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Research

Toward Operationalizing Resilience Concepts in Australian Marine Sectors Coping with Climate Change

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ABSTRACT. We seek to contribute to the scholarship on operationalizing resilience concepts via a working resilience indicator framework. Although it requires further refinement, this practical framework provides a useful baseline for generating awareness and understanding of the complexity and diversity of variables that impinge on resilience. It has potential value for the evaluation, benchmarking, monitoring, and reporting of marine system resilience. The necessity for such a framework is a consequence of the levels of complexity and uncertainty associated with climate change and other global change stressors in marine social-ecological systems, and the problems involved in assessing their resilience. There is a need for: (1) methodologies that bring together knowledge from diverse sources and disciplines to investigate the complexity and uncertainty of interactions between climate, ocean, and human systems and (2) frameworks to facilitate the evaluation and monitoring of the social-ecological resilience of marine-dependent sectors. Accordingly, our main objective is to demonstrate the virtues of combining a case study methodology with complex adaptive systems approaches as a means to improve understanding of the multifaceted dynamics of marine sectors experiencing climate change. The resilience indicator framework, the main product of the methodology, is developed using four case studies across key Australian marine biodiversity and resource sectors already experiencing impacts from climate and other global changes. It comprises a set of resilience dimensions with a candidate set of abstract and concrete resilience indicators. Its design ensures an integrated approach to resilience evaluation.

Key Words: *Australia; climate change impacts; marine sector; resilience assessment; resilience indicator*

INTRODUCTION

Marine systems are recognized as complex adaptive systems that are under considerable stress from a range of anthropogenic impacts (Levin and Lubchenco 2008). In many locations, nonclimate anthropogenic impacts on marine ecosystems from overfishing, bycatch, habitat destruction including from coastal development, and chemical and nutrient pollution are being further exacerbated by climate change (Crowder et al. 2008). Although we consider the consequences of wider global change, our particular focus is on the effects of climate change on marine-dependent industries and associated human populations, because these are expected to be especially affected by climate change (Badjeck et al. 2010, Brander 2010). Indeed, the future of services supplied by marine ecosystems is becoming increasingly uncertain (Gunderson 2003).

Australia's marine systems and biota are exposed to a range of likely impacts from human-induced climate change, including warming ocean temperatures, ocean acidification, sea level rise, changes in nutrient availability, and changes in variability and extremes such as storminess, rainfall intensity and runoff, and associated variation in salinity levels (Poloczanska et al. 2007, 2012). Diverse marine environments are already exhibiting climate change impacts, including extensive coral bleaching along the Great Barrier Reef (GBR; Hoegh-Guldberg et al. 2007, Hughes et al. 2010), poleward range shifting of species (Last et al. 2010), increasing frequency of harmful algal blooms (Hallegraeff 2010), habitat damage from changes in storm frequency and distribution, and ocean acidification (Howard et al. 2009, Poloczanska et al. 2012). All of these have knock-on effects for marine biodiversity and the resilience of marine social-ecological systems (SES; Poloczanska et al. 2012). Ocean warming of Australia's highly productive southeast and southwest marine waters (Holbrook and Bindoff 1997, Pearce and Feng 2007, Ridgway 2007), which are warming faster than 90% of oceans elsewhere, so-called "hotspots" (Tittensor et al. 2010), has serious implications for dependent marine sectors. As well as these significant climate stressors, marine sectors are subject to a range of nonclimate drivers that often interact with the former and can have a compounding or dampening effect.

As SES, the complex interactions between the social and ecological dimensions of marine sectors are influenced by nonlinearity of feedback effects between the two systems, by associated thresholds, surprises and perverse effects, legacy effects, resilience status, and by spatial, temporal, and organizational variation (Liu et al. 2007). To understand and temper the resulting levels of complexity and uncertainty, a

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marine system resilience, vulnerability, and adaptability approach can be beneficial (Young et al. 2006).

Operationalizing resilience in the marine environment is particularly challenging. From an ecological perspective, it is difficult and expensive to develop detailed scientific knowledge about marine systems given that they are large, poorly bounded systems, and often cross-jurisdictional. Consequently, observations of marine biological changes are much fewer than for terrestrial systems (Richardson and Poloczanska 2008). Marine systems often cannot readily be probed by means of experiments at relevant scales (Scheffer 2009), and detecting or predicting key changes like shifts between ocean system states is problematic (deYoung et al. 2004, 2008, Thrush et al. 2009). From a social perspective, it can be difficult to capture the totality of resilience either in measuring the impacts of ecosystem decline on the resilience of marine sectors and institutions, in observing the vulnerability of different resource groups in a meaningful manner (Adger 2000), or in collecting the relevant socioeconomic data (Cinner et al. 2009), especially given the context-specific nature of resilience. A further challenge for operationalization is that, unlike ecosystems, social patterns and structures are conditioned by symbolic construction or meaning, elements of which may divorce human systems from ecological systems and retard responsiveness to ecological signals (Westley 2002).

Additionally, operationalizing resilience is associated with some more general conceptual and practical challenges. The first set of challenges includes developing the commonplace acceptance of SES as complex adaptive systems (Walker and Salt 2006), definitional problems resulting from the ambiguity of the 'resilience' term (Brand and Jax 2007), its dynamic context (Nelson et al. 2007, Bohensky 2008), and constraints on further conceptual development by high levels of system complexity and dynamism (Marshall and Marshall 2007). The second set of challenges involves the practical difficulties of resilience measurement (Carpenter et al. 2005), such as determining which variables to measure (Cumming et al. 2005), developing standard metrics (Cutter et al. 2008), making resilience observable (Nyström et al. 2008, Robinson and Berkes 2010), locating and finding measures for thresholds (Walker and Meyers 2004, Eakin and Luers 2006), acquiring sufficient data (Malone and Brenkert 2008), and measuring resilience in a context of multiple fast- and slow-moving drivers of change (Nelson et al. 2007).

For our purposes, resilience operationalization is the practical application of resilience concepts in decision making and planning. Operationalization entails making resilience concepts useful and useable beyond their theoretical context to policy makers and managers in marine SES and using the lessons from such application to further inform resilience's conceptual and practical development.

As a contribution to the literature on operationalizing resilience, we develop and present a resilience indicator framework, based on investigations of the system dynamics of four Australian marine sectors experiencing impacts from climate and other sources of global change. We propose an approach to resilience diagnosis that reflects the multidimensionality and complexity of marine SES. We use four case studies to develop a set of critical resilience dimensions to underpin our framework.

METHODOLOGIES FOR A RESILIENCE INDICATOR FRAMEWORK

Resilience and complex adaptive systems

The theoretical grounding for this study is in the approach to SES proposed by the Resilience Alliance (2007) and its associates. This work owes much to ecologists such as Gunderson and Holling (2002; see also Holling 2001) and the concepts they propose for understanding complex SES, such as the adaptive cycle and panarchy. A key tenet of this theory is that change rather than equilibrium is the normal state of complex adaptive systems. As a result of enhanced interconnectedness between social and ecological systems, it is becoming clearer that change is increasingly predictable, whether it be gradual or unexpected change (Nelson et al. 2007). In marine environments subject to climate change and variability, such changes are a function of the complex nonlinear feedbacks among human production, ocean, and climate systems. The operation of feedbacks can generate unexpected disturbances and outcomes, which, in turn, create an environment of uncertainty for marine managers. One of the virtues of a resilience approach is that it opens up the possibility of operating in this "zone of uncertainty" (Bourdieu 1999).

If we follow Bourdieu's line of reasoning, we understand this zone to be one that allows for transformative spaces to be created in which the ways of behaving and acting that are taken for granted can be unsettled and interrogated so that novel responses to complex problems can emerge and be tested. Although predictions cannot be made with confidence, causes may be unclear, and contradictory conditions are evident, operating in the zone of uncertainty can enable the sort of reflexivity and adaptive practice that support rapid re-evaluation of dominant conceptualizations of conditions. The zone of uncertainty is paralleled in complex adaptive systems by the 'back loop' of the adaptive cycle in which levels of system resilience are low, and the system is open to external influences, novelty, innovation, experimentation, learning (Holling 2001), and 'windows of opportunity' (Olsson et al. 2004).

The potential of the back loop is complemented by the understanding that complex adaptive systems are capable of operating in multiple states, effectively allowing for the possibility of changing the system state. An associated concern for complex adaptive systems is avoiding transformation into a qualitatively different and undesirable state as a result of disturbance. This is a function of their resilience, which describes the amount of change they can undergo and retain the same controls on structure and function, their capacity for self-organization, and their ability to build capacity to learn and adapt (Walker et al. 2002, Folke 2006, Marshall and Marshall 2007; see also http://www.resalliance.org/index.php/resilience). Resilience analysis therefore needs to account for those slowly changing variables on which resilience depends, the key feedbacks operating among the different systems, nearness to thresholds that might carry the system into an undesirable state, and the capacity for reorganization in the face of both gradual and transformative change.

A case study approach to operationalizing resilience

Empirical robustness is achieved by using case examples of sectors currently dealing with climate change impacts. The particular case studies discussed here are instrumental case studies (Stake 2000), selected to provide insight into the interactions and interdependencies between linked social and ecological systems threatened by novel climate change impacts. The cases are also of the extreme and critical kind (Flyvberg 2006) because they comprise different types of marine-dependent sectors already dealing with climate change effects, although they utilize marine resources in different ways. As extreme cases, they exemplify instances in which climate change impacts are particularly problematic, e.g., the effects of species shifting their ranges in response to climate-induced changes in ocean circulation, impacts of ocean warming on fisheries and aquaculture in a global warming hotspot, and the impacts of extensive coral bleaching on marine tourism in the GBR. As critical and extreme cases, it was anticipated they would provide both the maximum amount of information and understanding about the dynamics of four different SES and therefore generate a valid set of data as the basis for an indicator framework.

The main purpose in combining case study and complex adaptive systems approaches to appraising marine sector resilience was to ensure that due consideration was given to the complexity, uncertainty, and multidimensionality that is inherent in such an enterprise in the context of global climate change, especially in marine-dependent sectors.

The four studies of marine sector resilience were undertaken in 2009/10 under the auspices of Australia's Climate Change Adaptation Research Network for Marine Biodiversity and Resources, one of the National Climate Change Adaptation Research Facility's eight national adaptation networks. The case studies, i.e., range shifting of marine species in response to ocean warming, the Tasmanian commercial rock lobster (*Jasus edwardsii*) fishery, oyster aquaculture in southeastern Australia, and tourism in the GBR were selected on the basis of climate change impacts of current concern, researcher expertise, and data availability. The sectoral cases were approached from a disciplinary perspective first, focusing initially on ecological (species range shifting), economic (rock lobster), institutional (oyster aquaculture), social (GBR tourism) resilience perspectives. Key aspects of the case sectors are outlined in Table 1.

Conclusions about the resilience of each case study system cannot easily be drawn at this stage. The evidence for range-shifting species is still emerging; however, some shifts will have dramatic repercussions for receiving ecosystems whereas others will be viewed as benign or even beneficial from a human perspective (Madin et al. 2012). Those in the former category may possibly cause regime shifts as is happening with the invasion of the urchin species, *Centrostephanus rogersii*, which is damaging the resilience of rocky reef ecosystems and dependent fisheries along Tasmania's east coast (Johnson et al. 2011). The Tasmanian rock lobster industry is rated as having high economic resilience in relation to its governance and management institutions and for its fleet capacity; however, the sector is vulnerable in terms of fuel costs, supply chain components such as information flow and innovation, and financial security (Pecl et al. 2009, van Putten and Gardner 2010).

Oyster aquaculture's vulnerabilities include water quality impacts resulting from catchment activities, absence of integrated terrestrial-marine governance, and lack of understanding of the biophysical basis of the industry (Leith and Haward 2010). However, emergence of collaborative management approaches between government and growers and improvements in oyster species' resistance to disease, maintenance of productive environmental conditions, and management improvements will contribute to sector resilience. The New South Wales industry is more vulnerable to climate change impacts, through outbreaks of disease and flooding, than the South Australian and Tasmanian segments. Great Barrier Reef tourism is especially vulnerable to climate change impacts through increased risk of vector-borne disease, increased intensity of natural hazards, e.g., cyclones, and reduced biodiversity (Marshall et al. 2009). However, the existence of multilevel, collaborative governance arrangements and interactions among scientists, environmental managers, tourism operators, fishing industries, and the broader community provides a high level of institutional and social resilience.

As a prelude to the presentation of the resilience indicator framework, we discuss the challenges for resilience frameworks, establish a rationale for the use of frameworks in SES studies, discuss the role that indicators can play in operationalizing resilience concepts, and consider precursors for resilience indicators.

Table 1. Case study descriptions: system characteristics, external drivers, and observed climate change impacts.

Case Study	Key System Characteristics	Main Climate Stressors/Drivers	Main Nonclimate Stressors/ Drivers	Observed Climate Change Impacts
Marine species range expansion	Marine species' range boundaries are often determined in part by habitat characteristics, both physical, e.g., temperature, substrate, and biological, e.g., competition, predation	Increasing sea surface temperatures (SSTs) via strengthening of the East Australian Current (EAC), aiding larval transport and bringing tropical water further south leading to changes in productivity	Habitat destruction from growth of coastal population and poorly planned coastal development, destructive fishing practices, shipping accidents, and boat anchorages	Strengthening of the EAC (20% since 1960), causing changes in physical, chemical, and biological properties of temperate waters (Malcolm et al. 2011). Southward EAC extension has caused silicate concentrations to decline off eastern Tasmania (Thompson et al. 2009)
	Changes in one or more of these range boundary determinants may cause a species range edge to shift		Nonclimate-related changes in oceanographic conditions	
	Climate change is likely to lead to changes in one or more of these determinants for some marine species		Fishing-mediated changes in competitor and predator assemblages	Over 2.0°C increase in SST (east coast Tasmania 1944-2005) and declines in precipitation via a long-term drying trend have led to increasing salinity and therefore changes in productivity (declines of 8% per year in chlorophyll *a* concentrations, 1944-2005; Thompson et al. 2009)
	The evidence is mounting that such range shifts are occurring as a result, either directly or indirectly, of climate change			
Southern rock lobster (*Jasus edwardsii*) industry	One of Tasmania's most valuable resources, with the industry worth over A$65 m 2011-12 (but below the 2005-06 peak)	Temperature increases have contributed to a decline in larval lobster settlement in eastern Tasmania over the last 15 years	Increasing numbers of urchins (*Centrostephanus rodgersii*) invading from warmer New South Wales (NSW) waters assisted by EAC extension	Change/decline in stock abundance particularly in northern parts of Tasmania (mainly last 5 years)
	Dependent on rocky reef/ macroalgal (kelp) habitat along the coastline	Southward extension of the warm EAC (350km since 1960s)	Kelp beds (rock lobster habitat) contracting due to urchin grazing	Relative geographic redistribution of fishing effort (declined by 50% in northern waters and doubled in cooler southern waters, 1970-2009; Pecl et al. 2009)
	Declining state-wide stock abundance (mainly last 5 years)		Increasing octopus (*Octopus tetricus*) sightings, a likely predator of rock lobster (www.redmap.org.au)	Interaction between increasing fishing pressure on high value red lobsters (Green et al. 2010), opportunities for rock lobster translocation, and climate driven temperature increases.
	Product value differentiation (higher value red lobster caught in north – lower value paler lobster caught in colder southern waters)		Increasing sightings of NSW rock lobster species (*Sagmariasus verreauxi*; www.redmap.org.au)	Urchin barrens now cover 50% of some northeast Tasmania rocky reefs since arriving in the late 1970s
	Reducing fisher participation since Individual Transferable Quota (ITQ) introduction (efficiency gains); around 312 licenses but 200 commercial fishers		Changing fishery demographic (fewer young fishers entering because of alternative higher-earning opportunities elsewhere)	Increasing octopus catch and octopus predation of lobster in pots
	Increasing investor ITQ ownership		Changing quota ownership characteristics are increasing variable fishing cost for lease quota fishers	Reduced Total Allowable Commercial Catch (TACC; 1523 tonnes in 2008/09 to 1193 tonnes for 2012/13). Actual catch declined from 2200 to 1500 tonnes, between 1985 and 2008 (Linnane et al. 2010)

(con'd)

	Aging fisher demographic		Increasing fishing costs due to greater search time and farther travel	
Oyster aquaculture	The value of the Australian oyster industry is estimated around A$120 m in 2011.	Warming SSTs; air temperature; zonal wind change; extreme rainfall events; sea-level rise limiting use of/access to land bases	Land use in catchments affecting runoff and water quality	Increased flood frequency in northern NSW is causing acidification of estuarine waters and resulting in higher estuary closure rates, i.e., farmers are unable to sell their stock more often (Dove and Sammut 2007)
	Distributed aquaculture sector spread across bays and estuaries of NSW, South Australia, and Tasmania		Disease outbreaks, which may be linked to climate drivers, such as herpes viruses and vibrios in Pacific oysters (*Crassostrea gigas*; POs), and the complex and fatal pathological conditions known as QX and winter mortality in Sydney rock oysters (*Saccostrea glomerata*; SROs).	
	POs and SROs are main species	Likely to be most substantial in estuarine regions where rainfall changes can exacerbate pre-existing stressors associated with upstream management and development		Increasing water temperature in northern NSW has been linked to increased risk and outbreaks of QX; aquaculture here has not recovered from QX outbreaks in the 1970s (Nell 2007)
	Numerous disease threats to both species		Issues relating to social license affect the legitimacy of the sector and thus the levels of political support	
	Numerous land use and surface runoff risks in estuarine systems	Likely to be caused by complex synergistic interactions between multiple climatic and other drivers rather than a single cause		
	Mostly small, family-run businesses		Energy costs of transport and cooling, related to distance to markets	
	Access to water based on leasehold; arrangements vary slightly between states			
Great Barrier Reef marine tourism	Reef tourism contributed around A$5.1 billion to the Australian economy in 2006	Reef based tourism is vulnerable to climate change impacts: sea level rise, increased water and air temperatures, increased storm/cyclone frequency and severity, ocean acidification, increased windspeed, changed rainfall and runoff, cloud cover affecting visibility, and changes in El Niño Southern Oscillation (Coghlan and Prideaux 2009, Wilson and Turton 2010).	Substantial falls in visitor numbers are expected if environmental conditions, e.g., water quality, are degraded (De'ath and Fabricius 2008) with significant implications for regional annual income (Huybers and Bennett 2000).	Sea and air temperatures are increasing; there is observed sea level rise, ocean acidification and more intense storms and more frequent rainfall (Poloczanska et al. 2012)
	Diversity of small-medium businesses (retail, accommodation, and tour based) Resilient to change (Fenton et al. 2007)			
	Spatially differentiated operations across inner and outer coral reefs and islands		Global economic activity and other factors influencing businesses' profitability	Coral bleaching events on nearshore reefs have increased in frequency and severity since 1990 (Thompson and Dolman 2010)

(con'd)

Marine tourism activities and operations are diverse, encompassing live-aboard vessels, cruise ship operators, catamaran and kayaking tours, fishing, and diving.		Existence of alternative reef destinations and competition with and economic viability of other iconic tourist attractions, such as North Queensland's Wet Tropics	
	Reef bleaching influences the number of visitors (Oxford Economics 2009).		Long lived corals are calcifying 15% less than prior to 1990 (Hoegh-Guldberg et al. 2007, De'ath et al. 2009).
Contributes to a growing hospitality industry of resort-style accommodations and restaurant services.	Recreational and tourism services are strongly related to coral reef biodiversity, coral cover, and water clarity (Wielgus et al. 2004).	Rapid coastal population growth (Great Barrier Reef Marine Park Authority 2009).	

Challenges for resilience frameworks

One of the challenges of resilience approaches to SES is to integrate understanding from multiple disciplines, methods, and perspectives (Berkes 2007). Indeed, the study of complex systems necessitates interdisciplinarity because of their multifaceted dimensions, limited predictability, and dynamism (Newell 2001). A further challenge is to enable improved management of uncertainty and surprise. Currently, uncertainty is most often handled within a risk management framework. In highly dynamic contexts, uncertainty can be managed more effectively using an emergent/contingent framework that explicitly deals with surprise. This is necessary because the kinds of events or outcomes associated with the nonlinear feedbacks that characterize complex interactions between the climate, ocean, and human production systems are concerned with what van der Heijden (1996) refers to as "structural uncertainties," i.e., possible events for which there is little or no evidence to judge the likelihood of an outcome, and "unknowables" or unimaginable events.

Consequently, some of the key functions of a resilience indicator framework should be to support ways of operating in the zone of uncertainty, facilitate identification of windows of opportunity and potential transformative spaces, and inform capacity building to better prepare for and respond to surprise.

Operationalizing resilience through indicator frameworks

Although resilience indicator frameworks are in their infancy, scholarship around the use of sustainability and environmental indicator frameworks hints at how indicators could help in operationalizing resilience. From a policy perspective, indicators can enhance the overall understanding of resilience as a concept because the resulting reflection of ongoing assessments can lead to the gradual incorporation of resilience goals and standards into policies and organizations, the so-called enlightenment effect (Gudmundsson 2003). Indicators are valuable in providing information on complex issues in a way that is accessible to decision makers (Niemeijer and de Groot 2008). They can also stimulate change in stakeholders and systems through ongoing processes of negotiation and learning (Reed et al. 2006), with the eventual and desirable outcome of such processes being legitimization of a resilience orientation (Cabell and Oelofse 2012).

From the perspective of dealing effectively with change, indicators perform several functions. First, they can be used to establish baselines and to determine the direction of change in relation to a particular condition of resilience such as a threshold. In monitoring change, thresholds, targets, or baselines, beyond which problems become critical, serve to trigger remedial action (Reed et al. 2006). Information from monitoring indicators can be used as the basis for adaptive management strategies that help stakeholders adapt to and manage change. Lastly, indicators can enhance processes of social learning through stakeholder participation in indicator development processes (Pretty 1995).

From a resilience perspective, the sustainability indicators literature is deficient in that, with few exceptions (for example, Grosskurth and Rotmans 2007), it has so far not captured the broader dynamics of systems, and these are critical to both sustainability and resilience. Although monitoring indicators can adequately support incremental adaptive change, a different class of indicators is required in uncertain contexts to capture the complexities of system dynamics. These indicators could be developed through futures planning techniques such as scenario analysis (Haward et al. 2013), thus facilitating the consideration of potential windows of opportunity and suggesting areas to build capacity to better respond to surprise. With respect to the latter, resilience indicators should be significant sources of social-ecological learning, identified as a critical element of resilience building and for coping with uncertainty and surprise (Kofinas and Chapin 2009).

Although aware that the selection of indicators ultimately depends on the research question being asked or the objectives of a particular study, we sought to identify a set of indicators that would be useful in a general sense in the diagnosis and monitoring of marine sector resilience. The decision to develop indicators as measures of resilience rather than resilience metrics per se is supported by the opinions of others that the value of resilience thinking is more likely to be realized in industry sectors and systems by identifying general rules of thumb that can guide sectors toward a resilience orientation (Bennett et al. 2005, Carpenter et al. 2005, Darnhofer et al. 2010, Cabell and Oelofse 2012). Consequently, we were not concerned at this stage to adhere closely to accepted ideals of data availability, measurability, and cost effectiveness in indicator selection.

Presentation of indicators in a framework format is supported by Walmsley (2002) who suggests that the use of frameworks for sustainability indicators is crucial to identifying, summarizing, and reporting on key issues because it enables the logical grouping of information and thus the promotion of indicator interpretation and integration. Frameworks also help in the identification of data collection needs and gaps. Similarly, Ostrom (2011:8) advocates the use of frameworks in diagnostic work because frameworks establish the "elements and general relationships among these elements that one needs to consider for ... analysis and they organize diagnostic and prescriptive enquiry. They attempt to identify the universal elements that any theory relevant to the same kind of phenomena needs to include." A key purpose of the framework presented here is to ensure that important aspects of resilience concerns are identified and considered in studying and managing marine sector resilience.

The process of resilience indicator framework development

The framework has three main components: a set of critical resilience dimensions, a capitals or assets framework to organize the indicators, and indicator subsets, both abstract and concrete. Following initial assessment of the respective social, economic, institutional, and ecological resilience foci for each case study, the lead researchers overseeing each case study combined their expertise at a workshop held in January 2011, where they drew on their links with marine researchers, policy makers, and managers to provide a more comprehensive, interdisciplinary assessment of marine system resilience dimensions across the four sectoral case studies. The methodology was guided by the systems dynamics approach developed by the Resilience Alliance (2007) and informed by Bennett et al.'s (2005) work on resilience surrogates. The researchers identified a set of eight resilience dimensions that could be applied to sectors to describe current and potential resilience (Table 2). Thus the resilience dimensions set, grounded in a rigorous interdisciplinary process, provided the ideal basis for a comprehensive indicator framework.

The case information was synthesized into a matrix composed of the eight resilience dimensions and five asset classes. The latter, which encompass a range of livelihood resources, i.e., ecological, social/human, economic/financial, political/institutional, and infrastructural/technological (physical) assets, adapted from Scoones' (1998) sustainable livelihoods framework, are used to elaborate the resilience dimensions (Table 3). Livelihood perspectives have been shown to be useful in complex, highly dynamic development contexts (Scoones 2009). Applying this framework helped to ensure the balanced treatment of all relevant system components, although the addition of political and institutional assets, in particular, secured the inclusion of governance and power factors.

To formulate the indicator component of the framework, exemplars were extracted for each resilience dimension and for as many asset classes as possible from the case study data (refers to columns 2 and 3 in Table 4). The exemplars represent abstract indicators of sector resilience, which, although useful at a conceptual level, are not usually sufficiently concrete as the basis for data collection (Niemeijer and de Groot 2008). In column 4, we suggest potential concrete indicators for each abstract indicator and provide a rationale for each indicator in column 5.

ANALYSIS AND DISCUSSION

Evaluation of the resilience indicator framework's utility as a first step in system resilience appraisal requires some consideration of its capacities for benchmarking, monitoring, evaluating, and reporting on SES resilience. In part, this capacity is dependent on the comprehensiveness of resilience-relevant content, and, in part, on the ease with which the framework can be operationalized. Operationalization will be influenced by (1) the development of appropriate resilience metrics, currently limited by data availability, and (2) the framework's further refinement. In our integrated approach to SES resilience, we addressed a range of resilience preconditions, including opportunities for social-ecological learning, preparedness for surprise, ability to cope with uncertainty, ways of dealing with complexity, and the presence of transformative spaces and windows of opportunity.

Social-ecological or resilience learning is catered for by ensuring multiple stakeholder perspectives and knowledge systems are incorporated in problem solving. This capacity for systematic learning through dialogue, deliberation, and meaningful social interaction to enhance long-term sustainability and resilience under uncertain conditions is determined by indicators for trust building and purposeful strategies to enhance social capital (Béné et al. 2011). Social capital is also a crucial ingredient in the necessary collaboration of industry, managers, policy makers, and other stakeholders to effect transformative action.

Preparedness for surprise and capacity to cope with uncertainty needs a substantial monitoring program, although there will always be unforeseeable events. In turn, monitoring aids the social learning needed in responding to change. Other

Table 2. Resilience dimensions, justification, and illustrative examples.

Resilience Dimension	Justification	Example
Factors undermining resilience	Awareness of factors contributing to social-ecological system (SES) vulnerability is needed to manage their capacity to produce ecosystem services.	Poor water quality caused by runoff from adjacent catchments is a significant stressor of North Queensland coral reefs (Fabricius 2011). Management authorities established the Reef Rescue program to improve agricultural practices and monitor water quality (Eberhard Consulting 2011).
Key slow variables affecting resilience	Slow variables are controlling variables that are buffered by stabilizing feedbacks and determine the ability of a system to stay in a particular system state (Chapin et al. 2009).	The resilience of coral reefs to cyclones, warming sea surface temperatures, and anthropogenic stressors determines whether or not reefs shift into less productive algal-dominated systems (Hughes et al. 2007).
Key fast variables affecting resilience	Fast variables are those operating at shorter temporal and smaller spatial scales that can cause changes in slow variables operating at longer time scales.	Fishing effort increases through technological intensification in conjunction with recent climate change-induced oceanographic changes contribute to localized rock lobster (*Jasus edwardsii*) depletion in southeastern Australia (Linnane et al. 2010).
Key feedbacks	Feedbacks between biotic and abiotic components of marine systems, and climate and socioeconomic systems can act synergistically to drive SES into less desirable states (Harley et al. 2006).	A synergistic interaction between climate variation (warming waters), fishing pressure (through technological intensification), and long-spined sea urchin (*Centrostephanus rodgersii*) predation on kelp beds affects abalone and lobster stocks (Last et al. 2010) and can be a first step transformation to a new SES state. The recently arrived urchins can now be harvested, partially replacing declining abalone and rock lobster fisheries and also redirecting diving effort and labor. Coastal communities and their fishing fleets may consequently change in composition and size.
Likelihood of crossing thresholds	Identifying the likelihood of a system crossing a threshold into a less desirable state will indicate its resilience and what should be done to strengthen adaptive capacity and increase sectors' or systems' ability to move toward institutions/practices that allow sectors to learn and innovate (Berkes 2007).	Overgrazing of Tasmania's productive east coast kelp forests by the range-extending long-spined sea urchin from warm temperate waters is contributing to a catastrophic regime shift (Ling et al. 2009). Restocking of rocky reefs with large lobsters (urchin predators) is intended to counter the effects of their earlier overfishing, which facilitated successful urchin invasion in the first place.
Response to uncertainty and surprise	The ability of a society to live with surprise and uncertainty is a key factor in building resilience (Folke et al. 2003, Berkes 2007).	Successive major cyclones and coral bleaching events along North Queensland coral reefs have put many coastal communities at risk of permanently losing the ability to attract tourists. In recognition of future change, tourism operators have implemented eco-efficiency measures such as risk management, energy reduction, and building climate change into business plans (Zeppel 2012).
Openness to resilience ideas	Openness to resilience ideas acts as a proxy for SES preparedness to adapt to change. This is especially relevant given increasing evidence that future changes may be sudden and disruptive.	The Fisheries Research and Development Corporation (2010) is encouraging Australian fisheries to adapt to climate change through providing research support (Hamon et al. 2013, Pecl and Hobday 2011) and fostering initiatives, such as conducting vulnerability assessments.
Potential to reorganize	SES resilience is largely dependent on ability to reorganize in the event of disturbance. Reorganization can be directed to a degree if critical capacities are maintained (Folke et al. 2003).	'No take' areas on coral reefs help to maintain biodiversity (ecological memory) which is crucial to regeneration after disturbance by tropical cyclones (Mumby et al. 2006).

indicators of enhanced response capacity under conditions of surprise and uncertainty comprise perceptions of risk (Marshall and Marshall 2007), infrastructure planning and flexibility, availability of a diverse range of responses, ongoing learning, planning for extreme events, and futures planning.

Indicators that account for complexity include planning for extreme events, openness to innovation, response diversity, resilience building, collaborative management and governance that can help to create learning (Booher and Innes 2010), self-organizing processes, diversity of risk responses, trends in economic diversification, adaptive management, and innovative approaches to environmental management. It is expected that guidance from these indicators would help to manage complexity.

Prospects for transformational change are indicated by the presence of transformative spaces in which accepted practices can be unsettled and interrogated. These could be evident where there are processes of critical reflection in place, such as in shadow networks, i.e., networks that operate outside the mainstream testing new or innovative ideas, practices, and approaches (Olsson et al. 2006). However, any threat to the current stability regime is also a potential site for transformation, e.g., natural disasters, declines in keystone species, a drop in fishing effort, catch trophic changes, stock collapses or declines, pest invasions, and economic crises,

Table 3. Description of asset classes relevant to marine sectors (adapted in part from Scoones 1998).

Asset Classes	Description
Ecological	Natural resource stocks (soil, water, air, genetic resources) and environmental services (carbon and hydrological cycles, pollution sinks, etc.) from which useful resource flows and services are derived
Social/human	Social resources (relationships of trust, connectedness, reciprocity, and exchanges) gained through membership of collective networks and individual endowments (skills, knowledge, information, health, ability to work) that facilitate access to social resources
Economic/financial	Economic conditions (profitability, economic activity, and market conditions) that influence business viability and financial resources (savings, access to credit, and liquid assets readily converted to goods, remittances, and pensions) essential for a viable business
Institutional/political	Formal and informal instruments for decision making and the influences applied in decision making
Infrastructural/technological	Infrastructure, technology, tools, and equipment needed for communications and to produce food, commodities, and services.

such as transport stoppages or declining economic returns. These may open windows of opportunity to contemplate new solutions, practice changes, and so on.

Although unexpected events may open windows of opportunity on an irregular basis, a more important question is: Can the framework facilitate the purposeful creation of windows of opportunity? Westley (2002) argues that, to allow a policy window to open, all the relevant actors and organizations at all levels have to create the right links, at the right time, and around the right issues. The fora of operators, managers, and scientists conducted within the aquaculture and fishing industries have the potential to create appropriate alignments of actors, organizations, and issues at crucial times but policy entrepreneurs need to provide leadership and generate the political will to push in new directions (Olsson et al. 2004). This reliance on the serendipitous alignment of the appropriate factors points to the importance of systematically prefiguring institutional reform to be prepared for brief windows of opportunity (Young 2010). Such fora must purposively incorporate processes of critical reflection on current practice and industry or sector direction. This aspect is reflected in the indicator requiring the installation of processes for critical reflection to reevaluate norms, values, rules, and practices.

Lastly, for transformation to be initiated, the system must be open to external influences, and have capacities for novelty, innovation, and learning. The relevant indicators that represent these values include maintenance of species diversity from an ecological perspective, flexibility of location or equipment from a marine sector perspective, innovative approaches to environmental management, potential for consumer preference revision, individuals' preparedness for change (Marshall et al. 2007, Marshall 2010), educational attainment, existence of multilevel networks, and stakeholder inclusiveness.

CONCLUSIONS AND FUTURE POTENTIAL

We conceptualized resilience as a complex and dynamic multidimensional model of change in SES. We anchored the resilience indicators framework in a case study methodology and a systems dynamics approach for the purpose of capturing this complexity. Key resilience dimensions and a related set of resilience indicators applicable to marine sectors experiencing climate change were identified. The comprehensiveness of the indicator framework relied on taking an interdisciplinary approach to data collection and a suitable framework to ensure that all relevant elements were considered. Although the method of indicator development is readily replicable, it should be understood that a different group of research participants may identify a different indicator set. Although the framework requires further refinement, we have been able to demonstrate through the methodology that it is possible to capture the complexity and variety of variables impinging on marine sector resilience.

Although the framework is not yet ready for immediate implementation, it provides a baseline that can be used for discussion and to focus attention on the diversity and complexity of factors influencing resilience. The indicators act as prompts for the kinds of variables that should be considered. They suggest negative factors or constraints on resilience that should be taken into account and positive or negative trends that may influence resilience-building efforts. They include reminders to allow for the unexpected and for the importance of having adequate responses to deal with uncertainty. They provide examples of critical feedback signals and possible signs of impending thresholds. Lastly, they suggest potential demonstrations of resilience action and the kinds of capacities and precursors required to respond to system change.

The immediate practical value of the indicator framework resides in its potential use in:

Table 4. Resilience indicators framework.

Resilience Dimensions	Asset Class†	Examples of Resilience Factors (Abstract Indicators)	Suggestions for Concrete Resilience Indicators	Rationale/Relevance
1. Factors undermining resilience	Ec	Nonavailability of suitable habitat	Habitat integrity index	Ecosystems with degraded habitat are less able to support diverse ecological and social communities
			Water quality index	
		Absence of refugia	Availability of refuge habitat	Habitat-specific species require suitable habitat and ecological conditions to migrate to in the event of disturbance
		Vulnerability to extreme events	Recovery time of species after extreme events	Some species are more vulnerable to disturbances than others, e. g., branching versus massive corals. Recovery after extreme events, e.g., cyclones, may be further hindered by reduced water quality and ocean acidification
		Environmental degradation	Loss of key habitat, e.g., seagrass, coral reefs, mangroves, kelp forest	Many of the key habitats that species depend on for food, security, and reproduction are being lost as a result of human activities
	S	Attitudinal change	Changes in consumer preferences	Growth in consumer preferences for particular seafoods or tourism destinations may have negative impacts on relevant species and habitats leading to their degradation or decline, but also causing economic and social instability
	E	Profitability	Declines in economic returns	The necessary buffering capacity provided by profitability is not available to respond to change or disturbance
		Changes in asset value	Declining asset value	Asset values are related to profitability and thus responsiveness to change
	I	Power relations	Identifiable vested interests	Vested interests may skew decision making away from the long-term focus required for resilience planning
		Political will	Absence of political support for resilience-oriented policy	Political will is needed to reform public institutions to be able to address the complex problems of resilient social-ecological systems
		International policy decisions	Changes in climate policy	International decisions on mitigating greenhouse gases may impact negatively on sectors dependent on export income
	P	Constraints on infrastructure/ gear flexibility	Inflexibility of infrastructure/ gear	Inflexibilities in infrastructure and gear may constrain sectors from adapting to the impacts of climate change
2. Key slow variables	Ec	Warming sea temperatures	Observed changes in sea temperatures	Warming sea temperatures are having a substantial impact on ecosystems and will likely affect the future shape of marine-dependent sectors
	E	Economic pressures	Number of people entering or exiting the industry	When people are constrained by the costs associated with entry into an industry, replacement of exiting operators is slow leading to industry stagnation
				Stagnation can also be due to retention of nonresilient individuals who have limited adaptation options
	I	Institutional constraints	Integrated governance/ management approaches	Governance and management of social-ecological systems is complex and it is essential that governance bodies and instruments are connected and coordinated across multiple levels and that governance is perceived as legitimate
			Acceptability of rules and management approaches	
	P	Longevity of infrastructure	Replacement of infrastructure	The longevity of some infrastructure and associated sunk (irrecoverable) costs may slow adaptation to change
3. Key fast variables	Ec	Occurrence and frequency of natural disasters	Frequency of cyclones/storms	Natural disasters may have unexpected and unpredictable effects on larger cycles; these effects may be catastrophic or open up windows of opportunity for management and/or emergence of novel species
			Annual catchment runoff	
			Torrential stream outflow events	
	S	Changes in consumer preferences	Changes in seafood and recreation preferences	Changes in preferences for particular seafoods or tourism experiences may result in further pressures on overloaded ecosystems thus pushing them toward an irreversible threshold but also causing economic and social instability

(con'd)

	E	Economic variables	Profitability	Profitability (including exchange values) and low debt ratios allow more flexibility in business decisions affecting resilience. Producer influence on prices and higher prices increase resilience
			Equity debt ratios	
			Market prices	
		Economic crises	Changes affecting profitability, e.g., transport stoppages	Economic crises may lower profitability and therefore buffering capacity over a very short time frame
	I	Unexpected policy changes	Changes in catch limits	Changing catch limits may cause relatively rapid responses in the species at issue especially if that species is an ecosystem engineer leading to substantial change in broader ecological and social systems
4. Key feedbacks	Ec	Pest species invasions	Abundance or areal coverage of invasive species	Pest invasions can signal changes in ecological integrity and result in habitat decline, in turn affecting habitat-dependent species
			Habitat changes	
		Removal of keystone species from climate change affected habitats	Changes in keystone species' abundance	Keystone species are said to be crucial to maintaining the organization and diversity of their communities so that their decline usually spells the decline of those communities
	E	Collapses or declines in key resource stocks	Changes in fishing catch, aquaculture harvest, or visitor numbers	These changes often signal changes in ecosystem health
		Increased fishing effort	Changes in economic incentives	Policy or market changes may improve incentives to fish and increase pressure on preferred species
		Overfishing	Trophic changes	Increases in populations of lower trophic level species, e.g., jellyfish
5. Likelihood of crossing thresholds	Ec	Occurrence of species range shifting	Changes in occurrence of overwintering species from other marine regions	Changes in species composition may signal a range shift, which may fundamentally alter associated ecological communities and fisheries dependent upon these communities
		Threats to current stability regimes	Number/frequency of novel species invasions	Increasing pest numbers may indicate that the current regime is being destabilized
	S	Social threats to particular sectors	Entry disincentives	High entry costs, increased fuel costs, and nonreplacement of aging operators may lead to decline of a sector
		Perceptions of environmental decline	Declines in tourism activity	Declines in sectors reliant on environmental integrity could signal potential regime shifts in ecosystems. Public perceptions can also significantly influence management outcomes and industry support
			Public perceptions of marine sectors	
	E	Contributions to greenhouse gas emissions	Greenhouse gas emissions	Increasing greenhouse gas emissions are associated with ocean warming
		Increased economic activity	Increased tourism impacts	Increased marine tourism impacts may result in pressures leading to ecological degradation of favoured ecosystems, e.g., coral reefs
6. Response to uncertainty and surprise	S	Perceptions of risk	Operators/managers accept global climate change science	Nonscientists' capacity to anticipate surprise is dependent on acceptance of scientists' analytical assessments of potential surprising climate impacts rather than reliance on direct experience of impacts
	I	Viability of risk response	Contingency as well as risk management measures are in place	A concentration on risk assessment ignores the importance of having the capacity to prepare for surprise
		Diversity of risk responses	A range of risk responses is available	Having a diversity of possible responses to deal with uncertainty and surprise improves the chances of maintaining system resilience
		Political commitment	Adaptive management policy in place	Action to deal with an uncertain future requires political commitment and leadership to transcend short-term concerns that often preoccupy political debate
		Institutional design	Long-term monitoring programs in place	Being prepared for surprises demands a substantial program to monitor shifts in social and ecological systems
	P	Infrastructure planning	Replacement program in place	A replacement program for infrastructure/gear and insurance protection lessen the likelihood that managers and operators will be taken by surprise when social and/or ecological conditions change

(con'd)

			Insurance protection	
7. Openness to resilience ideas	S	Engagement with science, including climate change science	Operator/manager/scientist forums	Engagement with science helps to build a sense of trust in and ownership of the science
		Engagement with social-ecological learning	Forms of social decision making to enhance long-term sustainability and resilience	Learning is essential in dealing with change and surprise
		Understanding of social capital	Strategies to build social capital and networks	Social capital and networks help to lower the transaction costs of undertaking collective action
		Openness to transformational change	Processes of critical reflection in place to reevaluate norms, values, and rules	When a system state becomes untenable, the system needs to be reconceptualized
	I	Climate change policies	Policies in place	Climate change policies are evidence of political will to act on climate change
		Planning for extreme events	Strategies and plans in place	Instability caused by climate change impacts is likely to increase as the climate becomes more unstable
		Use of future or anticipatory planning techniques	Scenario and other futures planning techniques in use	Anticipatory planning will lower the potential for surprise
		Adoption of adaptive management approaches	Adaptive management approaches are used	Adaptive management accepts the uncertainty of resource management conditions viewing policy as a process of hypothesis testing and learning through implementation to improve the state of knowledge.
	P	Infrastructure flexibility	Operators with flexibility of location or gear	Flexibility provides the capacity to respond to unexpected changes in desired species movements or damage to tourism infrastructure as a result of extreme weather events
8. Potential to reorganize	Ec	Natural variability in physiological tolerances	Quantification of species' physiological tolerance limits	Changing environmental conditions will likely change how species perform in new environments; understanding if/how species will perform/survive under new conditions will lend greater certainty to ecological forecasts.
			Quantification of species' performance at physiological limits	
		Functional diversity and redundancy	Indicators of species richness/ diversity	Healthy ecosystems will have high levels of biodiversity and functional redundancy; these ecosystems will be best placed to respond to perturbations and changing environmental conditions.
			Degree of niche overlap	
			Trophic changes	
		Healthy ecosystems, habitats, and biodiversity	Ecosystem integrity index	Considering multiple indices of ecosystem health simultaneously may provide a more holistic picture of ecosystem integrity than single indicators considered in isolation.
	S	Openness to innovation	Evidence of innovative environmental management: policies, production, greenhouse gas pollution, recycling, etc.	Actors need to be able to take advantage of windows of opportunity that open up during the reorganization phase of an adaptive cycle.
		Consumers' ability to revise preferences	Shifts to alternative seafood and/or tourism preferences	Operators' capacity to reorganize their businesses in response to climate change impacts is in part dependent on consumers' ability to revise their preferences toward alternative marine products
		Stocks of social capital and trust	Levels of trust in industry/ sector decision makers	Social capital and trust are crucial for the collaborative engagement needed to reorganize sectors
		Level of educational attainment	Employees with a post-secondary/tertiary qualification	Higher levels of educational attainment generally facilitate capacities for change
		Employment training and experience	Experience/training in other industries	Experience in other industries can influence openness to change
		Preparedness for change	Perceptions of ability to cope with and adapt to change	Individuals' level of resource dependency affects their ability to be resilient through their assessment of risk, perceived ability to experiment, and to plan and reorganize
	E	Economic buffering	Diversification trends	Diversification reduces the possibility of negative impacts of change and increases the options for successful responses to change

(con'd)

		Profitability	
I	Multilevel networks	Integrated governance	Integrated multilevel governance increases the capacity for coordination across governance levels and reduces the likelihood of a mismatch between governance system and ecosystem
	Flexibility of rules and governance	Ongoing dialogue among industry stakeholders	Some flexibility of institutions and instruments is needed to support adaptive governance
	Stakeholder inclusiveness	Operators’ involvement in management plans	Inclusiveness provides support for the idea that diverse sources of knowledge are needed in solving complex problems and to ensure stakeholders’ ongoing commitment to building resilience
	Commitments to monitoring and evaluation	Monitoring and evaluation programs	Monitoring aids the social and adaptive learning that is needed in responding to change
P	Infrastructure flexibility	Capacity to relocate or change target species	Infrastructure and gear flexibility allow operators to respond as required to locational and qualitative shifts in target species and policy changes
		Operators with flexibility	Operators also need to be flexible to take advantage of the flexibility of gear, area, etc., and make rapid changes when the need arises

[†] Ec refers to ecological assets; S includes social and human assets; E refers to economic and financial assets; I includes institutional, policy, and political dimensions; and P refers to physical, including infrastructural, technical, and technological assets.

- raising awareness of the breadth of internal and external preconditions for marine sector resilience, i.e., economic, financial, ecological, social, institutional, political, and physical;
- raising public awareness of resilience problems and their interconnectedness;
- making complex concepts meaningful and comprehensible by helping to develop a common language for discussion;
- helping stakeholders to understand resilience and to read resilience trends;
- informing decision making so that it is founded on logical, coherent, and transparent information;
- setting targets to improve resilience of a sector or sphere of activity that scores low on specific resilience dimensions or variables; and
- highlighting trends that can strengthen general and specific resilience of stakeholders and that of their sectors.

With refinement, this framework can ultimately be expected to support the operationalization of resilience concepts by: (1) guiding policy analysis and formulation toward more resilient marine sectors either directly, conceptually, or symbolically (Gudmundsson 2003); (2) developing operational approaches to benchmark, monitor, evaluate, and report on marine sector resilience; and (3) assisting marine sector decision makers and managers to embrace complexity and operate more effectively and easily in a context of uncertainty. The overall purpose of the framework is to guide marine sectors toward a more resilient orientation (Darnhofer et al. 2010, Cabell and Oelofse 2012).

To advance the framework, the next steps include its further testing and refinement within applied resilience-based management contexts. This could be achieved through participatory action research on resilience metrics and techniques to facilitate selection of key indicators, i.e., those that relate to multiple resilience dimensions and are representative of overall resilience performance, and so reduce the number of indicators. As a starting point, in Table 5, we offer a list of candidate variables, those found to recur in the framework. These are categorized in terms of generic resilience perspectives that could help facilitate dialogue to identify a subset of predictive or leading indicators, which are used to signal potentially significant change toward or away from desirable resilience states. For example, it may be important for resilience planning to identify which social or ecological components are more or less vulnerable, resistant, or resilient to change. Leading indicators are therefore essential to long-range or strategic planning, monitoring progress on resilience, and anticipatory adaptation.

Further indicator development would ideally involve collaboration with stakeholders in the diagnosis process to ensure relevance and social-ecological learning. Although much of the data for the framework originated in work undertaken by researchers with stakeholder groups, the data were inevitably filtered through expert perspectives.

Ultimately, the expectation for a more mature framework would be one that is able to map resilience, measure progress, and assist in setting priorities, while lessons from its application would further inform the conceptual and especially practical development and implementation of resilience.

Table 5. Potential key indicators.

Resilience perspective	Candidate variables for key indicators of marine sector resilience
Ecological resilience (capacity of ecosystems to absorb disturbance and maintain healthy habitats and biodiversity; important for supporting diverse ecological and social communities)	Status of key habitats
	Availability of refuge habitat
	Climate change impacts (extreme events, sea temperatures, catchment runoff, acidification, sea level rise)
	Status of keystone species
	Invasive species trends
	Functional diversity and redundancy
Social resilience (ability of individuals and groups to cope with and adapt to environmental and social change and withstand shocks to their social infrastructure[†])	Consumer preferences
	Public perceptions (e.g., of environmental decline, risk)
	Social capital, networks, and trust
	Social-ecological learning
	Openness to and preparedness for change and innovation among resource users, decision makers, managers, and community
	Education, experience, and training
Economic resilience (policy-induced ability of a sector's economy to recover from, adapt to, or avoid/withstand the effects of adverse economic and other shocks[‡])	Buffering capacity (profitability, asset value, diversification)
	Employment trends
	External conditions (domestic and export markets, exchange rates)
	Stock or tourism destination changes
	Changes in resource harvest or visitor numbers
	Industry impacts
Institutional resilience (ability of institutions to withstand disturbances by providing both stability to reduce uncertainty and flexibility to respond to the uncertainties of changing external conditions[§])	Power relations
	Supportive policy environment (political will and leadership)
	Institutional design (integrated governance and management, adaptive governance and management, monitoring, critical reflection processes, inclusiveness, flexibility)
	Governance legitimacy
	Viability of risk response (extreme events, strategies and plans, scenario planning)
Infrastructural resilience (operators' physical capacity to respond to and recover from disturbance or change in operating conditions)	Flexibility (gear, infrastructure, location)
	Infrastructure longevity
	Insurance protection
	Replacement planning

[†]Adger 2000
[‡]Briguglio et al. 2009
[§]Steinberg 2009, Herrfahrdt-Pähle and Pahl-Wostl 2012

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