Journal of Environmental Management 277 (2021) 111384

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Review

Using resilience assessments to inform the management and conservation of coral reef ecosystems

Elizabeth McLeod [a,*], Elizabeth C. Shaver [a], Maria Beger [b,c], Jennifer Koss [d], Gabriel Grimsditch [e]

[a] The Nature Conservancy, Arlington, VA, USA
[b] School of Biology, Faculty of Biological Sciences, University of Leeds, LS2 9JT, UK
[c] Centre for Biodiversity and Conservation Science, School of Biological Sciences, University of Queensland, Brisbane, QLD, 4072, Australia
[d] NOAA Coral Reef Conservation Program, Silver Spring, MD, USA
[e] United Nations Environment Programme, Nairobi, Kenya

ARTICLE INFO

Keywords:
Resilience assessment
Monitoring
Coral reef management
Climate change
Coral reef

ABSTRACT

Climate change is causing the decline of coral reef ecosystems globally. Recent research highlights the importance of reducing CO_2 emissions in combination with implementing local management actions to support reef health and recovery, particularly actions that protect sites which are more resilient to extreme events. Resilience assessments quantify the ecological, social, and environmental context of reefs through the lens of resilience, i.e., the capacity of a system to absorb or withstand stressors such that the system maintains its structure and functions and has the capacity to adapt to future disturbances and changes. Resilience assessments are an important tool to help marine managers and decision makers anticipate changes, identify areas with high survival prospects, and prioritize management actions to support resilience. While being widely implemented, however, there has not yet been an evaluation of whether resilience assessments have informed coral reef management. Here, we assess the primary and gray literature and input from coral reef managers to map where resilience assessments have been conducted. We explore if and how they have been used to inform management actions and provide recommendations for improving the likelihood that resilience assessments will result in management actions and positive conservation outcomes. These recommendations are applicable to other ecosystems in which resilience assessments are applied and will become increasingly important as climate impacts intensify and reduce the window of opportunity for protecting natural ecosystems.

1. Introduction

Climate change is increasingly impacting the world's coral reefs and the communities that depend upon them (Heron et al., 2016; Hughes et al., 2018). In 2014–2017, the world experienced the longest, most widespread, and possibly most damaging coral bleaching event on record due to a combination of a strong El Niño, La Niña, and ocean warming (NOAA, 2017). Unprecedented coral bleaching-related mortality affected coral reef ecosystems around the world (Hughes et al., 2018), resulting in substantial coral loss. It renewed the strong impetus for regulations to mitigate climate change and local management actions that support coral reef resilience.

The footprint of recurrent bleaching is expanding in parallel with the increasing frequency and severity of bleaching events (Hughes et al., 2017). A recent report suggested that reefs are projected to decline by 70–90% at 1.5 °C and increasing global temperatures to 2 °C above pre-industrial levels may result in irreversible loss of marine ecosystems (IPCC, 2018). By 2050, 90% of all reef locations may experience mass coral bleaching annually (Van Hooidonk et al., 2016), increasing the risk of coral disease, mortality, and habitat loss (Maynard et al., 2015). Changes in ocean chemistry are also reducing coral calcification and growth, weakening coral skeletons and making them more vulnerable to storms (Albright et al., 2016).

Against this backdrop of increased reef degradation and threats, strategies to protect reefs have been developed ranging from local to global scale interventions including marine protected areas, fisheries management, improvements in water quality, greenhouse gas mitigation (e.g., renewable energy, restoration of carbon sinks, geoengineering), and marine bioengineering (e.g., coral gardening, assisted migration; Mcleod et al., 2019; Morrison et al., 2020). Recent research

* Corresponding author. 4245 Fairfax Dr. Suite 100, Arlington, VA, 22203, USA.
E-mail address: emcleod@tnc.org (E. McLeod).

https://doi.org/10.1016/j.jenvman.2020.111384
Received 4 February 2020; Received in revised form 28 August 2020; Accepted 8 September 2020
Available online 13 October 2020
0301-4797/© 2020 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

supports the importance of local management efforts to support reef recovery in combination with reduction of CO_2 emissions (Hughes et al., 2017; Roberts et al., 2017; Wolff et al., 2018; Shaver et al., 2018; Steneck et al., 2019). For example, local actions that reduce algal abundance (e.g., protecting herbivores; reducing pollutants that stimulate algal growth) can increase the recovery potential for corals (Bellwood et al., 2004; Steneck et al., 2019).

Resilience assessments were developed to help marine managers and decision makers to identify reefs most likely to survive climate change and prioritize management actions to support resilience (McClanahan et al., 2012; Weeks and Jupiter, 2013; Conway-Cranos, 2012; Maynard et al., 2015). Resilience assessments differ from reef monitoring (Fig. 1). Typically, resilience assessments are conducted one time (rather than continuous monitoring) and build on data collected through traditional monitoring programs (e.g., coral and algal cover, coral and fish diversity, temperature, rugosity). Resilience assessments often include data on ecological processes that affect reef function especially related to recovery processes after mortality events (e.g., recruitment, connectivity) and data on anthropogenic impacts, environmental conditions (e.g. water quality), disturbance regimes and thermal regimes (Lam et al., 2017). They may be nested within, or may complement, existing coral reef monitoring programs. While there is no standard definition for resilience assessments, we define them here as data gathering and analysis that aims to obtain integrated ecological, environmental, and socio-economic information of a reef site with a focus on quantifying indicators pertaining to a reefs' resistance to stress and its ability to recover after experiencing a disturbance (Fig. 1).

Since 2007, resilience assessments have been conducted in all major coral reef areas including the Atlantic, South and East Asia, Pacific, Australia, and East Africa. After more than a decade of coral reef resilience assessments, it is important to assess their application to inform management. The aim of this review is to assess where reef resilience assessments have been implemented and whether they resulted in management actions. We also discuss the benefits and challenges of their implementation and provide recommendations to guide future resilience assessments based on case studies implemented around the world.

2. Methods

We completed a systematic review of resilience assessments, following standards set by the Collaboration for Environmental Evidence (2017). Search terms were trialed and refined using ISI Web of Knowledge and based on sensitivity to capture relevant literature. The final searches were conducted using ISI Web of Knowledge and Directory of Open Access Journals in April 2018 (4/28/18) using two topic searches for both databases: 1) reef AND resilience AND assessment; and 2) reef AND resilience AND monitoring). All journal articles resulting from searches were saved in Endnote and all abstracts were initially reviewed for fit into the general objectives of the study. Selected papers were then examined and filtered using reef resilience assessment

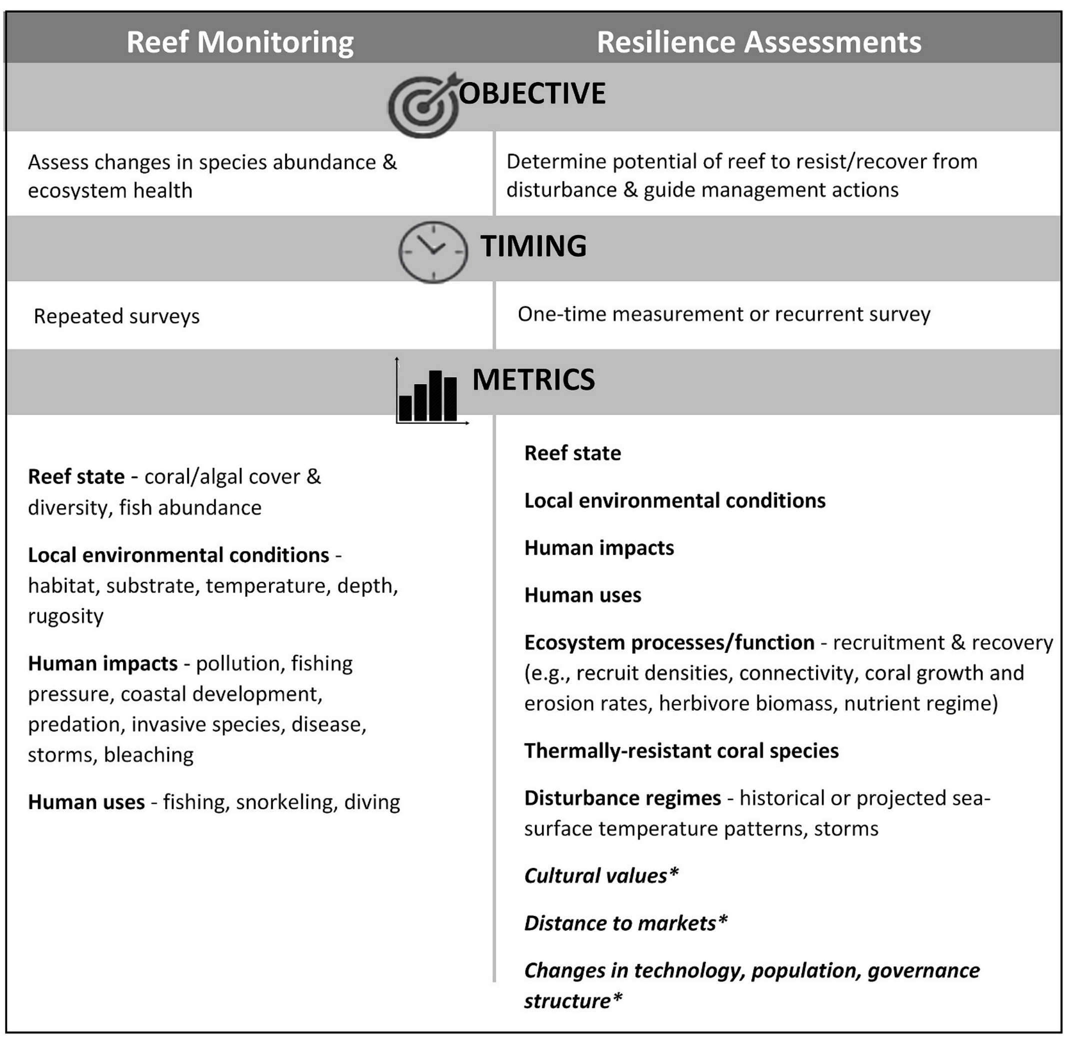

Fig. 1. Differences between traditional reef monitoring and resilience assessments. *refers to metrics that are not currently included in resilience assessments but would be valuable to consider.

criteria.

Following our resilience assessment definition, we applied the following criteria to capture the key components of reef resilience assessments to filter results: 1) coral reefs were assessed in situ; 2) assessment included multiple threats (>1 threat) facing reefs such as pollution, destructive fishing, etc.; 3) included indicators of both coral resistance and recovery (Levin and Lubchencho, 2008; McClanahan et al., 2012); 4) included data on thermal regimes (e.g., historical or projected sea-surface temperature patterns); and 5) included consideration of management actions to improve reef health or support reef recovery. A full examination of the quality of the assessments in the reviewed articles or the rigor of the methods used was beyond the scope of this analysis but would be valuable to consider in future reviews of resilience assessments.

We obtained 144 (topic 1: reef AND resilience AND assessment) and 185 (topic 2: reef AND resilience AND monitoring) studies from the Web of Knowledge search, which resulted in 40 studies (topic 1) and 43 (topic 2) studies for further examination and inclusion into the study. From the Directory of Open Access Journals, we obtained 12 (topic 1) and 24 (topic 2) studies, resulting in 2 (topic 1) and 7 (topic 2) studies for further review.

Further, many reef resilience assessments have not been published in peer reviewed journals and are buried in gray literature (e.g., conservation NGO and donor reports). A web-based search (www.google.com) was used for reference cross-checks using the same search terms above, and the first 50 hits were screened. To minimize publication and availability bias, a search of gray literature was also completed. Reef management agencies were sent emails asking whether resilience assessments had been completed. Managers were asked whether management actions had been implemented based on assessment results for assessments that fit the criteria above. The managers were identified from a list developed by the Nature Conservancy's Reef Resilience Network that included >700 reef managers from different management agencies in over 80 countries/territories. Reports provided by reef management agencies were combined with gray literature reports and publications from the web-based Google search.

3. Results

Using the criteria above, we identified a total of 65 reef resilience assessments that have been implemented in all major coral reef regions across 44 countries and territories (Fig. 2). Most of the resilience assessments have been completed in the Indian Ocean (n = 20) and Southeast Asia (n = 16) regions, two highly threatened reef areas globally based on human impacts and thermal stress (Table 1; Burke et al., 2011), followed closely by the Pacific (n = 15). Relatively fewer assessments were conducted in the Atlantic (n = 10), despite being the second most threatened reef region (Table 1; 92% of reefs threatened). Very few assessments have been completed in the Middle East (n = 3) and Australia (n = 1) regions. There was no correlation between the number of resilience assessments conducted in a region and the total reef area ($P = 0.378$, adjusted $R^2 = -0.004$), percent reef area ($P = 0.372$, adjusted $R^2 = 0.002$), or percent of threatened reefs in a region ($P = 0.225$, adjusted $R^2 = 0.174$).

Overall, 52% of resilience assessments were used to inform coral reef management (n = 34), 37% were not used to inform management actions (n = 24), and for 11% any conservation application remains unknown (n = 7). Management planning and actions resulting from resilience assessments included the following 5 categories: 1) spatial planning (e.g., designing MPAs and LMMAs; zoning plans); 2) monitoring and evaluation; 3) local threat management (e.g., anchor damage, invasive species, pollution); 4) fisheries management; and 5) reef restoration. All actions informed by assessments were counted, as some assessments led to multiple categories of management actions.

Table 1
Characteristics of major coral reef regions, including reef area (sq km and % of global), reef threat ranking (percent of reefs threatened), number of resilience assessments conducted, and standardized ranking for number of assessments based on total threat (ratio). Reef regions, reef area, and threat ranking were taken from Burke et al., (2011). Threat ranking includes overfishing and destructive fishing, pollution, coastal development, and thermal stress.

Region	Reef area (sq km)	Reef area (% of global)	% threatened (integrated local and thermal stress)	Total # resilience assessments	# Assessments per % threatened area (ratio)
Atlantic	25,849	10	92	10	0.11
Australia	42,315	17	40	1	0.03
Indian Ocean	31,543	13	82	20	0.22
Middle East	14,399	6	76	3	0.04
Pacific	65,972	26	65	15	0.23
Southeast Asia	69,637	28	95	16	0.19

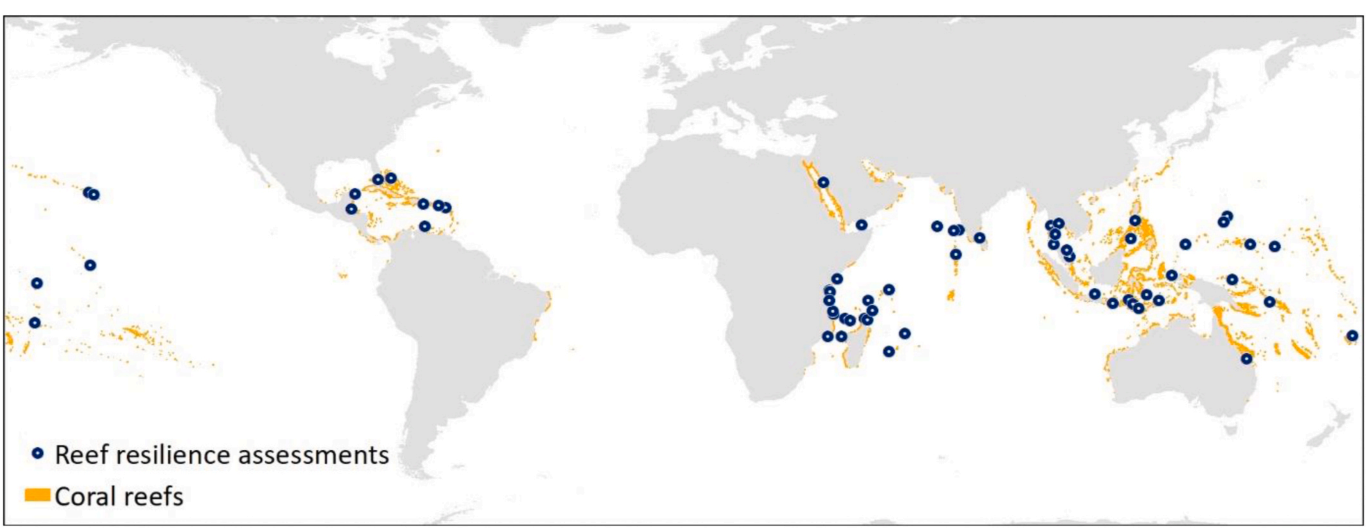

Fig. 2. Global map of reef resilience assessments based on surveys of coral reef managers and a literature search for scientific publications. Source for coral reef map (WCMC, 2010).

The vast majority of management actions implemented from resilience assessment results were categorized as spatial planning (n = 26) and included actions such as: informing the design, zoning, and management of marine protected areas (MPAs), MPA networks, and locally managed marine areas (LMMAs); identifying priority sites for protection due to bleaching vulnerability or high resilience (to serve as source reefs); and informing seascape or marine spatial planning. Assessments also were used to inform fisheries management actions (n = 7) including: outlawing and controlling harvesting; informing fisheries regulations; and setting export quotas. Some assessments were used to inform local threat management (n = 5), including reducing impacts from boat anchoring, tourism damage, invasive species, and nutrient and sediment pollution, and monitoring and evaluation (n = 5) including informing future resilience and bleaching monitoring protocols. Finally, one assessment was used to prioritize areas for coral reef restoration (n = 1, 3%). In addition to management actions, we also found 4 instances where assessments were used to support raising awareness with local communities.

The majority of the assessments were conducted by or in partnership with conservation NGOs (n = 35) or research institutions (n = 22; Fig. 3). Assessments were also conducted to a lesser extent by government agencies (n = 8). Of these institution types, conservation NGOs had the highest number and proportion of resilience assessments leading to management actions (66%, n = 23) (Fig. 3), followed by research institutions (45%, n = 10) and government agencies (25%, n = 2).

By region, the proportion of assessments leading to management actions was highest for Australia (100%, n = 1), however, only one assessment was completed for this region (Fig. 4). Southeast Asia had the second highest proportion of management actions taken (69%, n = 11), followed by the Indian Ocean (50%, n = 10), Atlantic (50%, n = 5), and Pacific (40%, n = 6). The lowest proportion of assessments leading to management actions occurred in the Middle East (33%, n = 1) due to the fact that only 3 assessments have been completed in this region and the outcomes of two assessments remain unknown.

The costs and time needed to complete resilience assessments varied widely (Supplementary Table 1). For instance, costs reported ranged from $1000 to $2.5 million (USD), with median costs for assessments around $27,000 USD. Additionally, the costs included also varied considerably (e.g., some assessments reported in-kind and salaried support while others reported costs on a 'per trip' basis). Time to complete the assessment ranged from 3 days to 4 years, with a median of 28 days, however several assessments did not specify the number of trips taken and many did not report time needed to analyze and report assessment findings. Additionally, some assessments included repeated surveys over a several year period.

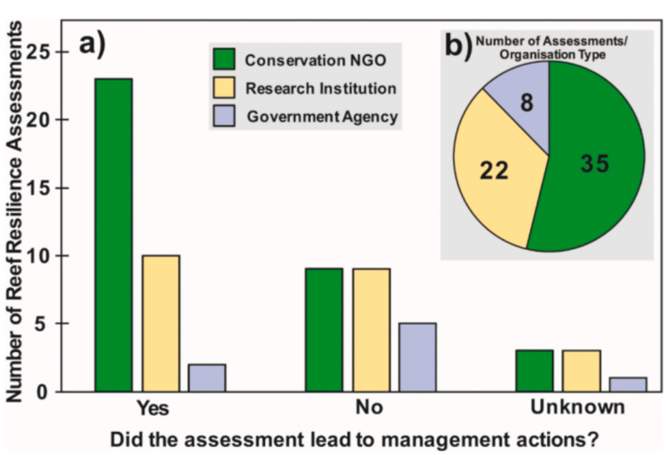

Fig. 3. Have resilience assessments informed management actions by institutional type (research institution, conservation NGO, government agency).

4. Discussion

4.1. Global application of resilience assessments

Resilience assessments have been implemented on a global scale, and the majority were completed in the Indian Ocean. One reason for this may be that the organization responsible for leading many of the assessments in the Indian Ocean is CORDIO, and one of their Founding Directors, Dr. David Obura, wrote the first guidance manual on how to conduct resilience assessments (Obura and Grimsdith, 2009). Interestingly, the Middle East and Australia have implemented far fewer resilience assessments than other reef regions (e.g., Southeast Asia, Pacific, Atlantic and Indian Ocean). While there is not a significant correlation between where assessments have been completed and level of threat to reefs, other factors may be influencing assessment locations. For example, the Middle East has the lowest percentage of reef areas in MPAs (Burke et al., 2011); it also has few marine NGOs working in the region which are one of the primary implementers of resilience assessments. While Australia holds the third largest reef area by region globally (Table 1), its largest reef system, the Great Barrier Reef, is managed by a single entity (i.e., Australia's Great Barrier Reef Marine Park Authority, GBRMPA). The GBRMPA has undergone an extensive multi-year process to develop a Zoning Plan (Day et al., 2019), and recent planning efforts have identified management recommendations for the Great Barrier Reef in the context of a changing climate (e.g., Blueprint for Resilience, GRBMPA, 2017; The Reef, 2050 Long-Term Sustainability Plan, 2018; Commonwealth of Australia, 2018). Such efforts are intended to achieve many of the same objectives as resilience assessments making a resilience assessment potentially duplicative at the national level. However, resilience assessments may provide valuable information for prioritizing management actions in specific reef areas (e.g., Keppel Bay, Australia; Beeden et al., 2014).

4.2. Objectives of resilience assessments

Resilience assessments can be used to prioritize different management actions including prioritization of sites (for protection in MPAs; bleaching monitoring; temporary closures during bleaching events, and reef restoration); targeting management actions; and outreach and stewardship programs (Maynard et al., 2015). The results of the analysis above identified the same suite of management recommendations. The most common application of resilience assessments was informing the zoning of MPAs and marine spatial planning, highlighting their value to help prioritize reefs for survival. This is likely because a key output of resilience assessments is a spatial map of resilience potential, thus directly informing a spatial prioritization of which areas to protect. Resilience assessment results also were used to identify sites with high resilience potential as priorities for no-take areas (Cabral, 2014). An important area for future research is a better understanding of the survival prospects for sites with high resilience potential in a changing climate.

Resilience assessments were also used to prioritize sites for specific management interventions such as improving water quality, fisheries management, no-anchoring areas, reducing damage to the reef from divers/snorkelers, controlling sediment from coastal development, or outreach and stewardship programs (e.g., Beeden et al., 2014; Maynard et al., 2015; Sutthacheep et al., 2018). New opportunities to apply resilience assessments include informing reef restoration and the maintenance of critical ecosystem services. Only one assessment in this review was used to prioritize areas for reef restoration. As support for reef restoration increases globally (e.g., the UN Decade of Restoration, 2021–2030; Australian Government's recent commitment of $6 million AUD for reef restoration), resilience assessments may become increasingly important to identify and prioritize areas for restoration projects. Additionally, as reef systems continue to degrade and managers target interventions toward the maintenance of key ecosystem services (e.g.,

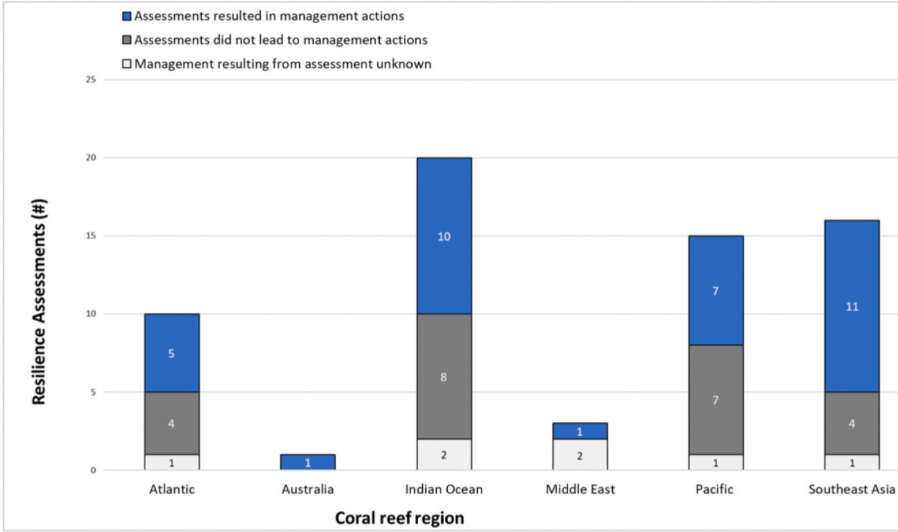

Fig. 4. Outcomes of resilience assessments by coral reef region (assessments resulted in management actions; assessments did not lead to management actions; management actions resulting from assessment were unknown).

coastal protection, fisheries, tourism), resilience assessments may provide opportunities to identify the ecological functions that are most important for sustaining specific reef services (Bellwood et al., 2019a). However, the ability to identify and assess critical ecological functions is complicated by the fact that these may change as reefs change in response to climate change and other human impacts (Bellwood et al., 2019b).

4.3. Enabling conditions to support implementation of management actions

Over half of the resilience assessments analyzed above resulted in management actions. One possible reason why the majority of reef resilience assessments led to management actions may be due to the fact that many of the assessments were led by or partnered with conservation NGOs whose objectives include improved reef protection. Another possible reason is that many of the assessments included government management agencies on the planning team. By comparison, an analysis of published *conservation* assessments over a four-year period showed that two-thirds did not deliver conservation actions largely because researchers did not plan for implementation (Knight et al., 2008). This "implementation gap" is a well noted challenge in conservation management more broadly (Noss et al., 1997; Prendergast et al., 1999; Knight et al., 2008), and it has been discussed in other fields of science including ecology (Higgs, 2005), ecosystem management (McNie, 2007), and environmental psychology (Sommer, 2003).

Researchers and managers have developed recommendations to increase the likelihood that a conservation assessment will lead to management actions (Knight et al., 2008). These recommendations, and those acknowledged in the assessments reviewed here, are helpful to consider to increase the likelihood that management actions will be implemented following a resilience assessment (Table 2).

4.4. Recommendations for increasing the potential for resilience assessments to result in management actions

4.4.1. Building local support for resilience assessments

A recent survey of marine managers (unpublished data, >60 managers from 28 countries; International Tropical Marine Ecosystem Management Symposium, 2016), identified "lack of political and community will to apply resilience assessment results" as one of the greatest challenges to using assessments to inform management. The importance of local and political support to achieve conservation objectives has been acknowledged for decades (e.g., Salafsky et al., 2002; Roux et al., 2006). Additionally, the importance of stakeholder engagement in the planning process, building trust, and the role of targeted communications to build political will and support management has also been extensively discussed in conservation research (Mascia, 2003; Knight and Cowling, 2006; Cooke et al., 2013). Guidance for designing communication materials to support resilience assessments and how to implement the results also has been developed (Maynard et al., 2017; http://www.reefresilience.org/).

Despite this, only 6% of the assessments reviewed here mentioned efforts to raise awareness with local stakeholders. Notably, most of the assessments reviewed did not include any information on the stakeholder engagement process, thus it was not possible to explore if and how levels of engagement affected the likelihood that the assessment resulted in management actions. Future assessments would benefit from including such details.

The assessments that did discuss awareness raising noted the importance of working closely with local stakeholders from planning to implementation to secure local support and communicating assessment planning and results to local stakeholders to influence decision makers and support management actions (Maynard et al., 2015; Eric Conklin *pers comm.*).

A Park Manager from Bonaire shared a story about how he had been working to engage a local legislator in conservation action to protect Bonaire's reefs and was unable to get support. After numerous presentations sharing resilience assessment data, the Park Manager learned that the legislator was a diver and took him diving regularly, using dive slates and underwater photography to describe healthy and unhealthy corals. The legislator spoke on coral reef health at a key legislative meeting and was instrumental in getting legislation passed to protect Bonaire's reef (Ramón de León, *pers.comm.*).

Similarly, in a resilience assessment in the Maldives, the team included a government focal point who communicated survey results regularly to the national government which helped to secure political support for the establishment of an MPA (Gabriel Grimsditch, *pers. comm*). Working with local scientists with established strong local relationships and engaging communities in data collection (e.g., through citizen science) were noted as important ways to build local support for an assessment.

Additional recommendations to increase political support for resilience assessments include mapping out the structure and hierarchy of

Table 2
Recommendations for using reef resilience assessments to inform management actions derived from resilience assessments and marine conservation research (italics)

Recommendations
Building local support (political will; stakeholder engagement; influencing decision-makers)
• Develop resilience assessment priorities in partnership with local stakeholders, ensure sharing of data collected, and explore citizen science opportunities (Maynard et al. 2015)
• Include reef managers and decision-makers (when possible) in all stages of the assessment from planning to implementation and identify local champion to support implementation (Rehm et al. 2014; Maynard et al. 2017)
• Develop communications regarding the importance of managing for resilience and how assessments can be used to build political will to support implementation of management actions
• Results of resilience assessments can provide a platform to promote reef conservation and greater awareness of the importance of reefs; workshops, campaigns and information displays can be helpful, including how local stakeholders (e.g., tourism operators, students, local government officials) can play a role in reducing damage to and encouraging protection of resilient areas (Sutthacheep 2015)
• Effective collaboration between scientists, local communities, and local government officials is needed to integrate scientific data into policy and adaptation measures
• *Conduct social assessment of the planning area to identify key stakeholders and to assess implementation opportunities and constraints (Knight et al. 2008)*
• *Map structure and hierarchy of decision-making within the local government to clarify key influencers, appropriate communication channels, and opportunities for influencing decision-makers (Arlettaz et al. 2010)*
Guidance on indicators
• Utilize locally-relevant resilience indicators that have strong links to resistance or recovery based on local knowledge and that can be assessed using the same methodology for all sites (Maynard et al. 2017)
• Important to consider coastal human population in combination with other factors influencing resilience potential, as higher populations around potentially resilient reefs may pose risk of eroding reef resilience (Macharia et al. 2016)
• Interpretation of assessment results should consider disturbance regime of reefs (e.g., historical bleaching events, storm impacts) and projections of future exposure (Bachtiar et al. 2012; Maynard et al. 2015)
• Resilience assessments provide snapshot of status of resilience indicators thus it is important to incorporate long-term trends of the status of indicators to assess the effectiveness of management actions and to inform adaptive management (Ladd et al. 2013)
• Remote-sensing data may be used to develop a remotely-sensed resilience index where field data are lacking (Rowlands et al. 2012)
• Improved access to downscaled and locally-validated coral reef habitat maps from remotely sensed technology are needed, especially in data poor regions (Macharia et al. 2016) [Note: the new Allen Coral Atlas, https://allencoralatlas.org/, to be completed in 2021 will provide geomorphic and benthic habitat maps globally]
• *Consider both social and ecological indicators of resilience (e.g., metrics of reef state, disturbance regimes, ecosystem process and function, and changes in population, governance and technology; Marshall et al. 2010; Cinner et al. 2013; Mcleod et al. 2019)*
Timing of assessment
• Align timing of resilience assessment with management decision-making processes (e.g., rezoning of MPA) (James True, pers. comm; Maynard et al. 2017)
• Consider how disturbance events (e.g., hurricanes, mass bleaching events) could provide opportunities for increased awareness of climate impacts on reefs and create public action to support reefs
Standardizing costs and value of cost-benefit analysis
• Standardize how costs are reported in resilience assessments (e.g., including planning costs, boats, gasoline, dive equipment, staff salaries, food and lodging for survey team, and in-kind contributions (Bayraktarov et al. 2016)
• Provide decision makers with a cost-benefit analysis of potential management actions in combination with assessment results to help prioritize management actions (Prendergast et al. 1999; Hughey et al 2003; Arlettaz et al. 2010)

decision-making within the government to clarify key influencers, appropriate communication channels, and opportunities for influencing decision-makers. Conducting a social assessment of the planning area can help to identify key stakeholders and clarify potential implementation opportunities and constraints (Knight et al., 2008).

4.4.2. Guidance on selection of indicators

Utilizing locally-relevant resilience indicators that have strong links to resistance or recovery based on local knowledge, and that can be reliably assessed using the same methodology for all sites, helps to support the scientific robustness and credibility of assessment results. Scientists have prioritized indicators and anthropogenic stressors that are likely to be the most important to support the resilience of coral reef ecosystems (McClanahan et al., 2012). Key ecological resilience indicators include resistant coral species, coral diversity, herbivore biomass, coral disease, macroalgae, coral recruitment. Additional indicators include temperature variability, herbivore diversity, and coral size-class distribution. Indicators of human impacts such as nutrient pollution, sedimentation, and fishing pressure are important to generate a management intervention (e.g., pollution mitigation, closure of areas to fishing or gear/harvest restrictions).

Many of the resilience assessments reviewed focused predominantly on ecological indicators based on the guidance in the literature (e.g., Obura and Grimsdith, 2009; Maynard et al., 2010; McClanahan et al., 2012). Very few of the reviewed assessments included any social indicators (beyond human impacts), highlighting a key gap and an opportunity to improve future assessments. This gap is notable considering the large body of research emphasizing the importance of incorporating both social and ecological data (McClanahan et al., 2008; Cinner et al. 2009, 2013; Mcleod et al., 2016) to map conservation opportunities. The inclusion of social indicators, such as distance to market, cultural values, and changes in population, technology, and governance structures (Fig. 1), may provide opportunities to enhance resilience and develop strategies to abate the threats (Marshall et al., 2010; Mcleod et al., 2019). Such indicators are important to consider due the fact that human actions, conditions, and adaptive capacity can exacerbate or support positive environmental conditions (McClanahan et al., 2008; Marshall et al., 2010).

4.4.3. Timing assessments to inform management

Reef assessments are more likely to inform management actions when the timing of the assessment is aligned to coordinate with management decision-making processes (e.g., plans for rezoning of an MPA; James True, *pers. comm;* Maynard et al., 2017). It is also important to understand how external events (e.g., hurricanes, mass bleaching events) might provide areas of opportunity. For example, mass bleaching events or storms could provide increased awareness of climate impacts on reef systems and create increased support for public action to support reef protection or restoration.

4.4.4. Standardizing how costs are reported

Finally, a key gap in resilience assessments currently is the lack of standardization of how costs are reported. Costs varied widely (Supplementary Table 1) due to differences in length of field time, local costs (e.g., for fuel, boats, salaries), and what costs were considered. Understanding the potential costs of implementing a resilience assessment is necessary for decision makers to determine whether the investment is warranted. It would be helpful to standardize how costs are reported in future assessments (e.g., including planning costs, boats, gasoline, dive equipment, staff salaries (researchers, captain), food and lodging for survey team, and in-kind contributions (e.g., donations or volunteer labor; Bayraktarov et al., 2016). Additionally, providing decision makers with a cost-benefit analysis of potential management actions in combination with assessment results can help to prioritize management actions (Prendergast et al., 1999; Arlettaz et al., 2010).

5. Conclusion

Climate change is a rapidly growing threat facing coral reefs worldwide, and efforts to protect reefs should be focused on those areas with the greatest chance of survival (Beyer et al., 2018). In addition to supporting the survival and recovery of reef ecosystems, high resilience sites also are more likely to continue to support human communities through maintaining the delivery of ecosystem goods and services (Mumby and Anthony, 2015). Resilience assessments are important tools to prioritize potentially resilient areas and reef restoration areas, target management actions, and support outreach programs to build awareness and stewardship of reef resources. However, they are also being increasingly applied in other ecosystems, e.g., rocky intertidal systems (Conway-Cranos, 2012), terrestrial forests (Reyer et al., 2015), and freshwater ecosystems (Angeler et al., 2014).

As research organizations, conservation NGOs, education organizations, and government agencies continue to assess resilience across ecosystems, attention to the recommendations above will help to increase the likelihood of the assessments resulting in management actions. A focus on potential barriers and the existence of enabling conditions (e.g., political will supporting implementation of management actions; timing resilience assessments with management decisions; engaging stakeholders from planning to implementation) can help to support the uptake of assessment results. Further, improved guidance regarding which indicators should be included in resilience assessments (McClanahan et al., 2012) and the inclusion of both social and ecological indicators (Cinner et al., 2009; Mcleod et al., 2016; Maynard et al., 2017) will help to improve the ability of assessments to identify sites with the greatest survival and recovery prospects.

The ability to prioritize limited conservation resources and effort in the areas with the greatest survival prospects will become increasingly important as climate changes continues to degrade coral reef ecosystems. In parallel, efforts to address root causes of coral decline also must be implemented urgently (i.e., GHG emissions reduction) along with exploring bold interventions including terrestrial-based investments in renewable energy, fossil fuel divestment, land-based aquaculture, and restoration of carbon sinks (Morrison et al., 2019). Such approaches require managing multi-scale threats and globally uneven power relations and development patterns.

Our window of opportunity is narrowing. Recent research on the Great Barrier Reef warns that the number of potential reef refuges is declining, as bleaching events increase in frequency and intensity with less time for recovery between events (Hughes et al., 2017). Ramping up reef conservation and restoration efforts, in parallel with rapidly reducing global emissions, provide coral reefs with the best chance of survival.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank all of the coral reef managers around the globe who shared their information and experiences with us for this publication. We thank the following for their contributions: Pierre-Andre Adam, Gabby Ahmadia, Rohan Arthur, Imam Bachtiar, Elisa Bayraktarov, Chris Bergh, Andy Bruckner, David Burdick, James Byrne, Alvin Chelliah, Eric Conklin, Camilo Cortés, Craig Dahlgren, Ramón de León, Norievill España, Chun Hong, Peter Houk, Stacy Jupiter, Denis Macharia, Joseph Maina, Sangeeta Mangubhai, Balakrishnan Manikandan, Jeffrey Maynard, Steve McKagan, Pete Mumby, David Obura, Valeria Pizarro, Puji Prihatinningsih, Lincoln Rehm, Gwilym Rowlands, Brett Schumacher, Bob Steneck, Eleanor Sterling, Jerker Tamelander, James Tan, James True, Camilo Cortés Useche, Lani Watson, Maria Retchie C. Pagliawan, Mochamad Iqbal, Herwata Putra, Purwanto, Rita Sellares, Rod Salm, and Nalinee Thongtham. Many thanks to Nate Peterson for GIS support and Hannah Barkley for coordination with reef managers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111384.

References

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J.K., Mason, B.M., Rivlin, T., 2016. Reversal of ocean acidification enhances net coral reef calcification. Nature 531 (7594), 362.

Angeler, D.G., Allen, C.R., Birgé, H.E., Drakare, S., McKie, B.G., Johnson, R.K., 2014. Assessing and managing freshwater ecosystems vulnerable to environmental change. Ambio 43 (1), 113–125.

Arlettaz, R., Schaub, M., Fournier, J., Reichlin, T.S., Sierro, A., Watson, J.E., Braunisch, V., 2010. From publications to public actions: when conservation biologists bridge the gap between research and implementation. Bioscience 60 (10), 835–842.

Bachtiar, I., Damar, A., Zamani, N.P., 2012. Assessing ecological resilience of Indonesian coral reefs. J. Coast. Dev. 14 (3), 214–222.

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Lovelock, C.E., 2016. The cost and feasibility of marine coastal restoration. Ecol. Appl. 26 (4), 1055–1074.

Beeden, R., Maynard, J., Johnson, J., Dryden, J., Kininmonth, S., Marshall, P., 2014. No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef. Australas. J. Environ. Manag. 21 (3), 311–319.

Bellwood, D.R., Hughes, T.P., Folke, C., Nyström, M., 2004. Confronting the coral reef crisis. Nature 429, 827–833.

Bellwood, D.R., Pratchett, M.S., Morrison, T.H., Gurney, G.G., Hughes, T.P., Álvarez-Romero, J.G., Day, J.C., Grantham, R., Grech, A., Hoey, A.S., Jones, G.P., 2019a. Coral reef conservation in the Anthropocene: confronting spatial mismatches and prioritizing functions. Biol. Conserv. 236, 604–615.

Bellwood, D.R., Streit, R.P., Brandl, S.J., Tebbett, S.B., 2019b. The meaning of the term 'function' in ecology: a coral reef perspective. Funct. Ecol. 33 (6), 948–961.

Beyer, H.L., Kennedy, E.V., Beger, M., Chen, C.A., Cinner, J.E., Darling, E.S., Obura, D.O., 2018. Risk-sensitive planning for conserving coral reefs under rapid climate change. Conserv. Lett., e12587

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at Risk Revisited. World Resources Institute, Washington, D.C., p. 114

Cabral, M.M.P., 2014. Resilience-based assessment for targeting coral reef management strategies in Koh Tao, Thailand (Doctoral dissertation). Available at: https://newheavenreefconservation.org/images/StudentPapers/Cabral_2014_Reselience-of-Koh-Taos-Reefs-using-IUCN-method.pdf. (Accessed 16 January 2019).

Cinner, J., Fuentes, M.M.P.B., Randriamahazo, H., 2009. Exploring social resilience in Madagascar's marine protected areas. Ecol. Soc. 14 (1), 41.

Cinner, J.E., Huchery, C., Darling, E.S., Humphries, A.T., Graham, N.A., Hicks, C.C., McClanahan, T.R., 2013. Evaluating social and ecological vulnerability of coral reef fisheries to climate change. PloS One 8 (9).

Collaboration for Environmental Evidence Guidelines for systematic review and evidence synthesis in environmental management. http://www.environmentalevidence.org/guidelines/table-of-contents.

Commonwealth of Australia, 2018. The reef 2050 long-term sustainability plan 2018. Available at: http://www.environment.gov.au/system/files/resources/35e55187-b76e-4aaf-a2fa-376a65c89810/files/reef-2050-long-term-sustainability-plan-2018.pdf. (Accessed 19 June 2020).

Cooke, S.J., Lapointe, N.W.R., Martins, E.G., Thiem, J.D., Raby, G.D., Taylor, M.K., Beard Jr., T.D., Cowx, I.G., 2013. Failure to engage the public in issues related to inland fishes and fisheries: strategies for building public and political will to promote meaningful conservation. J. Fish. Biol. 83 (4), 997–1018.

Conway-Cranos, L.L., 2012. Geographic variation in resilience: an experimental evaluation of four rocky intertidal assemblages. Mar. Ecol. Prog. Ser. 457, 67–83.

Day, J.C., Kenchington, R.A., Tanzer, J.M., Cameron, D.S., 2019. Marine zoning revisited: how decades of zoning the Great Barrier Reef has evolved as an effective spatial planning approach for marine ecosystem-based management. Aquat. Conserv. Mar. Freshw. Ecosyst. 29, 9–32.

Great Barrier Reef Marine Park Authority Great barrier reef Blueprint for resilience, Townsville, QLD, Australia: Great Barrier Reef Marine Park Authority. Available at: http://elibrary.gbrmpa.gov.au/jspui/handle/11017/3287–. (Accessed 19 June 2020).

Heron, S.F., Maynard, J.A., Van Hooidonk, R., Eakin, C.M., 2016. Warming trends and bleaching stress of the world's coral reefs 1985–2012. Sci. Rep. 6, 38402.

Higgs, E., 2005. The two-culture problems: ecological restoration and the integration of knowledge. Restor. Ecol. 13, 159–164.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Bridge, T.C., 2017. Global warming and recurrent mass bleaching of corals. Nature 543 (7645), 373.

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., McWilliam, M.J., 2018. Global warming transforms coral reef assemblages. Nature 1.

Hughey, K.F., Cullen, R., Moran, E., 2003. Integrating economics into priority setting and evaluation in conservation management. Conserv. Biol. 17 (1), 93–103.

IPCC, 2018. Summary for policymakers. In: Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), The Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate

Poverty [V. Masson-Delmotte. World Meteorological Organization, Geneva, Switzerland, p. 32.
Knight, A.T., Cowling, R.M., 2006. Into the thick of it: bridging the research-implementation gap in the Thicket Biome through the Thicket Forum. South Afr. J. Sci. 102, 406–408.
Knight, A.T., Cowling, R.M., Rouget, M., Balmford, A., Lombard, A.T., Campbell, B.M., 2008. Knowing but not doing: selecting priority conservation areas and the research–implementation gap. Conserv. Biol. 22 (3), 610–617.
Ladd, M.C., Collado-Vides, L., 2013. Practical applications of monitoring results to improve managing for coral reef resilience: a case study in the Mexican Caribbean. Biodivers. Conserv. 22 (8), 1591–1608.
Lam, V.Y., Doropoulos, C., Mumby, P.J., 2017. The influence of resilience-based management on coral reef monitoring: a systematic review. PloS One 12 (2), e0172064.
Levin, S.A., Lubchencho, J., 2008. Resilience, robustness, and marine ecosystem-based management. Bioscience 58 (1), 1–7.
Macharia, D., Grimsditch, G., Abdulla, A., Obura, D., 2016. Mapping Factors That Contribute to Coral Reef Resilience Using In situ and Satellite Data in East Africa. In: Diop, S., Scheren, P., Machiwa, FerdinandJ. (Eds.), Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean. Estuaries of the World. Springer, Cham. https://doi.org/10.1007/978-3-319-25370-1_16.
Marshall, N.A., Marshall, P.A., Tamelander, J., Obura, D., Mallaret King, D., Cinner, J.M., 2010. Sustaining Tropical Coastal Communities and Industries: a Framework for Social Adaptation to Climate Change. IUCN-The International Union for the Conservation of Nature, Gland.
Mascia, M.B., 2003. The human dimension of coral reef marine protected areas: recent social science research and its policy implications. Conserv. Biol. 17 (2), 630–632.
Maynard, J.A., Marshall, P.A., Parker, B., Mcleod, E., Ahmadia, G., van Hooidonk, R., Tamelander, J., 2017. A Guide to Assessing Coral Reef Resilience for Decision Support. UN Environment, Nairobi, Kenya, ISBN 978-92-807-3650-2.
Maynard, J.A., Marshall, P.A., Johnson, J.E., Harman, S., 2010. Building resilience into practical conservation: identifying local management responses to global climate change in the southern Great Barrier Reef. Coral Reefs 29 (2), 381–391.
Maynard, J.A., McKagan, S., Raymundo, L., Johnson, S., Ahmadia, G.N., Johnston, L., Van Hooidonk, R., 2015. Assessing relative resilience potential of coral reefs to inform management. Biol. Conserv. 192, 109–119.
McClanahan, T.R., Cinner, J.E., Maina, J., Graham, N.A.J., Daw, T.M., Stead, S.M., Polunin, N.V.C., 2008. Conservation action in a changing climate. Conserv. Lett. 1 (2), 53–59.
McClanahan, T.R., Donner, S.D., Maynard, J.A., MacNeil, M.A., Graham, N.A., Maina, J., Eakin, C.M., 2012. Prioritizing key resilience indicators to support coral reef management in a changing climate. PloS One 7 (8).
Mcleod, E., Anthony, K., Maynard, J., Mumby, P.J., Beeden, R., Graham, N.A.J., Heron, S.F., Hoegh-Guldberg, O., Jupiter, S., MacGowan, P., Mangubhai, S., Marshall, N., Marshall, P., McClanahan, T.R., Mcleod, K., Nyström, M., Obura, D., Parker, B., Possingham, H.P., Salm, R.V., Tamelander, J., 2019. The future of resilience-based management in coral reef ecosystems. J. Environ. Manag. 233, 291–301.
Mcleod, E., Szuster, B., Hinkel, J., Tompkins, E.L., Marshall, N., Downing, T., et al., 2016. Conservation organizations need to consider adaptive capacity: why local input matters. Conserv. Lett. 9 (5), 351–360.
McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environ. Sci. Pol. 10, 17–38.
Morrison, T.H., Adger, N., Barnett, J., Brown, K., Possingham, H., Hughes, T., 2020. Advancing coral reef governance into the Anthropocene. One Earth 2 (1), 64–74.
Morrison, T.H., Hughes, T.P., Adger, W.N., Brown, K., Barnett, J., Lemos, M.C., 2019. Save reefs to rescue all ecosystems. Nature 573 (7774), 333–336.
Mumby, P.J., Anthony, K., 2015. Resilience metrics to inform ecosystem management under global change with application to coral reefs. Methods Ecol. Evol. 6 (9), 1088–1096.
National Oceanic and Atmospheric Administration (NOAA), 2017. Global coral bleaching event likelyending. June 19. https://www.noaa.gov/media-release/global-coral-bleaching-event-likely-ending.
Noss, R.F., O'Connell, M.A., Murphy, D.D., 1997. The Science of Conservation Planning: Habitat Conservation under the Endangered Species Act. Island Press, Washington, D.C.
Obura, D.O., Grimsdith, G., 2009. Resilience Assessment of coral reefs – Assessment protocol for coral reefs, focusing on coral bleaching and thermal stress. IUCN working group on Climate Change and Coral Reefs. IUCN, Gland, Switzerland, p. 70.
Prendergast, J.R., Quinn, R.M., Lawton, J.H., 1999. The gaps between theory and practice in selecting nature reserves. Conserv. Biol. 13, 484–492.
Rehm, L., Polloi, K., Olsudong, D., Mereb, G., Oretamor, J., van Woesik, R., 2014. Reef resilience assessment in the Federated States OF Micronesia. Palau international coral reef center. The nature conservancy. Available at: http://picrc.org/picrcpage/wp-content/uploads/2016/01/Rehm_FSMReefResilience_20141.pdf.
Reyer, C.P., Brouwers, N., Rammig, A., Brook, B.W., Epila, J., Grant, R.F., Medlyn, B., 2015. Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. J. Ecol. 103 (1), 5–15.
Roberts, C.M., O'Leary, B.C., McCauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Worm, B., 2017. Marine reserves can mitigate and promote adaptation to climate change. Proc. Natl. Acad. Sci. Unit. States Am. 114 (24), 6167–6175.
Roux, D.J., Rogers, K.H., Biggs, H.C., Ashton, P.J., Sergeant, A., 2006. Bridging the science-management divide: moving from unidirectional knowledge transfer to knowledge interfacing and sharing. Ecol. Soc. 11.
Rowlands, G., Purkis, S., Riegl, B., Metsamaa, L., Bruckner, A., Renaud, P., 2012. Satellite imaging coral reef resilience at regional scale. A case-study from Saudi Arabia. Mar. Pollut. Bull. 64 (6), 1222–1237.
Salafsky, N., Margoluis, R., Redford, K.H., Robinson, J.G., 2002. Improving the practice of conservation: a conceptual framework and research agenda for conservation science. Conserv. Biol. 16, 1469–1479.
Shaver, E.C., Burkepile, D.E., Silliman, B.R., 2018. Local management actions can increase coral resilience to thermally-induced bleaching. Nat. Ecol. Evol. 1.
Sommer, R., 2003. Action research and big fuzzy concepts. Hum. Ecol. Rev. 10, 176–177.
Steneck, R., Arnold, S.N., Boenish, R., De Leon, R., Mumby, P.J., Rasher, D.B., Wilson, M., 2019. Managing recovery resilience in coral reefs against climate-induced bleaching and hurricanes: a 15 year case study from Bonaire, Dutch Caribbean. Front. Mar. Sci. 6, 265.
Sutthacheep, M., Sakai, K., Yeemin, T., Pensakun, S., Klinthong, W., Samsuvan, W., 2018. Assessing coral reef resilience to climate change in Thailand. Ramkhamhaeng Int. J. Sci. Technol. 1 (1), 22–34.
Sutthacheep, M., 2015. Impacts of coral reef bleaching events and recovery of coral communities in the Gulf of Thailand. University of the Ryukyus. Available at: http://hdl.handle.net/20.500.12000/30815S. (Accessed 16 January 2019).
Van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadia, G., Raymundo, L., et al., 2016. Local-scale projections of coral reef futures and implications of the Paris Agreement. Sci. Rep. 6, 39666.
Weeks, R., Jupiter, S.D., 2013. Adaptive co-management of a marine protected area network in Fiji. Conserv. Biol. 27 (6), 1234–1244.
Wolff, N.H., Mumby, P.J., Devlin, M., Anthony, K.R., 2018. Vulnerability of the Great Barrier Reef to climate change and local pressures. Global Change Biol. 24 (5), 1978–1991.