et al.* 2013). Such techniques may indicate systems undergoing 'reorganization' and show potential to rapidly detect subtle but important ecological responses to pressures at intraspecific, population and community scales (Shade *et al.* 2012).

To support these developments, many research and regulatory bodies are providing open source data including large spatial data sets and multiple biophysical and socio-economic indicators allowing the assessment of interactions between resilience-based management and service delivery. For example, Allan *et al.* (2013) mapped pressures impacting on ecosystem service delivery across the North American Great Lakes and demonstrated the importance of considering landscape spatial heterogeneity when planning restorative and preventative management. A range of national and international research projects are underway in which linkages between pressures, ecological structure and function and ecosystem service delivery will be examined across scales (aquatic ecosystems: Herring *et al.* 2014; forests: Cavers & Cottrell 2014). These projects provide a platform for scientific advances to consolidate our knowledge base of resilience that can then be translated into practical guidance for policy-makers and practitioners.

MODULE 2 DEVELOPING MORE EFFECTIVE RESILIENCE-BASED MANAGEMENT MEASURES

The balance of regulation and incentives to support management of ecological resilience may need to be redrawn (Moss *et al.* 2013). For example, in the EU, a number of policies call for restoration of degraded ecosystems (e.g. EU biodiversity strategy). The cost estimates for habitat restoration to achieve Target 2 of the EU biodiversity strategy (i.e. 'maintain and restore 15% of degraded ecosystems by 2020') across all habitat types ranges between €506 million and €10·9 billion per year (Tucker *et al.* 2013). Estimates of this kind are highly uncertain, partly due to a lack of confidence in the efficacy of available management measures (Kareiva *et al.* 2008). Furthermore, cost estimates for management of specific pressures in isolation (e.g. nutrient pollution) can be confounded by unintended consequences of the measure on other pressures acting on the target system (e.g. the potential effects of water quality management for climate change mitigation; Spears & Maberly 2014). The global economic burden of natural catastrophes has increased from US $528 billion in the 1980s to US $1213 billion in the 2000s (Michel-Kerjan 2012). As such, substantial economic savings may be made by considering the potential effects of existing restorative management measures to reduce the likelihood of future ecological degradation in the context of impending pressure changes. However, field-based experimental manipulations of feedback mechanisms, necessary to support such preventative action, are rare. Instead, relevant field studies have commonly strived to achieve an improvement of ecosystem state from a degraded state (Batt *et al.* 2013), but not an enhanced capacity to resist degradation. To address this, researchers need to revise experimental manipulations to demonstrate 'no response' treatment (i.e. enhanced resilience) in comparison with a 'regime shift' control (McGovern *et al.* 2013) allowing better understanding of adaptive capacity.

MODULE 3 ACHIEVING ADAPTIVE GOVERNANCE

Implementation of management measures at local scales is generally considered to be more susceptible to 'failure' as a result of an inability to control larger scale processes (Lake, Bond & Reich 2007). However, our understanding of ecological processes that regulate restoration effectiveness across scales is well-established in theory and may be used to inform adaptation within governance systems. For example, Allen *et al.* (2014) demonstrated the need to control processes operating across multiple scales, simultaneously, to achieve a desirable and relatively stable ecological response. Such developments offer a framework to integrate biophysical and socio-economic processes within hierarchical conceptual models. Temporal scale is also critical to effective management. Sharpley *et al.* (2014) demonstrated the importance of 'legacy' responses in restoration and recovery at the ecosystem and catchment scales where a combination of physical and ecological processes combine to delay recovery in watersheds following catchment management for up to centuries. As a result of these legacy effects, an apparent lack of response can be met with costly 'knee-jerk' management interventions. Superimposed onto these ecological processes are a series of socio-economic ones. For example, restoration objectives may be driven by socio-economic cycles including trade (Margolis, Shogren & Fischer 2005) and longer term changes in the social construct of a community (Olsson & Folke 2004). These issues of scale across socio-ecological systems must be considered more comprehensively to achieve resilience-based management. Bryan *et al.* (2013) provide a useful demonstration of combining hydrological modelling with socio-economic predictions to support decisions on the management of the River Murray, Australia, based on a combination of ecohydrological and socio-economic benefits.

Issues of scale across socio-ecological systems must be considered within a common framework to achieve resilience-based management. However, delineations exist within governance systems that can restrict the effective management of ecological systems at appropriate temporal and spatial scales. Garmestani & Benson (2013) propose expansive legal reform to allow for trials of new legislative approaches to combine with adaptive or iterative management. To achieve this, they propose (i) delineating ecological and governance scales, (ii) identifying critical slow variables, (iii) identifying scale-dependent ecological thresholds and (iv) linking ecological and legal thresholds. These changes have the potential to address the limitations of existing environmental policies and form the basis of Module 3 (Fig. 1). However, such institutional level change will not happen quickly and should be based on sound scientific evidence.

CONCLUSIONS

We argue that current knowledge supports the detection and prediction of 'ecological resilience'. However, there is a need to consolidate the approaches and techniques described above to produce an operational model capable of providing iterative resilience-based management of socio-ecological systems. We believe that the model presented here fills this gap by providing a clear route through identifying and using ecological indicators, identifying and applying appropriate management measures at appropriate scales to enhance resilience through to scenario testing and adapting policy in response to management outcomes. Following this, it is important that scales regulating governance of ecological systems are clearly defined and should include identification of barriers (i.e. policy, technical and social issues). Decision support tools with the potential to enhance resilience should be made available to practitioners and planners as has been demonstrated for the effective management of ecosystem services (US EPA 2009). Practical guidance documents for practitioners underpinning the assessment and management of resilience in socio-economic systems have been developed (Resilience Alliance 2010) and should be adapted as research progresses.

Data accessibility

Data have not been archived because this article does not contain data.

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