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Review

The future of resilience-based management in coral reef ecosystems

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ABSTRACT

Resilience underpins the sustainability of both ecological and social systems. Extensive loss of reef corals following recent mass bleaching events have challenged the notion that support of system resilience is a viable reef management strategy. While resilience-based management (RBM) cannot prevent the damaging effects of major disturbances, such as mass bleaching events, it can support natural processes that promote resistance and recovery. Here, we review the potential of RBM to help sustain coral reefs in the 21st century. We explore the scope for supporting resilience through existing management approaches and emerging technologies and discuss their opportunities and limitations in a changing climate. We argue that for RBM to be effective in a changing world, reef management strategies need to involve both existing and new interventions that together reduce stress, support the fitness of populations and species, and help people and economies to adapt to a highly altered ecosystem.

1. Introduction

Over the last several decades, climate impacts have intensified and the percent of hard coral cover on tropical reefs globally has declined (Gardner et al., 2003; Bruno and Selig, 2007; Hughes et al., 2018). The combination of global and local-scale human impacts (e.g., pollution, sedimentation, coastal development, and overfishing, coral disease, ocean warming, and ocean acidification) threaten the survival of coral reefs (Bozec and Mumby, 2015; van Hooidonk et al., 2016). Year 2017 marked the end of the world's longest, most widespread, and possibly most damaging coral bleaching event in history due to a combination of a strong El Niño, La Niña, and ocean warming (National Oceanic and

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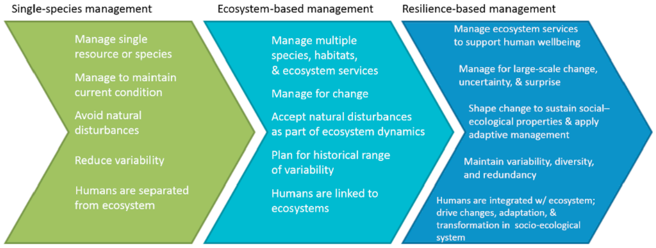

Fig. 1. Evolution of Natural Resource Management (modified from Chapin et al., 2009).

Atmospheric Administration (NOAA) 2018). Continued climate change, even if global warming can be kept within 2 °C above preindustrial levels, is likely to drive most coral reefs into further decline (e.g., Frieler et al., 2013).

To counter the global decline of reefs, scientists have called for a move beyond conventional management to a focus on supporting the resilience of coral reefs, dependent people, and economies – i.e., as a coupled social-ecological system (Bellwood et al., 2004; Hoegh-Guldberg et al., 2007; Mcleod et al., 2009, Fig. 1). Resilience is defined as the capacity of a system to absorb or withstand stressors such that the system maintains its structure and functions in the face of disturbance and change, and the capacity to adapt to future challenges (Holling, 1973; Keck and Sakdapolrak, 2013). Resilience definitions have evolved from emphasizing the persistence of ecosystem structure and function (Hughes et al., 2005) to the ability of coupled social-ecological systems to adapt and transform in the face of global change (Keck and Sakdapolrak, 2013). Resilience has been proposed as a guiding framework for coral reef management in an era characterized by rapid global change (Graham et al., 2013; Anthony et al., 2015).

Yet, recent decline of both isolated and intensively managed reefs raises the question of whether managing for resilience is still a viable strategy to protect reefs in the face of climate change (Rau et al., 2012; Anthony et al., 2017). There is a growing sense that coral reefs are at a turning point and urgent, interventionist, and frontier-pushing strategies are needed (e.g., translocation of species, assisted evolution, gene editing; Van Oppen et al., 2017). Such a shift requires an expansion of the reef management toolbox and the identification of new ways to support and build resilience.

While interventionist strategies using emerging technologies show promise (e.g., Chamberland et al., 2017), additional research and development is needed to gain license to operate and to be deployed at sufficient scales to counter the global decline of reef systems. To assess the scope for RBM to help sustain coral reefs, we describe the objectives of RBM and review the evidence for its implementation. We highlight key gaps, provide recommendations for reef managers, and identify research priorities (Table 1; Table 2).

2. What is resilience-based management (RBM)

Resilience-based management is defined as using knowledge of current and future drivers influencing ecosystem function (e.g., coral disease outbreaks; changes in land-use, trade, or fishing practices) to prioritize, implement, and adapt management actions that sustain ecosystems and human well-being.

The main goal of RBM is to identify and prioritize management actions that enhance system resilience (e.g., by protecting processes and species that support a system's capacity to withstand and recover from disturbance). Such actions include threat mitigation (e.g., controlling pollution, sedimentation, overfishing, etc.), actions that support ecosystem processes (e.g., recruitment and recovery) such as managing herbivores and improving water quality, and developing alternative livelihoods to reduce pressure on reef resources. RBM also includes strategies that build adaptive capacity and adaptation in society, communities, and industries that depend on reefs. Such strategies may include supporting the capacity of people to learn, share knowledge, innovate, and adjust responses and institutions to changing external drivers and internal processes (Folke, 2016), or supporting an ecosystem to change, yet maintain critical functions (Mumby et al., 2014a,b). Specific management objectives for RBM differ based on local context, but should incorporate baselines (known or projected), stakeholder needs, and the desired system state (e.g., high abundance and biodiversity of corals and fishes; Anthony et al., 2015).

RBM guides proactive decision-making under risk and uncertainty. It requires understanding how the system is likely to respond to a diversity of impacts, many of which act at different spatial and temporal scales (Mumby et al., 2014a,b). Effective RBM will consider a wide range of management strategies and will include strategies that are most likely to deliver against multiple, and potentially conflicting, objectives under different climate scenarios. Tradeoffs and prioritization will be a key theme for RBM under climate change.

2.1. How does RBM differ from other management approaches?

In the mid to late 20th century, resource management primarily focused on a single species, sector, activity or concern (McLeod et al., 2005). Over the last several decades, managers have moved to integrated approaches including multi-objective marine protected areas (MPAs), integrated coastal zone management, and ecosystem-based management (EBM). EBM was introduced to address limitations of conventional management approaches in marine systems (McLeod et al., 2005). EBM is an integrated approach to management that considers the entire ecosystem, including humans, and the full spectrum of ways that people use, benefit from, and value nature (McLeod and Leslie, 2009). EBM addresses connections between social and ecological systems, across multiple spatial scales of management, among cumulative impacts of multiple sectors, and across the range of ecosystem services that support human wellbeing. EBM recognizes the importance of managing for change and managing multiple species and ecosystem services (Fig. 1), and is centered on the protection of ecosystem structure, functioning, and key processes.

Both EBM and RBM consider resilience and connections across the socio-ecological system, but a key difference is that RBM acknowledges that humans are capable of driving change, adaptation and transformation (Fig. 1; Nyström et al., 2008; Feola, 2015; Folke, 2016). When management interventions and adaptation are insufficient to maintain resilience, building the capacity for transformation will be necessary (Morecroft et al., 2012). Transformations may be negative (from coral to algal-dominated reef), but also may be positive (development of a new livelihood that reduces pressure on coral reefs). Guidance for preparing for and navigating transformation includes identifying thresholds, plausible alternative states, and triggers for system change; identifying barriers to change, potential change agents, and strategies to overcome barriers; maintaining flexible strategies and transparency; and supporting institutions that facilitate cross-scale and cross-organizations interaction (Folke, 2016). Recent work highlights transformation as an essential property of a resilient system (Feola, 2015), thus it will be increasingly important to prepare for and maximize the potential for transformations that support healthy human and ecological communities.

3. Management recommendations and evidence for RBM

Resilience principles have been identified to support coral reef resilience (e.g., Hughes et al., 2005; Nyström et al., 2008) and the resilience of socio-ecological systems more broadly (Biggs et al., 2012; Morecroft et al., 2012). Resilience principles have been used to develop management recommendations for coral reefs. The following section discusses these management recommendations and explores the evidence for their application and their role in supporting RBM. The first

Table 1
Research Priorities to support the application of RBM.

Protect a diversity of species, habitats, and functional groups	● For specific reef sites and regions, identify and prioritize which species and functional groups are most important to protect to preserve key ecosystem functions (Green and Bellwood, 2009; Heenan and Williams, 2013) and which management actions are most likely to support reef recovery (Graham et al., 2011)
Maintain pathways of connectivity	● Guidance for identifying source and sink reefs and high connectivity reefs most likely to support recovery (Schill et al., 2015), including guidance that can be applied in regions with limited technical and financial capacity ● Evidence is needed to demonstrate if and how social connectivity can support reef health and resilience
Reduce reef stressors	● Guidance for identifying which stressors are driving reef decline and recovery at sites (Graham et al., 2011) and prioritizing which management interventions provide the greatest benefits to supporting reef resilience ● Case studies demonstrating if/when addressing local stressors supports reef resilience, including bleaching resistance and/or recovery
Implement MPAs to support reef resilience	● Increased evidence for when/where/and under what conditions MPAs support/do not support coral resistance and recovery (e.g., Micheli et al., 2012; Mellin et al., 2016) ● Strengths and limitations of MPAs in maintaining coral reefs and the services that they provide, especially compared to other forms of management (e.g., non-spatial fisheries management).
Manage adaptively to accommodate uncertainty and change	● Guidance for overcoming barriers of implementing adaptive management, such as challenges embracing uncertainty; lack of data on key processes (e.g., recruitment), and perceived threats to existing research programs and management regimes (Walters, 2007)
Prioritize areas with low environmental risk and high social adaptive capacity	● Given the limitations of climate models (uncertainty, spatial and temporal resolution; Porfirio et al., 2014) how should they be weighted alongside variables of current condition to prioritize areas for protection? ● Guidance for when to triage conservation at sites based on projections of climate impacts (i.e., are their climate thresholds that warrant eliminating management/conservation interventions at sites) (Bottrill et al., 2008) ● Identification of coral taxa with high acclimation/adaptation potential (McClanahan et al., 2014)
Incorporate social and ecological indicators to assess early warnings, recovery patterns, and regime shifts in conservation planning and monitoring	● Improved and finer scale climate models to prioritize when and where impacts are projected to inform management actions ● Guidance on how changes in social conditions can be incorporated into conservation planning and management (e.g., Cinner et al., 2013) ● Improved understanding of social and ecological resilience indicators for specific reef regions (metrics that assess recruitment and recovery, adaptive capacity), and how interactions among them may alter their importance ● Locally/regionally-specific guidance for predicting thresholds when reefs recover or undergo regime shifts (i.e., tipping points that precipitate regime shifts; how such tipping points vary in different environments) ● Improved guidance on assessing trade-offs between different management strategies in terms of their costs and social, economic, and ecological benefits (e.g., Morecroft et al., 2012)
Invest in experimental approaches to support resilience	● Viability of experimental approaches at relevant scales to protect coral reef ecosystems (Van Oppen et al., 2017) ● Cost-benefit analysis of active interventions to maintain marine communities and their benefits
Implement strategies to build social and ecological adaptive capacity	● Guidance on priority indicators of social adaptive capacity (e.g., Cinner et al., 2012; Mcleod et al., 2016) ● Clarity on metrics and methodologies to assess social adaptive capacity ● Guidance on how to prioritize management actions to protect key ecosystem functions and support adaptive capacity
Implement strategies to facilitate adaptation and transformation	● Guidance on facilitating adaptation and planning for social and ecological transformations (Gelcich et al., 2010; Nyström et al., 2012) ● Clarity regarding the degree to which RBM addresses problems that have not been amenable to other approaches (Allen et al., 2011; Steneck et al., 2014; Mellin et al., 2016)

five recommendations are well known by coral reef managers and are often implemented (e.g., integrated into management plans). They also primarily focus on the ecological aspects of RBM. The last five are rarely considered or implemented but are important for reefs to be managed as social-ecological systems (McClanahan et al., 2008). These include both social and ecological aspects of resilience. Marine managers need to consider reefs in this broader context to better understand and address the ecological, social, and economic drivers and governance systems that affect the use and management of reefs and the processes that affect resilience (Bellwood et al., 2004). Further, in reef areas where persistent poverty is coupled with resource degradation, improving human welfare and institutional capacities is a key component of sustaining reef ecosystems (Cinner et al., 2009a).

3.1. Management recommendation 1: protect a diversity and redundancy of species, habitats, and functional groups

Biodiversity and functional redundancy contribute to system resilience (e.g, Holling, 1973; Elmqvist et al., 2003; Biggs et al., 2012). Diversity encompasses both ecological and social aspects – e.g., biodiversity, spatial and temporal heterogeneity, and diversity of livelihood strategies and governance systems. Diversity can provide increased options for responding to change and disturbance because different species and habitats can support different functional traits and ecological processes (Nyström et al., 2008), and therefore reduce the risk for catastrophic regime shifts (van Nes and Scheffer, 2005). In social systems, diversity in management approaches and institutions can support resilience by providing the basis for innovation, learning, and adaptation (Biggs et al., 2012). However, diversity may not always support resilience. For example, while coral diversity may increase resistance, this depends on species composition and species-specific sensitivities to disturbance. In some cases, managing to support diverse species may increase the proportion of sensitive species (e.g., fast growing but less stress tolerant), thus lowering resilience (McClanahan et al., 2012). The role of diversity in supporting resilience thus remains unclear (Côté and Darling, 2010).

Protecting functional group diversity is a key strategy to support reef resilience (Bellwood et al., 2004; Mori et al., 2013), and has been implemented in the Caribbean (e.g., Belize, Bonaire, Turks and Caicos Islands). Diverse functional groups of herbivores can enhance coral recovery (Bellwood et al., 2006; Mumby et al., 2007; Steneck et al., 2014). Herbivores support recovery through their role in algal removal which creates settlement space for corals and coralline algae (Mumby and Harborne, 2010). However, the ability of herbivores to facilitate recovery is highly context-dependent (McClanahan et al., 2002; Aronson and Precht, 2006) and may be more important in some regions (e.g., Caribbean, due to reduced functional diversity and higher rates of algal recruitment) than others (e.g., Pacific) (Roff and Mumby, 2012).

Table 2
Management recommendation, evidence, and challenges to promoting reef resilience.

Management recommendation	Evidence for resilience principles	Challenges
Protect a diversity of species, habitats, and functional groups Maintain response diversity and redundancy within functional groups	A high diversity of coral habitat types helps to ensure that a wide range of functional traits, due to adaptations to local environmental conditions, are represented within the seascape (Nyström et al., 2008). Diverse functional groups of herbivores can enhance coral recovery (Bellwood et al., 2006; Mumby et al., 2007; Burkepile and Hay, 2008; Steneck et al., 2014). Spatial heterogeneity may reduce the risk for catastrophic regime shifts (van Nes and Scheffer, 2005).	Managing to support diverse species may, in some cases, increase the proportion of sensitive species The ability of herbivores to promote recovery is highly context-dependent (McClanahan et al., 2002; Aronson and Precht, 2006) and depends on their functional role, the algae that they graze (Graham et al., 2015), and diversity of species responses to environmental change (response diversity; Elmqvist et al., 2003) and other anthropogenic stressors (Edwards et al., 2014; Adam et al., 2015; Graham et al., 2015).
Reduce reef stressors (e.g., pollution, sedimentation, physical impacts)	Reducing stressors is important to reef resilience because nutrient pollution, sedimentation and physical impacts can cause adverse impacts to corals: ● reduced thermal tolerance of corals (Fabricius, 2005; Wooldridge, 2009; Humanes et al., 2017) ● decreased recovery potential (Connell et al., 1997; Fabricius, 2005; Carilli et al., 2009; Fourney and Figueiredo, 2017; Humanes et al., 2017) ● slower coral growth rates (McManus et al., 1997; Fox et al., 2005; Shantz and Burkepile, 2014) ● increased coral disease and bleaching (Vega Thurber et al., 2014) ● increased algal growth (Jompa and McCook, 2002) Maintaining water quality can support coral reef resilience (Bellwood et al., 2004; Wooldridge, 2009).	Impacts will be context-specific, based on local ecological and oceanographic conditions, and different sensitivities of corals to nutrients, sediments, and physical impacts (Fabricius, 2005; Erftemeijer et al., 2012) Impacts may not always be negative, e.g., physical impacts can, in some cases, create new habitat for coral settlement (Chabanet et al., 2005)
Implement MPAs to support reef resilience including the protection of refuges (e.g., area less vulnerable to climate impacts)	MPAs are an important tool to support reef resilience as they can help to: ● Reduce local stressors (Bellwood et al., 2004; Wooldridge, 2009) ● Restore coral reef food webs (Bellwood et al., 2004) ● Reduce outbreaks of coral predators (Sweatman, 2008) ● ● Reduce coral loss (Mellin et al., 2016; Wolff et al., 2018), and Support herbivory which can facilitate coral recruitment (Mumby et al., 2007; Selig and Bruno, 2010). ● Promote recovery (Mumby and Harborne, 2010; Micheli et al., 2012; Perry et al., 2015)	The role of MPAs in protecting coral reefs from climate change is equivocal (Côté and Darling, 2010; Hughes et al., 2017; Roberts et al., 2017), and there is only limited, regional evidence that MPAs are outperforming other areas (Selig and Bruno, 2010) The number of potential refuges is likely to decline through repeated bleaching events (Hughes et al., 2017).
Maintain pathways of connectivity	Connectivity can promote reef recovery by providing a supply of coral larvae from less impacted locations (Mumby and Hastings, 2008; Jones et al., 2009; Hock et al., 2017).	Connectivity may not always support recovery (Graham et al., 2011) and in some cases, it may facilitate the spread of invasive species or pollutants, thus, its role in supporting resilience depends upon the local context (McClanahan et al., 2002).
Manage adaptively to accommodate uncertainty and change	Key components of adaptive management include: monitoring and evaluation; a continuing cycle of experimentation and reevaluation; participatory approaches; and diverse stakeholder participation (Ostrom, 1990; Schreiber et al., 2004; Folke et al., 2005; Biggs et al., 2012).	Barriers to adaptive management include: lack of resources for monitoring; unwillingness to embrace uncertainty; lack of data on key processes (e.g., recruitment), and perceived as expensive and/or ecologically risky or as a threat to existing research programs and management regimes (Walters, 2007).
Prioritize areas with low environmental risk and high social adaptive capacity	Managers should prioritize areas with low environmental risk and high social adaptive capacity (McClanahan et al., 2008).	Areas of high environmental risk may be important when they also include high adaptive capacity -such areas may drive the development of innovation (e.g., in restoration practices; McClanahan et al., 2008).
Incorporate social and ecological indicators to assess early warnings, recovery patterns, and regime shifts in conservation planning and monitoring	By combining projected future exposure with data on resilience indicators (e.g., McClanahan et al., 2012), managers can map relative vulnerability to climate change and prioritize actions to support reef resilience (van Hooidonk et al., 2016). Social drivers (e.g., technologies, markets, demographic changes, and changes in governance structures or policy) can provide early indicators of regime shifts (Hicks et al., 2016).	Static measures (coral cover, fish abundance, diversity) can be poor indicators of resilience (Mumby et al., 2014a,b); high coral cover may fail to indicate changes in reduced recruitment potential or reduced herbivory (Anthony et al., 2015). Factors that determine recovery potential (reef structural complexity, water depth, herbivorous fish biomass, nutrient regime, and coral recruit densities) differ across regions making it challenging to prioritize management actions that support recovery (Graham et al., 2015)
Invest in experimental approaches to support resilience (e.g., enhance the natural adaptive capacity of reef organisms via assisted evolution)	Some corals in areas with wide temperature fluctuations resist stress better than corals from less extreme environments (e.g., transplanted corals into hotter and more variable conditions acquired thermal tolerance demonstrating short-term acclimatization and longer-term adaptive acquisition of climate resistance; Palumbi et al., 2014) Enhancement of the adaptive capacity of corals to warming through assisted evolution and experimental management trials can help promote the resilience and climate tolerance of key species (Van Oppen et al., 2017).	Corals differ in their ability to adapt or acclimatize (Baker et al., 2004), e.g., some can increase their proportion of heat-resistant symbiont types (Clade D providing an increased tolerance of ~ 1–1.5 °C; Berkelmans and van Oppen, 2006), while others cannot. Large potential for unintended consequences and cannot be implemented at the scales necessary to reverse reef decline
Implement strategies to build social and ecological adaptive capacity (e.g., maintaining diversity of human opportunities and economic options that	A key aspect of resilience in social-ecological systems is the flexibility of resource users to switch from one livelihood strategy to another (Berkes and Seixas, 2006; Cinner et al., 2009b) as it provides the conditions necessary for experimentation and the ability to respond to change (Olsson et al., 2004; Tompkins and Adger, 2004;	Livelihood diversification does not necessarily indicate high adaptive capacity – in some cases, it may reflect a low standard of living that requires increased effort to meet basic needs; in other cases, it may be a deliberate

(continued on next page)

Table 2 (*continued*)

Management recommendation	Evidence for resilience principles	Challenges
encourage adaptation and learning; broaden stakeholder participation)	Berkes and Seixas, 2006; Marshall et al., 2007). The participation of diverse stakeholders can improve legitimacy, facilitate monitoring and enforcement, promote understanding of system dynamics, improve a management system's capacity to respond to shocks and disturbances (Ostrom, 1990; Folke et al., 2005; Reed, 2008), and facilitate collective action (Schreiber et al., 2004; Biggs et al., 2012).	strategy to “spread the risk” and improve resilience to fluctuations/shocks (McClanahan and Cinner, 2011).
Implement strategies to facilitate adaptation and transformation (e.g., through promoting polycentric governance systems; providing buffer zones around protected sites)	Polycentric structures may support functional redundancy (e.g., national governance can step in if local governments fail to achieve desired outcome, or vice versa; Rohlf, 1991; Biggs et al., 2012). Polycentric systems can provide opportunities for learning and experimentation, broader levels of participation in governance, and consideration of local knowledge and knowledge sharing across scales (Olsson et al., 2004; Ostrom, 2005; Biggs et al., 2012). Buffer zones around protected areas can increase the potential of species to adapt and move	The long-term robustness of large-scale polycentric governance systems has recently been challenged (Morrison, 2017). Improved data on how species ranges shift in response to climate change is needed to inform location of buffer zones (Smith and Lenhart, 1996)

In the Bahamas, recovery of herbivores (parrotfishes) within a reserve resulted in faster coral recovery rates than areas subject to fishing pressure, reinforcing the importance of local herbivore management (Mumby and Harborne, 2010). By contrast, research in the Indian Ocean showed that while relatively low biomass of herbivores reduced the risk of a shift from coral to algal dominance, herbivory was a weaker predictor of recovery than other factors (e.g., structural complexity, depth, and the density of juvenile corals; Graham et al., 2015).

Maintaining response diversity, i.e., diversity of responses to environmental change among species that contribute to the same ecosystem function (Walker, 1995; Elmqvist et al., 2003), can provide an insurance policy against losing that function. However, incorporating this concept into management objectives (e.g., maintain functional group diversity) can be challenging. In some cases, it may be better to protect fewer functional groups that are more stress tolerant than protecting a greater number of functional groups that may be more vulnerable to stress (i.e., high redundancy does not necessarily ensure high response diversity and the preservation of ecosystem function in the face of environmental change; Mori et al., 2013).

The examples above illustrate the complexities of aiming to protect a diversity of species, habitats, and functional groups to support RBM. Other complexities arise from trophic linkages. For example, the ability of herbivores to promote recovery depends on many factors, such as their functional role, the algae that they graze (Graham et al., 2015), and their different susceptibilities to stressors (Adam et al., 2015). Reefs are highly heterogeneous and the factors supporting recovery differ. To prioritize management actions designed to support resilience, research is needed to clarify which species and functional groups are most important to protect on a given reef to preserve key ecosystem functions and promote reef recovery. Where such data are not available, generic guidance on protecting and monitoring key functional groups of herbivores to support reef resilience can be applied (Green and Bellwood, 2009).

3.2. *Management recommendation 2: maintain pathways of connectivity*

Connectivity can support reef resilience by facilitating the supply of coral larvae and hence reef recovery (Jones et al., 2009; Hock et al., 2017). Connectivity between reefs and adjacent seagrasses and mangroves can enhance the diversity of organisms on reefs that support recovery (Mumby and Hastings, 2008; Brown et al., 2016). Marine managers may determine criteria for incorporating connectivity into protected areas based on target species for protection, how far they move, and whether effective management is in place outside reserves.

While connectivity has been assessed across coral reefs globally (e.g., the Great Barrier Reef, Coral Triangle, Caribbean), utilizing connectivity to support ecological resilience can be problematic. For example, connectivity may facilitate the spread of invasive species or pollutants (McClanahan et al., 2002). A recent meta-analysis of coral reef recovery dynamics showed no relationship in the distance between reefs and their recovery (Graham et al., 2011). Other studies demonstrate both local-scale patterns of self-recruitment and ecologically significant connectivity among reefs at scales of tens of kilometers (and in some cases hundreds of kilometers) (Jones et al., 2009). Thus, the role of connectivity in supporting recovery depends on local conditions and oceanographic factors affecting larval transport. Therefore, we recommend prioritizing in MPAs high connectivity reefs likely to support recovery (e.g., identified through high-resolution coral larval dispersal simulations) with reefs likely to have a lower risk of exposure to bleaching (e.g., oceanographic and climate models) (e.g., Hock et al., 2017). Where such data are not available, we recommend applying general principles for incorporating connectivity and risk spreading into MPA design (e.g., Mcleod et al., 2009; Green et al., 2014).

3.3. *Management recommendation 3: reduce reef stressors to support resistance and recovery*

Local management efforts alone cannot mitigate the effects of large-scale events such as mass coral bleaching (Selig and Bruno, 2010; Hughes et al., 2017). However, evidence suggests that they can, in some cases, support recovery following disturbance and may support resistant coral assemblages (West and Salm, 2003; McClanahan et al., 2012). Maintaining good water quality and reducing coastal pollutants has been suggested to increase corals' thermal resistance (Fabricius, 2005; Wooldridge, 2009; Humanes et al., 2017). High sediment and nutrient loads can compromise coral recovery (Fabricius, 2005; Carilli et al., 2009; Humanes et al., 2017); decrease coral growth rates (Shantz and Burkepile, 2014); increase coral disease and bleaching (Vega Thurber et al., 2014); and increase algal growth (Jompa and McCook, 2002). Yet, many factors affect coral sensitivity to sediments and nutrients (e.g., size of particle, nutrient type, intensity, duration and frequency of exposure; Fabricius, 2005; Erftemeijer et al., 2012), thus impacts will be context-specific, based on local and regional ecological and oceanographic conditions.

Physical impacts on reefs (e.g., trampling, destructive fishing, ship groundings, dredging) can reduce reefs ability to resist stress (Zakai and Chadwick-Furman, 2002), and result in slower coral growth rates, lower reproductive potential, reduced recruitment, and increased disease (McManus et al., 1997; Fox et al., 2005). While mitigating stressors is a priority for reef managers, a recent analysis on the Great Barrier Reef revealed that water quality and fishing pressure had minimal effect on unprecedented bleaching in 2016, highlighting the limitations of local and regional management actions in the face of extreme heat stress (Hughes et al., 2017). Thus, while management actions may provide some reefs with improved capacity to cope with climate impacts, and buy time until global emissions can be reduced, they are not able to prevent reefs from succumbing to extreme climate impacts. Importantly, this does not mean that such efforts should be abandoned in favor of more novel approaches, but that efforts to control local and regional stressors should be implemented as part of a broader suite of management actions that includes experimental approaches and emissions reduction policies (Rau et al., 2012).

3.4. Management recommendation 4: implement MPAs to support reef resilience

Marine Protected Areas (MPAs) are a core strategy for applying RBM (Roberts et al., 2017). MPAs can support resilience by preventing or reducing destructive fishing practices, preventing overfishing, and restoring coral reef food webs (Bellwood et al., 2004). MPA management may also help reduce outbreaks of coral predators and support herbivory which can facilitate coral recruitment (Mumby et al., 2007; Selig and Bruno, 2010). MPAs have been shown to reduce coral loss (Mellin et al., 2016; Wolff et al., 2018) and promote recovery (Mumby and Harborne, 2010; Micheli et al., 2012; Perry et al., 2015). However, MPAs cannot protect coral reefs from climate change (Côté and Darling, 2010; Selig and Bruno, 2010; Hughes et al., 2017; Roberts et al., 2017). In some cases, following mass bleaching events, coral losses were less within MPAs compared to those outside protected areas (e.g., Mumby et al., 2007; Selig and Bruno, 2010). In other cases, corals within MPA have fared worse because MPAs may contain more sensitive species (McClanahan et al., 2007; Graham et al., 2008).

Most MPAs globally have not been designed to consider climate change impacts (i.e., by serving as temperature refugia or networks of larval supply), and global analyses of MPA effectiveness have shown that there is only limited, regional evidence that MPAs are outperforming other areas (Selig and Bruno, 2010). Further, potential refuges are likely to diminish as oceans warm (Hughes et al., 2017). For MPAs to continue be an effective RBM tool, their spatial and temporal design, and the portfolio of interventions they incorporate, need to be both anticipatory and adaptive (Rogers et al., 2015). MPAs should be designed to effectively manage local stressors, include the full suite of habitat types to ensure biodiversity and functional redundancy, include replicates of representative habitats, ensure connectivity between healthy and degraded reefs to support replenishment, and include refuges (Mcleod et al., 2009; Mumby et al., 2014a,b; Hock et al., 2017). The protection of refuges can help to protect larval sources and may include heat-resistant local populations (Oliver and Palumbi, 2011; Palumbi et al., 2014; Ainsworth et al., 2016) and deep reefs that may be important to support recovery of shallow reefs following disturbance (Riegl and Piller, 2003; Bongaerts et al., 2010; Harris et al., 2013; Bridge et al., 2013; Thomas et al., 2015). MPAs should incorporate a variety of thermal regimes to increase the likelihood of capturing diverse coral assemblages and coral taxa with acclimation and adaptation properties that support resilience (Mcleod et al., 2010; McClanahan et al., 2012; Mcleod et al., 2012; Davies et al., 2016).

A number of social factors also support the resilience of the linked social-ecological system. For example, local engagement in management and support for traditional knowledge and co-management regimes can reduce system vulnerability (Cinner et al., 2012; Weeks and Jupiter, 2013). While changing climatic conditions may make some aspects of traditional knowledge based on past environmental conditions less reliable (Ford and Smit, 2004), traditional knowledge is increasingly recognized as a key component of cost-effective, participatory, and sustainable climate mitigation and adaptation policies and strategies (Robinson and Herbert, 2001; Nyong et al., 2007). Co-management arrangements that rely on the collaboration among diverse stakeholders can support more robust implementation of MPAs, as well as other management measures (e.g., through strengthened governance, compliance, and enforcement; Olsson et al., 2004). Such management arrangements provide resource users with greater ownership, facilitate participatory decision-making over natural resources, and have resulted in social and ecological benefits (Cinner et al., 2012). In some cases, changes in fishing gear, species allowed to be caught, or access to resources may have greater effects on reef resource condition and across larger spatial areas, than MPAs (MacNeil et al., 2015). Political will is necessary to implement such changes, and national and international policies are important to provide catalysts for and enabling conditions to support co-management arrangements.

3.5. Management recommendation 5: manage adaptively to accommodate uncertainty and change

Adapting to the environmental changes anticipated under business as usual carbon emissions will require creativity, experimentation, learning and planning (Olsson et al., 2004; Marshall et al., 2007). Such adaptation is a core element of RBM. Adaptive management involves an iterative cycle of experimentation, evaluation, and exclusion of ineffective approaches (Tompkins and Adger, 2004). If implemented strategically, adaptive management principles can help to identify management solutions that are robust in the face of climate risk and uncertainty.

Adaptive management requires diverse stakeholder participation which is central to facilitating feedback, social learning, and the collective action needed to respond to disturbance and change (Schreiber et al., 2004; Biggs et al., 2012). Participatory approaches can increase the comprehension and perceived validity of information and its use in decision making (Reed, 2008). Active engagement of diverse stakeholders is suggested to improve legitimacy, facilitate monitoring and enforcement, promote understanding of system dynamics, and improve a management system's capacity to detect and interpret shocks and disturbances (Ostrom, 1990; Folke et al., 2005). The challenge of engaging diverse stakeholders is balancing potentially conflicting priorities and needs, but doing so early in the planning process reduces the risk of marginalizing groups or non-compliance with proposed management actions.

The importance of adaptive management in supporting coral reefs is not new, yet is increasingly highlighted to manage uncertainty and environmental and social change (McCook et al., 2010). For over a decade, researchers have reinforced the importance of flexible approaches to incorporate changes in reef management strategies and environmental and socioeconomic conditions (Salm et al., 2006). Such approaches include changes in zoning to accommodate ecosystem changes in response to disturbances or when disturbances are predicted (e.g., a bleaching event). Other approaches include changes in fishing regulations to accommodate changes in supply and demand and to enable the application of new knowledge. While such efforts may take years or decades, and require sufficient political will, examples exist to provide guidance for reef management, such as establishing requirements for reviewing and revising management plans (e.g., Great Barrier Reef; McCook et al., 2010).

What is often overlooked is that many attempts to apply adaptive management have failed (Walters, 2007). Barriers to adaptive management include lack of resources for the detailed monitoring needed to support large-scale experiments; unwillingness by decision makers to embrace uncertainty; lack of data on key processes (e.g., recruitment), and viewing experiments in adaptive management as excessively expensive and/or ecologically risky or as a threat to existing research programs and management regimes (Walters, 2007). Recommendations have been developed for how to overcome such barriers, including innovative approaches to monitoring and experimentation (Keith et al., 2011), and a framework to clarify when adaptive management is appropriate, feasible, and most likely to be successful (Rist et al., 2013).

3.6. Management recommendation 6: prioritize areas with low environmental risk and high social adaptive capacity

A key question is whether conservation efforts should focus on protecting areas at greatest or least risk. Some have recommended prioritizing areas with low environmental risk and high social adaptive capacity, because areas with low adaptive capacity (even if they have low environmental risk) may not achieve their conservation goals if communities are unable or unwilling to comply with protection measures (e.g., no-take areas) (McClanahan et al., 2008; Mcleod et al., 2012). However, areas of high environmental risk may also have high adaptive capacity and therefore, may be important to protect as they can drive conservation development and innovation. Others have incorporated areas of highest *and* lowest risk in MPA networks designed for resilience (Maina et al., 2015) or suggested prioritizing lower risk (high resilience) sites due to the continued degradation of reefs globally and increasing climate impacts (Maynard et al., 2015).

A number of tools (e.g., scenario planning; decision analysis) have been developed to identify the most robust strategies in the face of climate change. Scenario planning can help explore whether ecosystems, habitats, and species are likely to remain in an area given projected climate impacts, how climate change could affect the viability of conservation targets, and management effectiveness in response to changing conditions. Integration of ocean-atmosphere models with ecosystem response models, management objectives and societal values can help the process of prioritization of places and species for protection. While modelling, monitoring, and the effectiveness of management approaches are all associated with uncertainty (Porfirio et al., 2014), structured decision-making linked to adaptive management can inform robust strategies (Regan et al., 2005; Gregory et al., 2012).

With limited conservation resources and coral reef degradation increasing globally, it is imperative to make informed decisions that maximize the potential for success. Decision analyses that use a multiple-objectives and values trade-off approach can help to support decision-making despite the uncertainties of climate change (Keeney and Raiffa, 1993). They can help to determine whether protecting high risk is warranted (e.g., if they produce ecosystem services and can be kept healthy with available resources), or if low-risk sites should be supported (e.g., when they provide key ecosystem services that can be maintained cost-effectively; Game et al., 2008). Therefore, determining priorities for protection is not just about assessing risk, it also must consider social, ecological, and/or economic objectives, consideration of what can actually be achieved (can a few or many reefs be kept healthy and does that satisfy objectives), and what trade-offs are considered acceptable. Risks, feasibility of management success, benefits, and costs need to be considered to inform the prioritization of places to protect.

3.7. Management recommendation 7: incorporate social and ecological indicators to assess early warnings, recovery patterns, and regime shifts in conservation planning and monitoring

Reef managers recognize the importance of incorporating resilience into conservation planning, but guidance has focused on ecological resilience (e.g., Pressey et al., 2007; Maina et al., 2015; Maynard et al., 2015). For example, by combining projected future exposure with data on resilience indicators (e.g., resistant coral species, coral diversity, herbivore biomass, coral disease, macroalgae, and recruitment; McClanahan et al., 2012), managers can map relative vulnerability to climate change and inform actions to support reef resilience (van Hooidonk et al., 2016; Wolff et al., 2018).

A new and important task for managers is to incorporate social drivers as these also can affect reef vulnerability (Norström et al., 2016) and may provide earlier indicators of impending regime shifts (Hicks et al., 2016). Monitoring programs should, at a minimum, include the following social drivers: technologies (e.g., fishing gear), markets (e.g., changing distance to markets and demands), demographic changes (e.g., migration towards coastal areas), and changes in governance structures or policy (Hicks et al., 2016). Social, economic, political and cultural conditions also may represent opportunities to enhance resilience and develop strategies to abate the threats (McClanahan et al., 2008; Marshall et al., 2010).

In addition to considering social drivers, monitoring programs should expand beyond static measures of biodiversity (e.g., coral cover, fish abundance), as these can be poor indicators of resilience (Mumby et al., 2014a,b). High coral cover may be the legacy of past favorable conditions and may fail to indicate changes in reduced recruitment potential or reduced herbivory (Anthony et al., 2015);recruitment and herbivory are both important ecological processes that support reef resilience. Metrics that assess recruitment and recovery patterns (e.g., coral recruit densities, reef structural complexity, water depth, herbivorous fish biomass, and nutrient regime) are important considerations, as they can help to identify when thresholds are likely to be crossed and prioritize management actions (Graham et al., 2015). However, the importance of each indicator varies geographically, with physical environment and the successional stage of the reef. Thus, a key research gap is our limited understanding of resilience indicators for specific reef regions, and how interactions among them may alter their importance.

Currently, there are no guidelines on how to use reef monitoring data to predict the likelihood of future phase shifts or a diagnosis of reef resilience (but see Scheffer et al., 2009, 2012; deYoung et al., 2008; Dakos et al., 2012). To date, the only tipping points estimated are by combining complex simulation models of Caribbean reefs with long-term datasets (Mumby et al., 2014a,b). While reductions in herbivorous fishes and other stressors can certainly reduce coral recovery rates in many geographies, it is unclear which reefs – other than Caribbean forereefs – seem at risk of regime shifts (Mumby et al., 2013). Norström et al. (2016) collected data on individual thresholds for fishing, water quality, and anthropogenic climate change (i.e., mass bleaching and ocean acidification). They found no clear-cut threshold values, but rather a value range (i.e., zone of uncertainty), separating “safe operating space” (low probability for regime shifts) and a zone of high risk (i.e., high probability). They argued that spatial heterogeneity in responses with regards to reef type, depth, geographical position, etc., makes estimations of absolute threshold values difficult. McClanahan et al. (2011) found that once herbivore fish biomass fell below a threshold, many reef sites in the Indian Ocean were associated with less coral and more algae. Thus, research is needed to identify the existence of: (1) tipping points that can precipitate regime shifts; and (2) how such tipping points (where relevant) vary among biogeographic regions and environments.

3.8. Management recommendation 8: explore experimental approaches to support resilience

Current management methods are inadequate to protect reef ecosystems under climate change (Hoegh-Guldberg et al., 2008; Hughes et al., 2017). Even if global warming can be kept within 1.5 °C, tropical surface water will see another 0.3–0.4 warming in the coming decades (Lough et al., 2018). This is likely to exceed the tolerance of sensitive reef-building species (Ainsworth et al., 2016). To sustain coral reefs under any predicted warming scenario, resilience needs to be supported at every level: from gene to ecosystem (Anthony et al., 2017).

Ecological experiments could involve translocation of species from warmer to cooler regions, including outside their historic range (e.g., to provide opportunities for acclimatization and adaptation; Hoegh-Guldberg et al., 2008). Ecological niche models can be used to predict species shifts and adaptation potential and can be an important tool to evaluate sites for interventions (Nagaraju et al., 2013). Corals differ in their ability to adapt or acclimatize (Baker et al., 2004). Some are capable of acclimatization and develop enhanced resistance to bleaching (Berkelmans and van Oppen, 2006). Scientists demonstrated that some corals in American Samoa transplanted into hotter and more variable conditions acquired thermal tolerance demonstrating short-term acclimatization and longer-term climate resistance (Palumbi et al., 2014). Other experimental approaches include enhancing the adaptive capacity of reef organisms to warming via assisted evolution combined with experimental management trials to promote the resilience of key species (Van Oppen et al., 2017). While important to explore, such approaches will need to carefully weigh benefits against risks.

While it may be tempting to consider experimental approaches beyond the scope of reef managers, it is important for local management agencies to engage with researchers in these projects. Marine managers can provide important local knowledge on the social and ecological context and also provide input into methodologies for scaling up successful trials. This is particularly important as experimental approaches have been questioned for their potential for unintended consequences and their inability to be implemented at the scales necessary to support reef resilience (Laikre et al., 2010; Moran and Alexander, 2014). Indeed, assisted colonization will always carry risks, but these risks must be weighed against those of extinction and ecosystem loss. Failing to explore and evaluate all management options now will jeopardize our ability to quickly and effectively respond to threats (Rau et al., 2012). Therefore, research and evaluation of active interventions to maintain marine communities and associated benefits is necessary in parallel with global efforts to reduce emissions.

3.9. Management recommendation 9: implement strategies to build social and ecological adaptive capacity

The adaptive capacity of ecosystems including human communities affects the success of conservation actions and policies (McClanahan et al., 2008; Cinner et al., 2013), yet are rarely considered in reef management plans. Adaptive capacity is the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC, 2014). In some cases, management actions are implemented that enhance the ecological adaptive capacity of reefs such as those that support genetic and biological diversity and habitat heterogeneity (e.g., ensuring protected areas incorporate the full suite of species and habitats; diversity of symbionts). However, as noted above, prioritizing the protection of sites for diversity alone may result in sites that are more vulnerable to climate impacts (Selig et al., 2012). Thus, ecosystem dynamics, driven by the interactions between key functional groups and processes, are more critical in determining resilience than biodiversity alone (Nyström et al., 2008).

A new priority for reef management, and key component of RBM, is the implementation of strategies to build social adaptive capacity. Such strategies include empowering local communities to prepare for, cope with, and adapt to changes in reef condition or access (e.g., helping fishing or tourism industries to review strategies under various scenarios, understand risks and uncertainties, reorganize, learn and adapt; Marshall et al., 2007). Other strategies to support social adaptive capacity include: supporting economic diversity and alternative livelihood opportunities; strengthening social networks among reef users to share management approaches, and support for traditional knowledge and co-management regimes (Berkes and Seixas, 2006; Cinner et al., 2012). Institutional flexibility provides the necessary conditions for experimentation and the ability to respond to change (Berkes and Seixas, 2006). Flexibility in livelihood strategies may provide latent ability to adaptively manage marine resources and support social resilience (Cinner et al., 2009b). However, livelihood diversification does not necessarily indicate high adaptive capacity – in some cases, it may reflect a low standard of living that requires increased effort to meet basic needs; in other cases, it may be a deliberate strategy to “spread the risk” and improve resilience to fluctuations and shocks (McClanahan and Cinner, 2011).

Reef management plans should consider strategies to increase social adaptive capacity because communities with reduced adaptive capacity have greater potential for environmental degradation (Marshall et al., 2010) and may be less able to cope with, and thus comply with, restrictions on resource use (McClanahan et al., 2008). Ignoring adaptive capacity means that key considerations (e.g., political will, institutional capacity, and cultural support) that influence the ability to manage risk and the effectiveness of conservation actions are not incorporated into conservation planning and management (Mcleod et al., 2016).

3.10. Management recommendation 10: implement strategies to facilitate adaptation and transformation

RBM calls for managers to support adaptation and transformation but guidance is needed to articulate how this can be done. To support ecological adaptation, protection of buffer-zones may be implemented to accommodate species range shifts in response to climate change. However, supporting ecological adaptation can be challenging, for example, when disturbances result in winners and losers among coral species due to differential susceptibility and recovery potential. Following disturbance, there may be a loss of susceptible corals and emergence of more resistant species, resulting in a transformation to novel coral-dominated assemblages, that may, in turn, change ecosystem processes and services (Alvarez-Filip et al., 2013). While restoration efforts to re-establish more genetically robust populations of susceptible coral species may help retain some species at local scales (e.g., *Acropora cervicornis* in parts of Florida and the Caribbean; Schopmeyer et al., 2017), social-ecological adaptation is likely to be necessary elsewhere. Social-ecological adaptation can be facilitated by social learning, a diversity of adaptation options, promotion of strong local social cohesion, and mechanisms for collective action (Tompkins, 2005).

Another way to support adaptation is through supporting polycentric governance systems, which are characterized by multiple governing authorities that function independently at different scales but seek to achieve shared goals (Morrison, 2017). They have been identified as an important element of resilient systems, because they can provide opportunities for learning and experimentation, broader levels of participation in governance, and consideration of local knowledge and knowledge sharing across scales (Ostrom, 2005; Biggs et al., 2012). Participatory and inclusive decision-making can improve legitimacy, promote understanding of system dynamics, and improve a management system's capacity to detect and interpret shocks and disturbances (Folke et al., 2005). Polycentric governance systems also can support functional redundancy (e.g., national governance can step in if local governments fail to achieve desired outcome, or vice versa; Biggs et al., 2012). However, the long-term robustness of large-scale polycentric governance systems has recently been challenged, and researchers highlight the importance of anticipating change in designing and implementing polycentric environmental governance (Morrison, 2017).

Crises often represent opportunities for transformations in management by encouraging safe-to-fail experimentation and allowing cross-learning and new initiatives to emerge and spread (Folke, 2016). Doing so will require avoiding thresholds that threaten the capacity of the biosphere to sustain human well-being (Folke, 2016). While planning for transformations may seem complex and unrealistic, based on the need to manage overwhelming threats facing marine ecosystems, successful examples exist. Marine managers have demonstrated how change, if prepared for, can be used to trigger transformation such as the re-zoning of Great Barrier Reef (Olsson et al., 2004), altered fisheries governance (Gelcich et al., 2010), and breaking biophysical feedbacks reinforcing unwanted states (Nyström et al., 2012). Building on these examples, managers can better plan for the uncertainties associated with climate change.

4. Conclusion

Resilience-based management (RBM) supports processes that contribute to stress tolerance, promote recovery and facilitate adaptation within all aspects of the coupled social-ecological system. As climate change unfolds and the resilience of human and natural systems becomes increasingly challenged, evidence suggests that RBM has an important role in helping to support reef ecosystems and the communities that rely on them. The recommendations above highlight key processes that should be considered in management and policy initiatives seeking to support social-ecological resilience.

To scale up resilience-based management globally, it will be important to integrate RBM management recommendations and best practices into policy frameworks such as the United Nations Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC). Influencing policy and governance systems guides the focus of important funding streams such as the Green Climate Fund (GCF) and those that flow through Global Environment Facility (GEF). Mechanisms such as these, together with international finance institutions such as the World Bank, can play a significant role in the scaling of RBM efforts through supporting investments in the implementation of RBM. Additionally, developing cost-benefit analyses of the management recommendations above, can help reef managers and decision-makers to prioritize the suite of management interventions to be considered in a given reef area.

Climate change, ocean acidification and the increasing needs of a growing global population place increasing pressures on coral reefs. Successful management plans and policies are likely to be those that minimize the risks to critical ecosystem functions and support biodiversity and key ecosystem services. Here, RBM provides a lens to inform decision-making that reduces such risks and, by extension, helps to sustain ecosystem benefits that support human well-being. While RBM is not new, we argue that new modes of RBM implementation that consider the recommendations presented here can improve the effectiveness of reef conservation initiatives globally.

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