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QUANTIFYING RESILIENCE

Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives

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Summary

1. Increased interest in managing resilience has led to efforts to develop standardized tools for assessments and quantitative measures. Resilience, however, as a property of complex adaptive systems, does not lend itself easily to measurement. Whereas assessment approaches tend to focus on deepening understanding of system dynamics, resilience measurement aims to capture and quantify resilience in a rigorous and repeatable way.

2. We discuss the strengths, limitations and trade-offs involved in both assessing and measuring resilience, as well as the relationship between the two. We use a range of disciplinary perspectives to draw lessons on distilling complex concepts into useful metrics.

3. Measuring and monitoring a narrow set of indicators or reducing resilience to a single unit of measurement may block the deeper understanding of system dynamics needed to apply resilience thinking and inform management actions.

4. *Synthesis and applications.* Resilience assessment and measurement can be complementary. In both cases it is important that: (i) the approach aligns with how resilience is being defined, (ii) the application suits the specific context and (iii) understanding of system dynamics is increased. Ongoing efforts to measure resilience would benefit from the integration of key principles that have been identified for building resilience.

Key-words: indicators, metrics, multidisciplinary, resilience assessment, resilience measurement, social-ecological systems

Introduction

Resilience has emerged as a unifying concept in a number of disciplines linked to the sustainability sciences (Curtin & Parker 2014). However, interest in resilience extends beyond ecology and natural resource management to fields such as international development, health, food security, community planning and disaster management (Xu, Marinova & Guo 2014). Efforts to apply resilience within these different fields have stimulated interest in assessing and measuring resilience and given rise to an array of approaches spanning qualitative and quantitative methods, participatory assessments, statistical analyses, modelling and metrics. The application and measurement of resilience is varied and often only indirectly linked to theoretical frameworks. We draw on multiple disciplinary perspectives to explore resilience assessment and measurement in a range of contexts, and discuss some of the opportunities and challenges that come with its broadened applicability. From this discussion a clear set of recommendations emerge to guide the practice of resilience assessment and measurement.

The application of resilience in ecology and natural resource management has mostly been an heuristic to help frame and explore issues although the concept has also been implemented in adaptive management and planning processes (Roux & Foxcroft 2011; Namoi CMA 2013). More recently efforts to quantify or measure resilience have intensified. Walker & Salt (2012) state that 'resilience is not a single number or a result. It is an emergent property that applies in different ways and in the different domains that make up your system. It is contextual and it depends on which part of the system you are looking at and what questions you are asking.' A less flexible, albeit not incompatible view is that 'managers must monitor

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and measure what they manage' (Kerner & Thomas 2014). These perspectives reflect a broader tension between the notion of metrics as essential to guide management and policy vs. the sentiment that measurement while useful, has inherent trade-offs by focusing on performance indicators that are easy to measure and manipulate, rather than deeper, more difficult to quantify goals.

Taking a broad view of resilience affords an opportunity to reflect on the relationship between measuring and assessing resilience and the wide variety of ways and contexts in which the concept is being applied. We begin by distinguishing among the multiple ways resilience is being defined with relevance to a range of resilience assessment and measurement approaches. We then examine some of the goals, methods and tools being used to measure and assess resilience, highlighting both opportunities and challenges. Our emphasis is on social-ecological resilience because of its focus on interactions that are relevant in managing human–environment systems in the context of change. Turning to other disciplines, we seek practical insights on translating complex concepts into metrics. We suggest that with the necessary simplification required to measure resilience, one should address potential trade-offs with a key objective of resilience assessment, namely, a deeper understanding of system dynamics. We discuss how a set of principles for enhancing social-ecological resilience offers a theoretical foundation and basis for consistency across assessment and measurement approaches. Finally, we conclude with a set of recommendations broadly applicable in implementing resilience in different contexts.

A multiplicity of resilience definitions – what are we measuring?

Resilience has been conceptualized and applied in a variety of ways and in recent years definitions have proliferated (Table 1). Three predominant definitions have emerged from the ecological literature including: engineering, ecological and social-ecological resilience. Engineering resilience is defined as a system's speed of return to equilibrium following a shock, indicating that a system can only have a single stability regime (Holling 1996). With its focus on stability and efficiency, engineering resilience has quite different implications for the management of ecosystems than that of ecological resilience. Holling's (1996) definition of ecological resilience refers to the magnitude of disturbance that a system can absorb before shifting to an alternate regime or system state. Ecological resilience thus assumes that a system has multiple alternate equilibria and focuses on the capacity of a system to maintain, including through reorganization, its essential structure and function when confronted with shocks. This capacity for self-organization has not always been clearly defined, but it is a key aspect of complex adaptive systems that enables them to regenerate and transform. Social-

Table 1. Resilience definitions in different domains

Resilience	Definition	Emphasis	Key references
Engineering resilience	System's speed of return to equilibrium following a shock	Return time to recover, efficiency, equilibrium	Pimm (1984)
Ecological resilience	Ability of a system to withstand shock and maintain critical relationships and functions	Buffer capacity, withstand shock, persistence, robustness	Holling (1996)
Social-ecological resilience	(i) Amount of disturbance a system can absorb and remain within a domain of attraction; (ii) capacity for learning and adaptation (iii) degree to which the system is capable of self-organizing	Adaptive capacity, learning, innovation	Carpenter *et al.* (2001)
Social resilience	Ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change	Social dimensions, heuristic device	Adger (2000)
Development resilience	Capacity of a person, household or other aggregate unit to avoid poverty in the face of various stressors and in the wake of myriad shocks over time	Vulnerability, robustness	Pasteur (2011) and Barrett & Constas (2014)
Socioeconomic resilience	Socioeconomic resilience refers to the policy-induced ability of an economy to recover from or adjust to the negative impacts of adverse exogenous shocks and to benefit from positive shocks	Economic response capacity	Mancini *et al.* (2012)
Community resilience	A process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance	Adaptive capacity, disturbance, social	Norris *et al.* (2008)
Psychological resilience	An individual's ability to adapt to stress and adversity. Resilience is a process and can be learned by anyone using positive emotions	Coping, adaptation, process	Tugade, Fredrickson & Feldman Barrett (2004)

ecological resilience extends the definition of resilience from ecology to include: (i) the amount of disturbance that a system can absorb and still remain within a domain of attraction; (ii) the capacity of a system to learn and adapt; and (iii) the degree to which the system is capable of self-organizing (Carpenter *et al*. 2001). The differences among engineering, ecological and social-ecological resilience have consequences for assessing and measuring resilience, just as they do for understanding and managing complexity and change.

While the above definitions consider resilience as an emergent property of complex systems, more recent variations stem from the application of resilience thinking to particular contexts. For example, development resilience has been defined as the capacity of a person, household or other aggregate unit to avoid poverty over time in the face of various stressors and in the wake of a myriad of shocks (e.g. drought, climate change and volatility in food availability) (Barrett & Constas 2014). A related, more specific, definition of resilience to food insecurity has been defined as a household's ability to maintain a specific level of well-being (expressed as food security) in the face of risks (Alinovi, Mane & Romano 2008).

Other strands of resilience research that focus more on people include community resilience, health and psychological resilience and social resilience (Adger 2000; Norris *et al*. 2008; Berkes & Ross 2013). Although emerging from distinct disciplines there is common ground among these research areas that provides an opportunity for their integration where appropriate (Berkes & Ross 2013). Psychological resilience, which refers to an individual's capacity to recover from adversity, is an active area of research that could inform and enhance the application of community resilience (Tugade, Fredrickson & Feldman Barrett 2004; Berkes & Ross 2013). Community resilience is defined by Norris *et al*. (2008) as a process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance. The related concept of social resilience is defined by Adger (2000) as the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change. Each of these perspectives, and in particular psychological resilience which has suggested ways of quantifying resilience, have developed methods relevant to assess and measure resilience in social-ecological systems (Ong *et al*. 2006).

The variety of resilience definitions highlights a diversity of applications in particular contexts. As others have noted and we concur, the specific application of resilience ('resilience of what and to what'?) and the way in which it is defined, will largely determine how it is assessed or measured (Carpenter *et al*. 2001; Alinovi, Mane & Romano 2008). While multiple conceptions of resilience can be problematic in terms of common indicators and comparable metrics, they can also extend the concept to a broader spectrum of contexts and drive exploration for better approaches to implementation. The heightened interest in resilience, however, increases the likelihood of existing metrics being repackaged as resilience metrics to serve the demand for new paradigms (Kapoor 2008) thus reinforcing the need to be explicit about how resilience is defined and what exactly is being measured.

Assessing and measuring resilience

ASSESSING RESILIENCE

A resilience assessment builds on a theoretical foundation and case study history to offer guidance toward understanding system dynamics of a given place and time in order to inform management interventions [Resilience Alliance (RA) 2010; Walker & Salt 2012]. Continually developed for over a decade, the focus has been on social-ecological systems in the context of natural resource management (Walker *et al*. 2002; Bennett, Cumming & Peterson 2005). Other more recent approaches to resilience assessment are tailored to specific types of systems such as social-ecological production landscapes and seascapes, drylands and urban systems (Tyler & Moench 2012; UNDP 2013; UNU-IAS, Bioversity International, IGES & UNDP 2014). The format of an assessment can vary, as well as the degree to which it is participatory vs. expert-driven and the level of detail sought. Core concepts included in the RA (2010) assessment guide include: thresholds and tipping points, adaptive cycles of change, cross-scale interactions and adaptive governance. Here we focus primarily on the RA (2010) approach because it is the one with which we are most familiar and the one with the largest body of research. In contrast to resilience assessment we consider the measurement of resilience to refer specifically to quantitative methods and numeric values of resilience. A limited selection of assessment and measurement approaches in Table 2 illustrates the range of methods that have been designed for various purposes.

Resilience assessment involves a process of identifying how resilience is created, maintained or broken down. A primary objective is to reconceptualize a place and associated issue(s) by focusing on system dynamics to compare various future pathways and to identify those that are robust to shocks and other drivers of change (Walker *et al*. 2002). Resilience assessment builds upon adaptive management (Holling 1978), complexity theory (Gunderson & Holling 2002), soft-systems methodology (Checkland 1981), as well as participatory approaches to learn and act (Pretty 1995). Acknowledging people and ecosystems as an integrated social-ecological system, represents an important advance in sustainability science more broadly, and is a foundational concept for resilience assessment (Berkes & Folke 1998). Building on this framework, resilience assessment guides the development of a conceptual model of an integrated social-ecological system where key actors, ecological structures and their interactions are identified in relation to the larger context in which they are embedded.

Table 2. Summary of approaches to measure and assess resilience that has emerged in a variety of social-ecological contexts (see Table 1 for resilience definitions)

Approach	Resilience definition most applicable	General purpose	Framework and methods	Metrics
Resilience Assessment Workbook for Practitioners (Resilience Alliance 2010)	Social-ecological resilience	Understand resource issues from a complex system's perspective and develop strategic management goals	Modules: system boundaries, system dynamics, interactions, adaptive governance, acting on the assessment. Methods: modelling, timelines, scale analysis, scenarios, network analysis, discussion	Attributes of resilience identified, some measured. No use of specific indicators
The Resilience, Adaptation and Transformation Assessment Framework (O'Connell *et al.* 2015)	Social-ecological resilience	Operationalize concepts of resilience, adaptation and transformation in broader global policy domains	Modular framework: Assessment procedure – system description, assessment, adaptive governance and management, stakeholder engagement; indicators for key variables; summary action indicators; meta-indicators	Summary action indicators and meta-indicators of coverage and quality of assessment
A Guiding Toolkit for Increasing Climate Change Resilience (IUCN 2014)	Social-ecological resilience	Guidance on developing climate change-resilient strategies and plans at national, subnational and local levels	Themes: diversity, self-organization and adaptive governance, learning and sustainable infrastructure, technology, participation, information sharing, gender and coordination. Methods: decision support and qualitative modelling	Ranking of 47 qualitative, hierarchical attributes
Toolkit for Indicators of Resilience in Socio-ecological Production Landscapes and Seascapes (UNU-IAS, Bioversity International, IGES & UNDP 2014)	Social-ecological resilience	Stakeholder-led. Purpose determined by the community	Themes: Landscape/seascape diversity and ecosystem protection, biodiversity, knowledge and innovation, governance and social equity, livelihoods and well-being. Methods: Participatory mapping, community discussion, lists and timelines	20 Indicators (scored 1–5)
Community-based resilience analysis (CoBRA), (UNDP 2013)	Development resilience	Quantify results of interventions and measure the ability of households to cope with drought in the Horn of Africa	Sustainable Livelihoods Framework with five categories of capital: human, natural, financial, social and physical. Methods: interviews, focus groups, participatory approach, household economy approach	Community-developed, quantitative indicators linked to five capitals
Indicator framework for assessing agro-ecosystem resilience (Cabell & Oelofse 2012)	Social-ecological resilience	Assess resilience of agro-ecosystems	Resilience attributes linked to specific phases of the adaptive cycle. Multimethods specific to each indicator	Thirteen behaviour-based indicators
Assessing resilience in stressed watersheds (Nemec *et al.* 2014)	Social-ecological resilience	Simplified desktop application for rapid resilience assessment	Properties: ecological variability, diversity, modularity, acknowledgement of slow variables, tight feedbacks, social capital, innovation, overlap in governance, and ecosystem services. Methods: Literature review, rapid prototyping and scoring	Nine resilience properties ranking from 1 to 5

(continued)

Table 2. (continued)

Approach	Resilience definition most applicable	General purpose	Framework and methods	Metrics
Indicators of critical slowing down (CSD) (Dakos & Bascompte 2014)	Ecological resilience	To detect critical transitions that may be associated with regime shifts	Framework describes a shift between alternate stable states and CSD as system approaches threshold. Various statistical tools and modelling of empirical data	Indicator is statistical signature of CSD
A common analytical model for resilience measurement (FSIN 2014)	Development resilience	Measure resilience in a development context with a focus on food security	Components: construct assumptions, causal framework, indicators and data structure, expected trajectory, data collection, estimation procedures. Variety of quantitative and qualitative methods	Categories of indicators provided, specific indicators depend on context
Framework for urban climate resilience (Tyler & Moench 2012)	Social-ecological resilience	To inform priority interventions as part of a resilience strategy	Elements: systems (e.g. flexibility and diversity), social agents (e.g. responsiveness, capacity to learn) and institutions (e.g. rights and entitlements, decision making). Methods: vulnerability assessment, shared learning dialogues	No use of specific indicators

WHY DO A RESILIENCE ASSESSMENT?

While originally developed with natural resource managers as the target user, there are many reasons for undertaking a resilience assessment and the approach is often adapted to suit the context (Liu 2014; Sellberg, Wilkinson & Peterson 2015). A common objective of resilience assessment is to identify risks, opportunities and alternate strategies to those identified by conventional management. Resilience assessment has been tested and applied in a number of settings and perhaps most extensively in Australia where catchment management authorities have adopted the approach to inform the development of catchment plans (Walker *et al*. 2009; Namoi CMA 2013; Mitchell *et al*. 2014). A number of regional natural resource management plans, strategies and other outputs have been developed through processes involving resilience assessment and analysis, providing practical examples as well as opportunities for experimenting and learning from the process (Mitchell *et al*. 2014). Novel outputs and reporting frameworks for monitoring potential system thresholds that are continuously updated with information as new knowledge and understanding becomes available, illustrate some of the opportunities for integrating resilience thinking into strategic planning and management (Roux & Foxcroft 2011; Wheatbelt NRM 2014).

Resilience assessment has also been applied to the purposeful transformation of social-ecological systems (Mitchell *et al*. 2014). It has been used in urban and peri-urban settings, engaging municipal councillors and other governance parties to address the influence of global environmental change drivers at the local level (e.g. on food systems), as well as increasing urbanization (Liu 2014; Sellberg, Wilkinson & Peterson 2015). In development contexts resilience assessment has been applied to pasture management systems (Haider, Quinlan & Peterson 2012) and as a tool for building capacity among development agency staff and the communities with which they work (L. J. Haider, pers. comm.). Different aspects of resilience are important in different systems and a resilience assessment approach is flexible and can be easily adapted. A challenge remains regarding how to quantify resilience in ways that are similarly flexible and appropriate across a range of systems.

By identifying which aspects of resilience are most relevant to different cases, the assessment approach recognizes that resilience is a dynamic property shaped by many different processes as well as the larger context in which a system is embedded. These include cross-scale dynamics such as competition and succession, as well as climate variation and species movement, as well as social processes, such as how people respond to regulation and changes in global markets or inter-generational shifts in activities. These cross-scale dynamics that infer causation from changes in resilience measures require careful analysis, and evaluating resilience-building programmes needs to be done in ways that take these cross-scale dynamics into account. In the Goulburn-Broken catchment of Australia, where resilience assessment has played a key role in natural resource management planning over the

past decade, understanding of system thresholds and their potential interactions, including across levels of governance, help inform management options that directly impact the economy, people's livelihoods and the long-term sustainability of the landscape (Walker *et al.* 2009; Walker & Salt 2012). Furthermore, resilience assessments of social-ecological systems provide a foundation for devising ways that social and ecological variables can be measured without necessarily need to be decoupled (Davoudi *et al.* 2012).

MEASURING RESILIENCE

A variety of methods for measuring resilience have emerged across disciplines. The quantification of ecological resilience has been actively explored with numerous ways of detecting change in complex systems developed in recent years that are covered in depth elsewhere (Dakos *et al.* 2015). Current ecological approaches emphasize statistical signals such as critical slowing down that may be detected when some ecosystems cross thresholds into alternate stability domains (Dakos & Bascompte 2014). Bennett, Cumming & Peterson (2005) proposed a systems model approach to determine proxy variables for resilience in managing different ecosystems. In this case, the proxies selected often corresponded to the slow variables of the ecosystem (*sensu* Walker *et al.* 2012). Since slow variables are tied to the resilience of the system, it makes sense that close monitoring of these would be a good approach to guide policy.

Other approaches to measure resilience have developed in fields such as climate change adaptation (Tyler & Moench 2012) as well as for military applications for improving risk analysis practices to address emerging and unforeseen threats (Eisenberg *et al.* 2014). Advances in the development of resilience metrics have also come from the field of economics with the application of inclusive wealth measurements as an economic measure of sustainability (Pearson *et al.* 2013). Additionally, modelling complex systems has drawn comparisons to measures of health, with the suggestion that resilience metrics may need to be complex functions that combine several different metrics (Heckbert, Costanza & Parrott 2014).

In the field of social science and practice one also sees a growing demand for resilience metrics. In development for example, this trend arises in part from the cross-pollination of resilience science with social science perspectives on vulnerability, disaster and risk. Many development scholars and practitioners have enthusiastically adopted the concept of resilience, especially for disaster risk reduction (World Bank 2013; USAID 2014). Although the relevance of resilience for the economics of development has been discussed for over 20 years, the pursuit of quantitative metrics is more recent (Perrings 2006). International development is an interesting focus to better understand the relationship between assessment and measurement, due to the surge in demand for resilience metrics (2013) and for the field's own pioneering work in measuring complex concepts (see Discussion below), which may offer some valuable lessons for resilience assessment and measurement.

Food systems are one area where there has been recent substantial effort to measure resilience in a development context [see e.g.: Alinovi, Mane & Romano 2008; IISD 2013; UNU-IAS, Bioversity International, IGES & UNDP 2014]. The Food and Agriculture Organization (FAO) approach assumes that food security and resilience at a given point in time depends on options available to make a living (i.e. assets, income-generating activities, public services and safety nets), with a second measurement 5 years later to detect change over time (Alinovi, Mane & Romano 2008). Measuring resilience over time against a baseline as a function of the change in livelihood and environmental variables acknowledges the importance of cross-scale temporal dynamics. The FAO example also highlights the need to be explicit regarding how resilience is being defined and what exactly is being measured.

To date there has been relatively little cross-fertilization between the different disciplines exploring resilience measurement despite their shared theoretical foundations (Barrett & Constas 2014). As a result the ability to compare and synthesize results remains a challenge, however, researchers continue to work toward approaches that will enable the comparison of results and more specifically, improve the accountability of programmes (Bene 2013). The benefits gained through a common metric must however also be appropriately tuned to a particular place and be accountable to the 'beneficiaries' it intends to serve. In social-ecological systems the creation of legitimate, useful and rich measures of resilience usually require that indicators for resilience be co-created with local stakeholders, practitioners and knowledge-holders (UNU-IAS, Bioversity International, IGES & UNDP 2014). Resilience metrics that emerge from local contexts may limit cross-case comparisons, but with careful hierarchical definitions of terms, common properties of resilience may be scaled-up and compared across sites, thus allowing multiple knowledge systems to inform results (Tengö *et al.* 2014).

Discussion

This section lays out the trade-offs of simplifying complex concepts so that they can be measured while still deepening an understanding of underlying systems dynamics. As an attempt to scale up the context dependent nature of any resilience measurement, we propose a meta-framing of resilience principles to seek consistency across the approaches. The paper concludes with recommendations for the application and practice of resilience assessment and measurement.

SIMPLIFYING COMPLEX CONCEPTS

The need to assess or measure a complex situation is not unique to resilience. A variety of disciplines outside of

ecology have long dealt with what can be broadly considered 'wicked' problems. In these situations metrics can play a role in monitoring, evaluating and reporting, but more importantly, they are used to guide decision-making. Similarly, resilience metrics can simplify important system attributes to help evaluate the impact or merit of interventions, enable the comparison of similar places across time and space, and inform strategies at multiple scales.

The field of international development with its long history of devising metrics for monitoring, evaluating and reporting purposes offers a learning opportunity. For example, the emergence of the Human Development Index (HDI) involved a process of simplifying the complex outcome of human well-being. The HDI is inspired by Sen's capabilities approach (1999), in which people's well-being depends on 'functionings', which are things that a person may value doing or being. Capability refers to a person's freedom to achieve and enjoy those functionings. Thus improving well-being depends on removing the obstacles that stand in the way of people's freedom to achieve the functionings they value. But one of the difficulties with the capabilities approach was dealing with the fact that there were as many combinations of functionings as there were people, making it difficult to both communicate and to compare across countries or over time. The creation of the HDI partially solved the issue by creating a composite indicator that contained measurements of income, literacy and life expectancy (functionings that are universally shared by all people) (Fukuda-Parr 2003). Arguably, the HDI does not transmit the richness that the capabilities approach intends, but it allows for easy comparison while being theoretically anchored in the capabilities approach. In the same way, for social-ecological systems, it may be possible to select indicators of resilience while making explicit underlying assumptions.

Another and perhaps complementary approach is to determine appropriate surrogates for resilience depending on the context. Marschke & Berkes (2006) used human well-being as a surrogate of resilience to explore how households in two Cambodian fishing villages dealt with shocks and stresses to their livelihoods. In this case, they framed their study using a livelihoods approach and considered the strategies that fishers used, including increasing diversification, fostering learning and improving self-organization to cope with stresses and uncertainty, providing a good example of how resilience definitions can be aligned with the approach.

There are lessons to draw from measurement approaches taken by other fields dealing with complexity. A focus on measurement means necessary simplification, which requires strong theoretical grounding to justify one simplification over another. Further, there is a tension around the degree of simplification that measurement demands and at what point these simplifications diverge from a holistic and systemic perspective. We may need to question what a composite measurement might bring in terms of being able to inform specific management actions that require a level of understanding beyond an aggregated set of indicators.

DEEPENING UNDERSTANDING OF SYSTEM DYNAMICS

Simplifying resilience for measurement need not detract from deepening our understanding of systems dynamics. Efforts to quantify resilience share aspects of assessment approaches in that they require addressing the questions 'resilience of what and to what'? The practice of resilience assessment has reinforced the value of learning about and understanding complex adaptive systems dynamics. Developing a shared understanding of an issue from a systems perspective is an important objective of resilience assessment. Participatory activities such as bounding the problem, defining the focal scale, developing timelines based on past disturbances and considering cross-scale interactions, contribute a complex adaptive systems perspective, which in turn has been shown to enhance resilience of social-ecological systems (Biggs *et al.* 2012; Biggs, Schlüter & Schoon 2015). Methods that can help relate general properties of resilient social-ecological systems, such as fostering complex adaptive systems thinking, with more specific manifestations of these properties could be very useful for developing resilience metrics that can be adapted to specific places.

One aspect of complex system dynamics that has important implications for the design of resilience metrics is that of spatial resilience in social-ecological systems (Cumming 2011). Bridging landscape ecology and complex systems, spatial resilience draws attention to the influence of structure and variation across space. For example, connectivity can enhance the resilience of social-ecological systems by facilitating processes such as information sharing or recolonization following some disturbance, but highly connected systems can also increase the speed and extent of disturbances (e.g. forest fires) (Biggs, Schlüter & Schoon 2015). Understanding the ways in which spatial variables interact with resilience should improve the design of resilience metrics.

Our understanding of complex adaptive systems will always be partial and incomplete because of their dynamic nature as well as imprecise measurement and imperfect system models. Thus it follows that resilience assessment as well as resilience metrics, will always be partial and incomplete. It is therefore useful to design approaches like resilience assessment, that acknowledge this uncertainty and plan for evaluation, learning and revision. Precisely because resilience is dynamic, approaches to measuring that do not take endogenous/internal dynamics into account, risk misrepresenting the potential impacts of interventions. Explicit consideration of slow variables (Walker *et al.* 2012) as mentioned in the section above is one such approach that considers endogenous dynamics. The recently released Resilience, Adaptation and Transformation Assessment framework, builds on existing resilience assessment frameworks, including the Resilience

Alliance's Workbook for Practitioners (RA 2010), and retains a focus on dynamic systems concepts while also guiding the identification of relevant indicators to measure and monitor over time (O'Connell *et al.* 2015). Others have found the use of identity criteria to be useful in the context of operationalizing resilience in complex systems, with continuity through space and time helping define the identity of a system in addition to its component parts and their interactions (Cumming & Collier 2005).

RESILIENCE PRINCIPLES FOR ENHANCING RESILIENCE

Decades of research on resilience in social-ecological systems have identified a number of strategies for building and enhancing resilience. These strategies embody the properties of resilient social-ecological systems in particular rather than complex systems in general and have implications for both the measurement and assessment of resilience. Seven strategies have been shown to build resilience: maintain diversity and redundancy; manage connectivity; manage slow variables and feedbacks; foster an understanding of social-ecological systems as complex adaptive systems; encourage learning and experimentation; broaden participation; and promote polycentric governance systems (Biggs *et al.* 2012; Biggs, Schlüter & Schoon 2015).

The resilience building strategies can be organized along two axes, the first, according to whether they primarily focus on the resilience of a social-ecological system or on the resilience of its governance, and the second, whether the focus emphasizes system structure or dynamics (Fig. 1). The distinction between system structure and dynamics corresponds to a focus on the processes and organization that maintain resilience, with that of dynamic interacting systems. The distinction between strategies focused on the 'system-to-be-governed' and the 'governance system' can also be interpreted as distinguishing between whether a social-ecological system is being approached from a more analytical scientific perspective vs. a management or governance perspective (Jentoft, van Son & Bjørkan 2007; Biggs, Schlüter & Schoon 2015). The difference is directly relevant to the design of resilience metrics as it shifts the focus from the resilience of the system alone to the management or governance of the system. This can for example, shift the focus from evaluating whether a local agricultural system is resilient, to whether management interventions applied to the agricultural system are resilient. The distinction is particularly important because much of the focus on measuring resilience has been on the systems being governed, rather than on (or including) the governance of those systems, and strengthening resilience also requires analysing the resilience of intervention strategies (Enfors *et al.* 2008).

The key lessons that these principles for building resilience provide for the design of resilience metrics and assessment are the importance of considering both static (structural) and dynamic aspects of the system, as well as the resilience of both interventions and the system itself. Furthermore, the different types of strategies suggest different approaches to measure resilience. The relationships among these strategies may point to ways of constructing theoretically grounded, composite resilience indices and potential ways of comparing broader concepts, such as learning, across different places and over time. Exploratory approaches to rapid resilience assessment have already begun to use resilience properties as a basis for indicators ranked by experts in the field (Nemec *et al.* 2014; Cosens & Fremier 2014). Building on these approaches while integrating aspects of participatory resilience assessment seems worthy of further exploration. Resilience theory, by defining structural, dynamic, analytical and governance dimensions of resilience, can provide a framework to guide the development of a common set of resilience indicators that can be used for a variety of

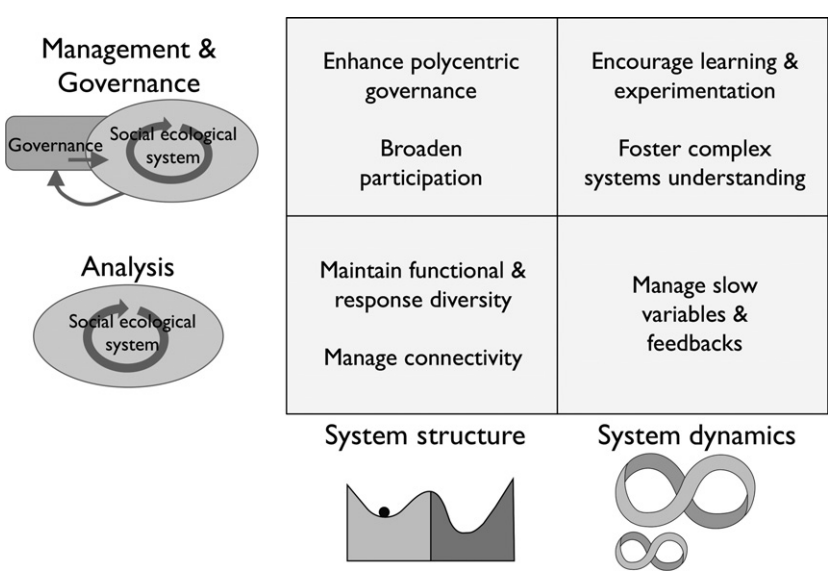

Fig. 1. Strategies for enhancing resilience (Biggs, Schlüter & Schoon 2015) can be divided along two axes by whether they focus primarily on the resilience of a social-ecological system or its governance, and by whether they focus on resilience based on system structure or its dynamics. These strategies are complementary and can be combined.

purposes without limiting their utility and comparison across cases.

RECOMMENDATIONS

To be effective, measuring resilience should adopt an iterative and ongoing approach, as is recommended for resilience assessment. The need for continuous monitoring and for incorporating new knowledge into policy and practice as it becomes available means that project targets may need to be adjusted accordingly. Furthermore, as major donors around the world aim to fund projects that 'enhance livelihood resilience', 'enhance market resilience' or 'enhance the resilience of landscapes' (e.g. World Bank, International Livestock Research Institute, FAO, Global Resilience Program), a commitment to resilience building requires institutional reform. Scaling up from local projects and implementing resilience at large scales, implies a significant restructuring of governance institutions, for which there are noted challenges (Gunderson & Light 2006). Finally, how resilience is defined and understood is critical, and while some degree of conceptual vagueness may have benefits, being clear about what exactly is being measured, how and any limitations, must be made explicit (Struntz 2012; Dakos *et al*. 2015). We provide a list of recommendations for applying resilience thinking in management activities, in the context of resilience assessment and measurement:

1. Ongoing efforts to develop ways of quantifying resilience should be grounded in theory. The integration of key principles for enhancing resilience could fulfil this need while also offering a level of consistency across different disciplinary approaches.

2. A prudent approach to measurement would ensure that the opportunity to deepen understanding of system dynamics is not lost, possibly through a hybrid approach that incorporates aspects of resilience assessment.

3. Tension may exist between top–down expert led assessment and measurement vs. participatory approaches. Self-organization and agency as described in community resilience literature could be a critical factor to explicitly recognize and mediate between these approaches.

4. Understanding the specific context of a resilience assessment/measurement project is necessary to be able to adequately determine the appropriateness of an approach which can be informed by answering the questions: Resilience of what? To what? For whom? And for what purpose?

5. In particular with respect to resilience measurement, there is a need to be clear about how resilience is conceptualized and defined in relation to the approach by explicitly acknowledging what is being measured along with any underlying assumptions and known trade-offs.

6. With respect to scale, spatial and temporal aspects of resilience need to be taken into consideration. A hierarchical approach involving the specific context nested within general resilience principles may be useful.

CONCLUSION

Resilience assessment and measurement are essential ways of distilling complex systems to make sense of broad patterns and to identify emergent properties. Both approaches require reducing information to what is important and useful for decision-making. One expectation is that from a rigorous process of simplification in which learning is maximized, new insights about the system can emerge, in addition to tracking progress toward pre-defined goals (Stirzaker *et al*. 2010). Being clear in advance as to *why* one wants to measure or assess resilience is the key to *how* the simplification should occur. For example, wanting to identify which communities or ecosystems are more or less resilient to drought or other potential crises are an altogether different objective from developing strategic plans for a particular place to navigate into an uncertain future. In the first case, a resilience metric that compares similar communities makes sense. In the latter, a collaborative process that is designed to fill in gaps in understanding and generate new ways of looking at persistent issues would be better informed through a resilience assessment that may include some quantitative system measures. In general, resilience metrics on their own are less likely to inform novel solutions, particularly when the issues of concern involve system components interacting across scales or sectors (Heckbert, Costanza & Parrott 2014), or where there is strong disagreement about system boundaries or goals.

Measuring resilience provides a potentially powerful way to evaluate both intentional change, as in the change that results from programmes or policies, and unintentional change that comes about as a result of unforeseen system dynamics. Resilience metrics could be used to help maintain or move a system towards more desirable and sustainable system states, track thresholds of potential concern and help with evaluations on how the system is being managed. It is worth repeating however, that how a complex system behaves is not a function of the sum of its parts. In response to planned interventions and unplanned change, a system's key feedbacks and dynamics shift, and consequently processes or attributes that are important for resilience also change over time. To be effective, metrics of resilience need to be evaluated to determine if they are actually meeting the needs for which they are designed, suggesting that unlike resilience assessment that does not necessarily require resilience metrics, resilience metrics do require some degree of resilience assessment.

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Data accessibility

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

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