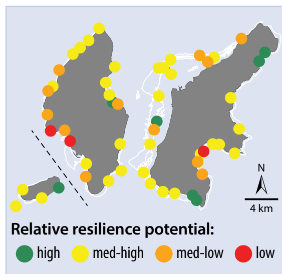
UN environment 2017

A Guide to Assessing **Coral Reef Resilience**

FOR DECISION SUPPORT

A Guide to Assessing **Coral Reef Resilience**

FOR DECISION SUPPORT


Jeffrey Maynard[1,2], Paul Marshall[3,4], Britt Parker[5], Elizabeth Mcleod[6], Gabby Ahmadia[7], Ruben van Hooidonk[8,9], Serge Planes[2], Gareth J Williams[10], Laurie Raymundo[11], Roger Beeden[12], Jerker Tamelander[13]

1 — SymbioSeas (www.symbioseas.org) and the Marine Applied Research Center, Wilmington NC, 28411, USA; 2 — Laboratoire d'Excellence «CORAIL» USR 3278 CNRS – EPHE, CRIOBE, Papetoai, Moorea, Polynésie Française; 3 — Reef Ecologic (www.reefecologic.org), Townsville QLD 4810, Australia; 4 — Centre for Biodiversity and Conservation Science, University of Queensland; 5 — The Baldwin Group on contract with the NOAA Coral Reef Conservation Program, 1315 East-West Highway, Silver Spring, MD 20910; 6 — The Nature Conservancy, 7707 Vail Valley Dr., Austin, TX 78749; 7 — Oceans, World Wildlife Fund, 1250 24th St., Washington, D.C. 20037, USA; 8 — NOAA Atlantic Oceanographic and Meteorological Laboratory, Ocean Chemistry and Ecosystems Division, 4301 Rickenbacker Causeway, Miami, FL 33149, USA; 9 — Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA; 10 — School of Ocean Sciences, Bangor University, LL59 5AB, UK; 11 — University of Guam Marine Laboratory, UOG Station, Mangilao, GU 96913, USA; 12 — Great Barrier Reef Marine Park Authority, Townsville QLD 4810 Australia; 13 — United Nations Environment, Bangkok, Thailand

Published by UN Environment, Nairobi, Kenya

This publication should be cited as:

Maynard, J.A., Marshall, P.A., Parker, B., Mcleod, E., Ahmadia, G., van Hooidonk, R., Planes, S., Williams, G.J., Raymundo, L., Beeden, R., Tamelander, J. (2017). *A Guide to Assessing Coral Reef Resilience for Decision Support*. Nairobi, Kenya: UN Environment.

Cataloguing-in-Publication entry:

A Guide to Assessing Coral Reef Resilience for Decision Support

ISBN No: 978-92-807-3650-2

Job No: DEP/2104/BA

Production: Dieter Tracey (dieter@sciencegraphics.com.au)

Acknowledgements:

The content of this guide builds upon many published papers and reports, as well as on discussions between the authors and a large number of coral reef scientists and managers. We acknowledge all of those that have contributed to developing and applying the concept of assessing reef resilience to support management and conservation decision-making. We thank these reviewers for helping improve the Guide: Angelique Brathwaite, Alessandrea Vanzella-Khouri, Georgina Bustamante, Steve Fletcher, Hazel Thornton, Nicolas Pascal and Chloe Harvey.

Photograph credits:

Jerker Tamelander (front cover, page 8 #2 top-left, page 14, page 18, page 24); **Roger Beeden** (first inset on front cover, page 2 top-left, page 6, page 8 #2 bottom-right, page 8 #3, page 20 right); **Great Barrier Reef Marine Park Authority** (third and fourth insets on front cover, page 8 #2 bottom-left, page 8 #9 far left and mid-left, page 13, page 15 top two); **XL Catlin Seaview Survey** (page ii); **Australian Institute of Marine Science** (page 2 top-middle, page 16); **Paul Marshall** (page 2 top-right and bottom, page 7, page 8 #1, page 9, page 33); **Chris Roelfsema** (page 4, back cover); **Jeffrey Maynard** (page 5, page 22); **Conchasdiver | Dreamstime** (page 8 #2 top-right); **Lisa Carne | Marine Photobank** (page 8 #2 far left); **Malik Naumann | Marine Photobank** (page 8 #6 mid-left, page 15 far left); **Alex Wu | Marine Photobank** (page 8 #6 mid-right, page 15 bottom mid-right); **Junior Libby | PDP** (page 8 #6 far right); **NASA Scientific Visualization Studio** (page 8 #8, page 31); **Stephen Lewis** (page 8 #9 mid-right); **Association of Marine Park Tourism Operators** (page 8 #9 far-right); **Corinn Strickland** (page 10); **Ed Roberts** (page 11); **Rafael Ben Ari | Dreamstime** (page 12); **Steve Spring | Marine Photobank** (page 15 bottom mid-left); **Ayana Elizabeth Johnson** (page 15 bottom far right); **National Oceanic and Atmospheric Administration** (page 20 left); **WWF Indonesia** (page 23, page 34); **Matthew D Potenski | Marine Photobank** (page 32); **totajla | fotolia** (page 36); **Coral Restoration Foundation** (page 39).

Contents

Coral reefs are losing their resilience. These photos are of a reef near American Samoa in the south Pacific on December of 2014 (left) and then two months later (right). The photo on right is representative of the global-scale coral bleaching event that took place between 2014 and 2016. Photos: XL Catlin Seaview Survey.

Introduction

- *Coral reefs are naturally resilient*
- *Reefs are losing their resilience because of pressure from human activities combined with increasing climate impacts*
- *Resilience can readily be assessed*
- *Supporting resilience needs to be a management priority*
- *Local actions can influence the future resilience of reefs*

Coral reef resilience is the capacity of a reef to resist or recover from degradation and maintain provision of ecosystem goods and services (Mumby et al., 2007).

This resilience helps reefs to resist and recover after major disturbances such as severe tropical storms and mass bleaching events. Coral reefs are being exposed to these potentially devastating events with greater frequency, making resilience an increasingly important property.

Yet, through the cumulative impacts of human use and the activities associated with human settlements, coral reefs are losing their resilience. We are seeing the signs of this all around the world. Examples include regional declines in coral cover in the Caribbean (Jackson et al. 2014). and widespread conversion of fringing reefs to algal-covered rubble beds in many areas in the Pacific and Indian Oceans.

Maintaining and restoring resilience is now a major focus of most coral reef managers around the world.

A focus on resilience gives us options – and hope – in the face of new and often daunting challenges.

Underpinning this is the fact that local actions can positively influence the future of coral reefs, despite powerful external forces like climate change. As examples, coral recovery from disturbances in Bermuda and the Bahamas has been greater in recent decades than in other parts of the Caribbean. Differences in recovery rates in the Caribbean have been partially attributed to establishing and enforcing fishing regulations, especially on key herbivores such as parrotfish (Jackson et al. 2014). Overall though, the application of resilience theory to management planning and the day-to-day business of coral reef management has been challenging. One of the key stumbling blocks has been the lack of a robust and easily implementable method for assessing coral reef resilience in a way that can inform marine spatial planning and help to prioritize the implementation of management strategies.

Fortunately, our ability to assess relative resilience of coral reefs has advanced dramatically in recent years, and we are now at a point where a feasible and useful process can be recommended for use in environmental planning and management.

This guide is first and foremost intended for the individuals in charge of commissioning, planning, leading or coordinating a resilience assessment. It also provides a resource for 'reef managers' of all kinds, including decision-makers, environmental planners and managers in coral reef areas, with influence over pressures affecting coral reefs.

Outreach coordinators and educators working in coral reef areas may also benefit from the Guide, and they can participate in parts of the resilience assessment process, but the Guide focuses on the needs of decision-makers and the scientists who support them.

The guidance presented here represents the culmination of over a decade of experience and builds on ideas first presented by West and Salm (2003), Obura and Grimsditch (2009), and McClanahan and coauthors (2012). This Guide puts into managers' hands the means to assess, map and monitor coral reef resilience, and the means to identify and prioritize actions that support resilience in the face of climate change. Previously, resilience to climate change was rarely formally accounted for in marine spatial and conservation planning processes. We hope this Guide will help change that!

About this Guide

The introductory section familiarizes you with resilience and vulnerability concepts and reviews the various frameworks that are necessary to move from resilience theory to practical application. We help you define the decision-making contexts that can benefit from resilience assessments, and to clarify the objectives, scope and intended outcomes for your resilience assessment. A 10-step Guide is then presented for anyone who wishes to use the resilience assessment process to inform planning or management decisions. The guidance draws on practical experience in applying resilience concepts to coral reef management (see references to case study examples), and highlights both technical and process considerations for successful delivery of a resilience assessment project. We begin by reviewing the context for resilience assessments, followed by the considerations that can help you decide if resilience assessments are right for you.

The context for resilience assessments: Coral reefs in times of change

Coral reefs have persisted in various forms for hundreds of millions of years. Even today we can observe their amazing ability to resist and recover after devastating events such as hurricanes, crown-of-thorns seastar outbreaks and mass coral bleaching. Dramatic recovery of coral cover in places like .like Chagos Archipelago (Sheppard et al. 2013), Palau (Golbuu et al. 2007), and western Australia (Depczynski et al. 2013) are vivid illustrations of the importance of resilience when coral reefs are exposed to major disturbances.


Cyclone damage


Crown-of-thorns seastar outbreaks


Coral bleaching

Coral reefs are the marine ecosystem most vulnerable to climate change, and we are currently witnessing alarming and persistent declines in their health and abundance. Local pressures associated with human settlements and human uses are reducing the natural resilience of coral reefs. These impacts compromise the ability of coral reefs to recover after disturbances, such as coral bleaching events, which are becoming more frequent and severe as a result of climate change.

The scale and inexorable progression of climate change can lead to a sense of hopelessness and futility for anyone engaged in coral reef management. Yet, regional and local actions make a difference. This is exemplified by the relatively rapid recovery of corals from bleaching in the Chagos Archipelago of the Indian ocean where there are few human impacts and the ecological processes (e.g., herbivory and coral recruitment) are intact (Graham et al. 2013).

While some of the greatest threats are beyond the direct influence of managers, conservationists and community stewards, reversing the loss of resilience is not.

Vulnerability and resilience

- *Vulnerability of a coral reef is a function of exposure and resilience*
- *'Exposure' refers to pressures external to the system, such as effects of climate change*
- *Resilience is a product of sensitivity and adaptive capacity*
- *Local pressures increase sensitivity of coral reefs to climate change*
- *Information on exposure is often publicly available in global datasets*
- *Information on local pressures should be collated or collected as part of the resilience assessment*
- *Combining exposure and resilience information helps target actions*

In the IPCC's widely-used vulnerability assessment framework, vulnerability is the product of exposure, sensitivity and adaptive capacity. Exposure and sensitivity combine to provide an estimate of potential impact. Adaptive capacity moderates potential impact to provide a measure of system vulnerability (Turner et al. 2003, Figure 1). Sensitivity and adaptive capacity are inherent properties of the system that determine how it responds to exposure. This enables us to define resilience as the combination of sensitivity and adaptive capacity in the context of vulnerability (Figure 1, Marshall and Marshall, 2007). Set out this way, assessing vulnerability can be seen as requiring information about two key aspects of coral reef dynamics: exposure and resilience.

Exposure captures current or potential external pressures. Resilience describes the actual or likely response of the system upon exposure to that stress or pressure. A resilient system is more likely to maintain key functions and sustain provision of ecosystem goods and services when exposed to external pressures.

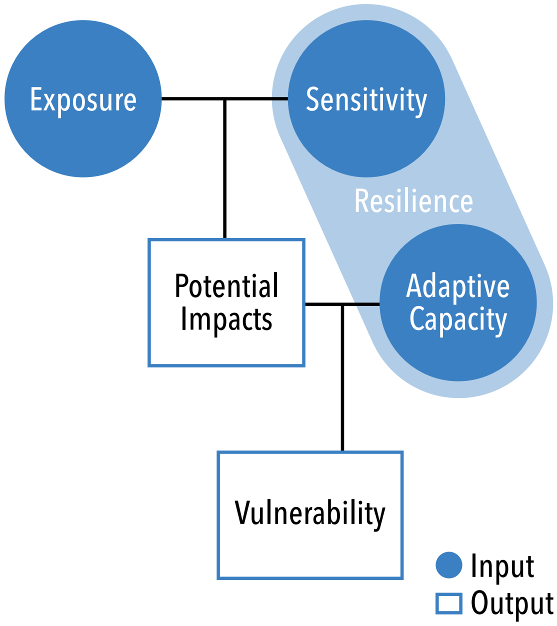


Figure 1. Vulnerability assessment framework used by the IPCC; vulnerability is a function of exposure to disturbances (especially those that originate outside the system, such as climate-related stresses) and resilience describes how the system (social-ecological) responds (Turner et al. 2003).

This conceptualization of resilience helps us focus on what we can do to reduce vulnerability (reduce sensitivity or increase adaptive capacity), while acknowledging the importance of factors largely beyond our control (exposure to climate-related threats).

On-the-ground actions to support resilience are the key to reducing vulnerability to climate change and giving coral reefs the best chance of coping with the major challenges ahead.

In the context of management of coral reefs, 'exposure' is best used to capture pressures that originate outside the system, such as climate change-related stresses and extreme events. These are outside the direct control of individual environmental management agencies. Pressures that can be controlled or influenced through direct management interventions, such as water quality and overfishing, should be considered as aspects of sensitivity. Characterizing local pressures provides an important window into the sensitivity of our coral reef system to external pressures, and provides the basis for identifying the 'levers' available to us for building resilience of the system. By measuring both ecological resilience indicators and local stress indicators we are able to assess resilience and identify local actions that can make a difference to the condition and trend of coral reefs in the face of un-manageable external pressures like climate change.

Information on exposure to external pressures associated with climate change is, fortunately, readily available to coral reef managers. For example, data on exposure to temperatures that trigger coral bleaching are available as high-resolution (4-km) projections of future bleaching event frequency (van Hooidonk et al., 2016). In this Guide, we discuss how to combine these projections with resilience assessment results to produce a vulnerability assessment. We also discuss the importance of ecological connectivity to resilience.

Climate exposure and connectivity information can be combined with resilience assessment results to further inform efforts to identify, prioritize and target actions that can support site and system resilience.

In summary, resilience assessments allow decision makers to anticipate change and to focus efforts on improving the ability of the system to cope with those changes and unpredictable surprises. In the next section we outline the approach to and benefits from a resilience assessment.

What is a resilience assessment and why go through the process?

Resilience assessments involve measuring or assessing the attributes ('resilience indicators') that contribute to making a coral reef resilient, and also collecting measures of the stress related to human activities that can reduce reef resilience. Resilience assessments make it possible to map relative resilience in your area of interest, and to track changes in resilience through time.

By looking at the source of resilience at different locations, and the causes of differences in resilience, managers and stakeholders can evaluate the potential for management or stewardship actions to improve resilience in different areas.

Repeating resilience assessments through time enables us to measure and monitor change in resilience potential and management progress, in order to allow us to adapt management.

By going through the resilience assessment process, you can:

1. Examine spatial variation in resilience indicators, resilience scores, and anthropogenic stress.
2. Identify which indicators most account for differences in resilience among sites.
3. Identify sites that have coral communities likely to be more resilient to climate change and other human stressors
4. Examine the extent to which reefs with high or low resilience are represented within the various use zones of an existing MPA or MPA network.
5. Identify and prioritize management actions or strategies that will reduce stress at the greatest number of sites, at high resilience sites, and/or at sites that are conservation priorities for other reasons, such as climate refugia or sites with high biodiversity or cultural value.
6. Monitor trends in resilience indicators and resilience through time.

Resilience assessments can provide information for environmental planning and a range of management decisions, including which areas to prioritize for long-term conservation, and where to target efforts to improve water quality or reduce fishing pressure, among others. Additionally, resilience is increasingly being used as a framing concept, or overarching goal, for coral reef management, making assessing resilience centrally important to many management efforts.

Conducting a resilience assessment

A resilience assessment includes 10 sequential steps (see Figure 2).

Thoughtful design, clear pathways to decision-making, regular engagement with planning and management agencies as well as local stakeholders, and clear and accessible data and reporting products are the ingredients of a successful resilience assessment.

All resilience assessments comprise these 10 steps. The methods used and degree of investment in each step can be tailored to suit local capacity and resource constraints. Steps 2-10 follow on from the critical first step, which is deciding whether to do a resilience assessment. Deciding involves identifying pathways of influence and characterizing benefits, and then planning your assessment and making the case to others, including management agencies and stakeholders expected to use findings and recommendations.

Importantly, resilience assessments start by identifying the types of management actions the assessment can influence (Step 1).

The steps that follow build towards steps 9 and 10 when you will formulate management recommendations and develop and share final versions of data and reporting products.

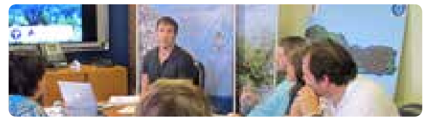
Adaptive management of coral reefs in this era of climate change means that the resilience assessment process is iterative and cyclical.

Reporting on a resilience assessment should involve identifying research gaps and which parts of the process can be strengthened (i.e., increasing confidence in data used in the assessment through better or different data collection methods). Filling of research gaps, uncovering new information (e.g., high-resolution connectivity data or new climate model projections) or identifying new decision-making processes or opportunities (e.g., revision of existing MPAs) are all reasons to conduct another resilience assessment. The resilience assessment process is summarized within Figure 2 on p 8. The circle from Step 1 back to Step 1 reflects the possibility you may conclude 'Not now' when evaluating whether a resilience assessment is right for you. We recommend that you keep open the option to re-visit that decision later (e.g., when new data becomes available indicating changes in exposure to impacts, or a new opportunity to influence a management decision arises).

Not now

1. Decide whether to do a resilience assessment, identify pathways of influence, and plan

- What decision(s) can the assessment inform?
- What management processes or agencies are end users of the assessment findings?
- What resources and capacity will you need?
- Need to plan for: clear pathways to decision uptake, meaningful and regular manager partner and stakeholder engagement, clear and accessible data and reporting products



2. Select resilience indicators and anthropogenic stressors

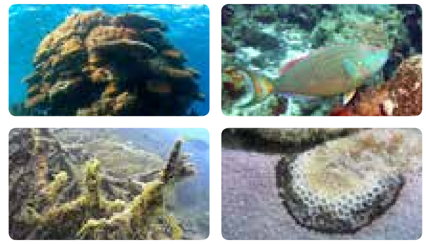
Resilience indicators:

1. *Resistant coral species
2. *Coral diversity
3. *Herbivore biomass
4. *Coral disease
5. *Macroalgae cover
6. *Recruitment
7. Temperature variability
8. Herbivore diversity
9. Habitat/structural complexity
10. Mature colonies
11. Light (stress)
12. Coral size-class distribution
13. Substrate suitability

Anthropogenic stressors:

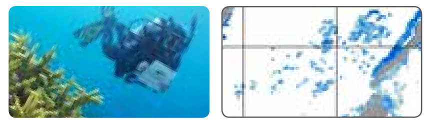
1. Nutrients (pollution)
2. Sedimentation
3. Physical human impacts
4. Fishing pressure

At least 6 indicators; include all relevant stressors. Ideally, selected indicators will be of roughly equal importance and then equally weighted in assessment.



3. Collect or compile data for resilience indicators

- Indicators are measured quantitatively
- Survey sites using standard methods at all sites
- Access remote sensing and reef monitoring data as required
- Compile existing data if available from the last 3 years and sites undisturbed



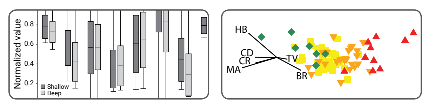
4. Analyze data

Eight steps: (1) normalize data to 0-1 scale, (2) make scale uni-directional (high score = high resilience), (3) optional – weight indicators, (4) average indicator scores for each site, (5) normalize average scores, (6) rank sites from high to low resilience, (7) categorize sites (low to high) based on resilience scores, (8) categorize individual indicator scores from low to high for each site.

Island Rank	Overall Rank	Final RS	Raw RS	MA	BR	CR	CD	TV	HB
1	14	1.00	0.88	1.00	0.74	1.00	1.00	[illegible]	0.11
2	16	0.99	0.87	0.99	0.72	0.89	0.94	0.89	0.22
3	8	0.98	0.87	0.94	0.85	0.64	0.92	0.89	0.40
4	31	0.95	0.84	1.00	0.73	0.58	0.95	[illegible]	0.45
5	45	0.93	0.83	0.80	0.71	0.37	0.89	0.86	1.00

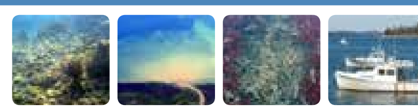
5. Identify key drivers of differences in resilience scores

- Highly variable indicators have greater influence on resilience score differences
- Optional — multivariate analyses can be used to identify indicators strongly associated with high and low resilience.



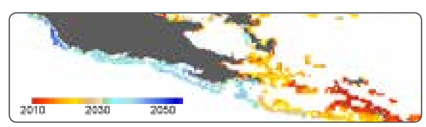
6. Assess anthropogenic stress

- Stressors can be measured quantitatively or assessed qualitatively in the field or using monitoring data
- Proxies can be useful; e.g., distance to pollutant sources for water quality
- High scores = high stress



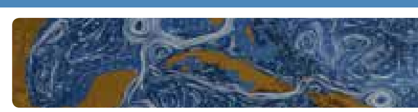
7. Review climate exposure information

- High-resolution (4-km) climate model projections of bleaching frequency are now publicly accessible and can vary greatly over local scales.
- Resilience and exposure data can readily be combined to produce a vulnerability assessment
- Priority sites will be those that are relative climate refugia (i.e., projected to experience annual severe bleaching >10 years later than other sites in your area)



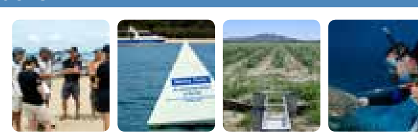
8. Review connectivity information

- Connectivity information can be used to interpret assessment results and help identify priority targets for management actions
- Priority sites will be those that are relatively greater sources and not weak sinks



9. Formulate management recommendations

- Meet with manager partners and stakeholders
- Recommendations may relate to Marine Protected Area zoning or targeted reduction of stress through other sectoral actions
- Priority sites have higher relative resilience, or lower relative vulnerability, are greater relative sources of fish and coral larvae and not weak sinks, and are exposed to a manageable anthropogenic stress



10. Provide data and share results

- Ongoing effort during assessment process
- Products tailored to target audience and able to support all intended uses
- Broad communication can increase compliance and promote stewardship
- Should identify research gaps and parts of assessment with room for improvement

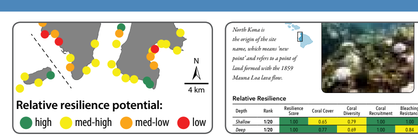


Figure 2. Resilience assessment framework.

1 Decide whether to do a resilience assessment, identify pathways of influence, and develop a plan

- *The decision step involves identifying pathways of influence, characterizing the benefits the assessment may bring, drafting an assessment plan, and making the case to others*
- *Identify the management or policy decisions a resilience assessment can inform, and the entities that can act on recommendations from the assessment*
- *Design your assessment plan by defining the spatial area of interest, planning how you will conduct each step in the process and estimating the resources and capacity required*
- *Your plan will include regular consultation with end-users and stakeholders to ensure a clear path for uptake of the results in decision-making processes.*

1. Identifying pathways of influence and characterizing benefits – You first have to determine whether and how coral reefs and reef-dependent industries and community members will benefit both from assessment findings and the eventual management outcomes. On p 33 we identify some ways resilience assessments findings are relevant to management decisions. Could management of coral reefs in your area benefit from any of that information; i.e., knowing which sites are likely to be more resilient to climate change? Answering this question will require identifying what decision processes the assessment may influence as well as the management authorities or stakeholders that can act on assessment findings. Are there obvious upcoming opportunities for resilience assessment results to inform decision-making, such as establishment, revision or review of a MPA network? Is a marine spatial planning process planned that can include reef resilience as a consideration? What institutions have a mandate to take actions that can reduce pressure on coral reefs? Perhaps there is a management plan that already includes addressing water quality and/or fishing pressure – in this case resilience to climate change information can be used to target planned actions to reduce these stressors. Has a recent coral bleaching event or other disturbance caused coral reefs to receive an increase in attention by the media or policymakers, and a greater demand for action?

Attention following bleaching events or other disturbances can arouse interest in resilience assessments. This is an action-oriented process that has managers and stakeholders proactively collaborating to address climate change, and can help overcome feelings of helplessness.

Having put thought to how findings of a resilience assessment can be used to strengthen reef management and the way reefs and people could benefit, you will be ready to draft an assessment plan that can deliver those benefits.

2. Drafting an assessment plan – Like any project or management activity, resilience assessments should be designed to address clear objectives, have a well-defined scope and a clear vision for desired outcomes.

Having determined what management decisions COULD be informed by a resilience assessment, you now need to design the assessment so that it DOES inform those decisions.

You will need to determine the optimal timing for starting the assessment, define the spatial area of the assessment, determine whether and how data will be collected or compiled, and identify the types and nature of desired data and reporting products. In defining the spatial area, take a moment to consider whether resilience to climate change is likely to vary among reefs within this area. Homogeneity among all of the recommended resilience indicators is highly unlikely if your area of interest is larger than a few km. However, if you have reason to believe resilience indicators do not vary in your area of interest, consider that parts of the resilience assessment process may still be relevant to management planning in your area. You may decide to only conduct steps 7-10, whereby management recommendations are formulated based on reviews of climate change exposure information (see Box 3, p 30 on publicly accessible high-resolution (4-km) coral bleaching projections) and/or connectivity information.

You will need to consider all of the remaining 9 steps in the resilience assessment process; these steps can serve as a template for the design of your resilience assessment. How will you conduct each step? What resources, expertise and capacity are available for the assessment and what resources, expertise and capacity will you need for each step? In thinking about the Steps, consider whether you should conduct Steps 7 and 8 prior to Step 2; i.e., understanding climate exposure and connectivity patterns may lead to insights that determine whether you do a resilience assessment and, if you proceed, how you determine where to sample, and how intensively. This suggestion is especially relevant to those working in large reef systems, such as the Great Barrier Reef in Australia.

Capacity requirements include diving and snorkeling, managing and analyzing quantitative data and qualitative observations, spatial data storage and visualization, graphic design, and written and verbal communication skills.

Regular engagement with management agencies and other stakeholders is another design consideration. Who will be involved and when and how will they collaborate, provide input on assessment outputs, and influence outcomes?

All entities that could act on recommendations that result from a resilience assessment are stakeholders as are all those expected to comply with any resultant management actions. This means local and regional management authorities, conservation organizations, industries that use or benefit from reefs and the services that reefs provide, and all other reef users are potential stakeholders.

All stakeholders expected to act on recommendations or comply with resultant actions should be engaged early and regularly through the resilience assessment process.

Stakeholders can help design the resilience assessment by assisting in the selection of indicators or survey sites. Then, a collaborative approach to discussing and selecting assessment methods can help ensure that stakeholders understand and have interest in data collection. From that point, stakeholders can help interpret results, identify and prioritize from among management actions, and provide input to how results are communicated and disseminated.

Your resilience assessment can be tailored to your resource constraints and capacity. However, there are a number of resources designed to support reef managers in conducting resilience assessments.

The Nature Conservancy's Reef Resilience Network and Toolkit provide access to online tools, case studies of resilience assessments, and guidance for implementation.

Online webinars and discussion forums can help you find answers to questions and collaborate with or be mentored by global experts that have conducted resilience assessments (see Additional Resources section for more detail).

Remember that the key is for the assessment to inform the management decisions you have identified. You need to ensure your plan creates a pathway to uptake of the results and the making of those intended decisions. If conducting the assessment with locally available resources and capacity does not enable you to utilize the identified influence pathways, you can explore partnerships with other relevant organizations and/or apply for grant funding.

3. Making the case to others — You should clearly document both the expected benefits of a resilience assessment and how your design or plan ensures the assessment can deliver those intended benefits. You will then be ready to 'make the case' for conducting a resilience assessment to superiors, funders and end-users. This may take place through regular meetings or a workshop specifically for this purpose.

The most important part of making the case to others involves clearly explaining how the resilience assessment process can inform management decisions and that the process will be responsive to end user needs.

We recommend that you use specific examples of the management actions and policies a resilience assessment will inform as this will help generate the momentum to get started. By being responsive to feedback from intended end users of resilience assessment findings you also increase their ownership of assessment findings and the likelihood that recommendations will be turned into management or policy actions.

Assuming you decide to conduct the resilience assessment process, the next step is to select the resilience indicators and anthropogenic stressors you will assess.

2 Select resilience indicators and anthropogenic stressors

- *Resilience indicators provide an indication of the likelihood the site can resist and recover from disturbances, especially coral bleaching*
- *13 indicators and 4 stressors are recommended for use in resilience assessments*
- *At least 6 of the 13 indicators and all relevant stressors should be included*
- *The 6 essential indicators are: Resistant coral species, Coral diversity, Herbivore biomass, Coral disease, Macroalgae cover, Recruitment*
- *Additional indicators can be selected if deemed to be as important to resistance and recovery as the 6 considered essential*

Your resilience assessment will involve measuring or assessing ecological factors that contribute to resistance and recovery (e.g., bleaching-resistant coral species and coral recruitment) and anthropogenic stressors that reduce resilience.

Ecological factors that contribute to resistance and recovery are called resilience indicators.

Recommended resilience indicators and anthropogenic stressors

Reef scientists and managers have collaborated to identify and prioritize resilience indicators and anthropogenic stressors (McClanahan et al. 2012). This effort identified indicators for which there is strong evidence of a link to the capacity of corals or a coral community to resist impacts or recover from disturbances. Thirty indicators were rated with respect to perceived importance, strength of scientific evidence and feasibility of assessment/ measurement. Complementary research by Graham et al. (2015) added evidence to the importance of structural complexity (and depth) in understanding recovery after bleaching events in the Seychelles.

Based on these studies and experiences from past resilience assessments, we recommend 13 resilience indicators and 4 anthropogenic stressors for consideration in your resilience assessment.

Recommended resilience indicators and anthropogenic stressors are ranked in our list from highest to lowest perceived importance to resilience (following McClanahan et al. 2012). The first six (*) are considered essential and will be important to include in nearly all resilience assessments. See Table 1 for descriptions of these indicators and stressors along with common units.

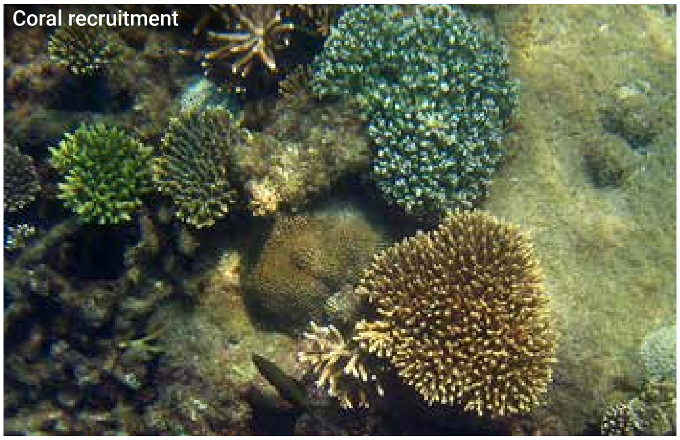
Resilience indicators:

1. *Resistant coral species
2. *Coral diversity
3. *Herbivore biomass
4. *Coral disease
5. *Macroalgae cover
6. *Recruitment
7. Temperature variability
8. Herbivore diversity
9. Habitat/structural complexity
10. Mature colonies
11. Light (stress)
12. Coral size-class distribution
13. Substrate suitability

Anthropogenic stressors:

1. Nutrients (pollution)
2. Sedimentation
3. Physical human impacts
4. Fishing pressure


Herbivore biomass


Coral recruitment


Nutrients


Sedimentation


Physical impacts


Fishing pressure

Selecting indicators

As many of the anthropogenic stressors should be measured or assessed as makes sense given the local context (i.e., given which of the four stressors affect reef resilience in your area). While determining which stressors need to be assessed is likely to be straightforward, selecting ecological resilience indicators is more challenging (see case study examples from assessing resilience in the U.S. Virgin Islands, Northern Mariana Islands and Mozambique). Therefore, we offer the following guidance.

Six priority ecological resilience indicators should be included in any resilience assessment (those with an asterisk in the list on p 15). These have been found to be the most important predictors of resilience, and also the most useful for discerning differences in resilience among sites. Temperature variability can also be very important. As temperature data are available at 4-km resolution for all coral reef areas from NOAA remote sensing archives, we suggest including temperature variability in assessments (Heron et al. 2016). However, this indicator may not vary significantly within your area of interest (especially if your assessment spans 20 km^2 or less); in these cases you can exclude that indicator. Selecting additional indicators requires asking yourself whether any other indicators in the list are likely to be as important for resistance and resilience as the 6 considered essential. If this is the case, those indicators can be added as long as they can be reliably measured or assessed within available expertise and resources.

At this point, it is important to understand that including as many indicators as possible is not the goal. The total number of indicators included in an assessment will affect the power that each indicator has to determine differences among sites in resilience; i.e., the importance of each individual indicator is diluted with each additional indicator included. Note that you can include more indicators, and can include indicators that you feel are important but much less so than other indicators you are including and can then weight the indicators based on their relative importance. Weighting approaches are reviewed in Box 1 on p 24. You are likely to find the assessment process easier if you select only indicators you deem to be of roughly equal importance – i.e., strength of links to resistance and recovery in your area – and then equally weight them.

3 Collect or compile data for resilience indicators

- → *Planned use of the results drives the spatial extent of the assessment*
- → *Sampling intensity needs to capture spatial variation in indicators*
- → *You may use existing data less than 3 years old provided you do not mix data from both before and after a major disturbance*
- → *Consistent, or at least comparable, methods should be used for each indicator and stressor at all survey sites*
- → *Resilience indicators and stressors are considered separately in the assessment*
- → *Quantitative data are collected or compiled for resilience indicators*
- → *Quantitative **or** qualitative data are collected or compiled for anthropogenic stressors*

The desired spatial extent of the assessment is the key first consideration in determining your data collection/compilation strategy.

The desired spatial extent of the assessment should be driven by your planned use(s) of the resilience assessment results. Spatial extent and sampling intensity may both be greater if planning a new MPA or MPA network than if, for example, you want to determine the relative resilience of sites within a small area adjacent to a proposed coastal development (see case study examples from Indonesia and Palau). In either case, sites should be surveyed across the entire area over which you want to conduct the assessment. A sufficient number of sites should be surveyed to capture spatial variation over the sampling area in the resilience indicators you choose to include. More sites will need to be surveyed where benthic and fish communities are more variable. Fewer sites can be surveyed in areas that have lower benthic and fish community variability. The resilience assessment approach described here can be used at both small and large spatial scales. Where assessments are conducted over large areas, there may be large gaps between survey sites; there may be anthropogenic stress, climate or connectivity information (Steps 6, 7 and 8) for these areas that can be used to formulate management recommendations (Step 9). This highlights that for large reef areas, different parts of the area may have different combinations of information from which you can formulate recommendations.

You may use existing data or may need to collect new data for all or some of the indicators that you select. For this reason, your sampling strategy may be determined wholly or partially by your local regular monitoring program. You may conduct your assessment including only those sites regularly surveyed or may supplement by adding sites to increase spatial coverage. Examples of resilience assessment results are shown in Figure 3 on p 23 from data collected specifically for an assessment (a) and from data compiled from a long-term monitoring program (b).

It is recommended that all data used be fairly recent (within 3 years) and be considered to be, to the best of your knowledge, representative of the current spatial variation in the various indicators.

In determining the age of the data you allow to be included, you will need to consider whether disturbances occurred recently. For example, if conducting an assessment in 2016 and a severe disturbance, such as a cyclone or major bleaching event, occurred in early 2015, you should include data from 2016 and late 2015 but not from 2014 or early 2015.

It is key that the methods for collecting the data for each resilience indicator are standardized across all sites surveyed, or at least that they are comparable. It is also essential that the methods for the resilience indicators are quantitative rather than qualitative. Resilience is assessed using the resilience indicators only.

In the analysis, ecological indicators of resilience are separated from anthropogenic stressors that reduce reef resilience.

Given the separation of ecological resilience indicators from anthropogenic stressors, the stressors can be assessed either quantitatively or qualitatively. Further, several of the stressors may be assessed via useful proxies, defined by local conditions and knowledge. For example, site accessibility based on average wave height can be used in some areas as a proxy for fishing pressure (e.g., Maynard et al. 2015).

Many methods exist for assessing or measuring the indicators we recommend here. Management agencies or research institutions working in your area are likely to have a standard suite of methods for monitoring coral reef benthic and fish communities. We do not recommend any specific set of methods, but present a suite of possible methods in Table 1 on p 19. The GCRMN publication *Methods for Ecological Monitoring of Coral Reefs: A Resource for Managers* provides detailed descriptions of popularly used survey methods for all of the recommended resilience indicators. There may also be regionally established protocols and recommended standards, such as in the Caribbean.

Table 1. A description of the recommended resilience indicators, along with common units, and a list of potential field methods.

Resilience indicators	Description	Possible methods	Common units
Resistant coral species	Proportion of the reef-building coral community made up by species that have demonstrated or are thought to be relatively resistant to thermal coral bleaching (Marshall and Baird 2000; McClanahan et al. 2004).	Timed swims, quadrats, belt transects, point-intercept transects	% of community
Coral diversity	A quantitative measure that reflects how many different coral species there are in a dataset, while simultaneously taking into account how evenly the species are distributed. Common indices express the probability that two species selected at random from a community will be different.	Indices: Shannon or Simpson's Index	Unitless
Herbivore biomass	Weight per unit area of herbivorous fish and invertebrates. Can be inclusive of all major herbivore functional groups (scrapers, grazers, excavators, browsers) or can separate these.	Timed swims, belt transects, stationary point counts	$kg/100m^2$, g/m^2
Coral disease	Proportion of the coral community that is affected by diseases. You may choose to use a 'total prevalence', which combines all diseases and all corals, or a subset of diseases or corals to assess effects from a particular disease or on a particular coral.	Belt transects	% (of colonies affected; a 'total prevalence'; i.e., all or a subset of diseases combined)
Recruitment	Abundance and density of recently settled corals that are less than 2 years old.	Quadrats	$\#/m^2$
Temperature variability	Variability of temperatures during the warm season. Higher variability has been associated with bleaching resistance.	Remotely sensed, available for all coral reefs at 4-km resolution from NOAA remote sensing archives	Unitless
Herbivore diversity	See 'coral diversity' description; same for herbivorous fish and invertebrates. Can also be assessed as the number of key herbivore functional groups present at a minimum abundance (e.g., scrapers, grazers, browsers and excavators).	Timed swims, belt transects, stationary point counts	Unitless (diversity indices), or number present at a minimum abundance
Habitat/structural complexity	Three-dimensionality of the substrate and crack and crevice depth and diversity. Ratio of reef surface contour distance to linear distance.	Chain over substrate	m
Habitat/structural complexity	Three-dimensionality of the substrate and crack and crevice depth and diversity. Ratio of reef surface contour distance to a standard linear distance (often 3 m).	Chain over substrate	m
Mature colonies	Proportion of the benthic community made up by long-lived corals (i.e., >10 years old).	Timed swims, belt transects, stationary point counts	% of community
Light (stress)	Amount of light per square meter reaching the substrate during typical oceanographic conditions during the warm season.	Requires instrumentation	$watts/cm^2$
Coral size-class distribution	Evenness of corals within a range of size classes that includes recruits and mature colonies.	Timed swims, quadrats, belt transects, point-intercept transects	Unitless
Substrate suitability	Ratio expressing available substrate for coral recruits as being suitable and unsuitable for coral settlement.	Timed swims, quadrats, belt transects, point-intercept transects	Unitless

4 Analyze data

The resilience assessment analysis examines differences in resilience potential (estimated by your resilience indicators) by comparing all sites included in the assessment.

Resilience is assessed relative to other sites included in the assessment.

Managers or collaborating scientists may want to analyze relative resilience to compare resilience among sites considered for protection, specific stress reduction measures or to monitor changes in resilience through time. The 'relative resilience score' can be calculated to give us this information. The process for calculating relative resilience scores is provided in the 8 steps below.

Calculate a Relative Resilience Score

Calculating the relative resilience scores involves 8 steps.

1 – All scores for resilience indicators are normalized to a scale of 0-1.

2 – All scales are made uni-directional, where a high score means high resilience.

3 – (Optional) If weighting indicators, scores are multiplied by a weighting or 'scaling' factor.

4 – Scores are averaged to produce a raw resilience score.

5 – Average scores are normalized to a scale of 0-1.

6 – Sites are ranked from highest to lowest score.

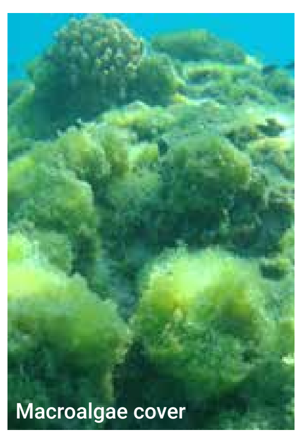
7 – Sites are categorized into relative 'low' to 'high' classes.

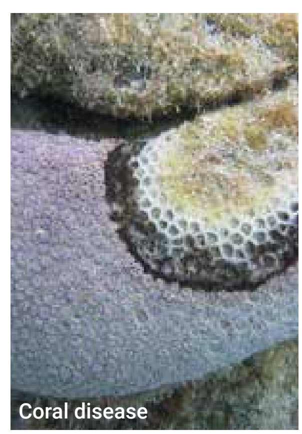
8 – Scores for indicators are categorized into relative 'low' to 'high' classes.

An MS Excel-based tutorial is available with data tables that show each of these steps (see "Additional resources on p 43).

1 — Since resilience indicators are assessed using different units (e.g., g/m^2, %, #/m^2, etc.) and scales (i.e., they have different maximum values), the values for all indicators must be converted into a standard scale using a process called normalizing. To normalize the data, the values for each indicator are divided by the maximum value for the indicator.

Example: If the maximum bleaching resistance value is 64%, then a site with 64% receives a 1 (because 64 divided by 64 is 1) and a site with 60% receives a 0.94 (60 divided by 64); all sites with zeros would receive a zero (zero divided by any number is zero).


Macroalgae cover


Coral disease

2 — For most of the resilience indicators (e.g., resistant coral species, coral diversity, herbivore biomass), a high value indicates greater resilience. However, a high value for some of the resilience indicators suggests reduced resilience (e.g., presence of macroalgae and coral disease). We want to ensure that our scale is uni-directional and that a high score always means higher relative resilience (what we are aiming for from a management perspective). To address this, the scores for macroalgae and coral disease (if included in the assessment) are subtracted from 1.

3 — You then must decide whether the indicators will be equally weighted; i.e., whether they are of equal or near-equal importance to resistance and recovery processes. If so, you would move to Step 4 and do nothing at Step 3. If you are weighting the indicators, the normalized uni-directional scores are multiplied by a weighting factor (mathematically, this is a ‘scaling factor’). Box 1 on p 24 discusses weighting rationale, approaches, and pitfalls.

4 —The normalized, uni-directional (and weighted, if you chose to) scores for the indicators for each survey site are averaged to produce the raw resilience score for each site.

5 — The raw resilience scores are normalized by dividing by the maximum score. The end result is a score for each site that is on a standard 0-1 scale. The final resilience score or value is 1 for the site(s) with the highest relative resilience and for all others a decimal value (e.g., 0.73) between 0 and 1. This expresses the ‘assessed resilience’ of all sites relative to the site with the highest resilience. The higher the score, the higher the relative resilience.

6 — Sites are then ranked from highest to lowest score (see Table 2).

7 — Sites can be categorized into relative classes for resilience, such as low, medium-low, medium-high, and high, following calculating the average and standard deviation of the final normalized resilience scores. These classes can be set as follows where avg = average and sd = standard deviation:

- low (<avg-1sd)
- medium-low (>avg-1sd and <avg)
- medium-high (>avg and <avg+1sd)
- high (>avg+1sd)

In recent case studies, these four classes were used in combination with the colors red (low), orange (medium-low), yellow (medium-high) and green (high), respectively, to aid in visualizing and interpreting the resilience assessment results in tables and maps (see Table 2).

8 — The normalized scores for the individual resilience indicators can be categorized into relative classes. Such classification, in combination with colors (as described above), as shown in tables (Table 2 on p 22) and maps (Figure 3 on p 23) can help with comparing assessment results among sites; i.e., answering questions, such as: which resilience indicators does this high resilience site have medium-high or high scores for? An example table and map of results from the resilience assessment in the Commonwealth of the Northern Mariana Islands are shown as Table 2 and Figure 3. You may find that a resilience indicator hardly varies among the survey sites and all, or almost all, indicators have similar scores or are categorized into the same relative class. Relatively homogeneous indicators have little to no bearing on the assessment results. This is because indicators with low variance do little to distinguish sites from one another (see more details in the next section). You should retain this indicator in your assessment and present those results since the indicator is thought to be important (i.e., you decided that in the indicator selection process). Collaborating managers and scientists and stakeholders may be interested in those results.

An MS Excel-based tutorial is available with data tables that show each of the 8 steps, excepting step 3 as indicators are equally weighted in the tutorial example (See “Additional resources on p 43).

Table 2. Example resilience assessment table from an intra-island analysis at Rota in the Commonwealth of the Northern Mariana Islands (CNMI). Tables similar to that presented here provide a snapshot of the assessment results. Viewers can quickly see and understand relative classifications for the resilience indicators, for example, for the high or low resilience sites. Colored cells denote low-high relative classifications (green –high, yellow – medium-high, orange – medium-low, and red – low; reversed for stressors with green – low, see Table 4). Scores shown for resilience indicators (light-grey shade) are normalized uni-directional scores (i.e., outputs after steps 1 and 2 of 8). The anthropogenic stressors shown (dark grey shade) are not included in the calculation of the resilience scores. Indicators and stressor codes are: MA – macroalgae cover, BR – bleaching resistance, CR – coral recruitment, CD – coral diversity, TV – temperature variability, HB – herbivore biomass, FA – fishing access, and NS – nutrients and sediments. Table adapted from Maynard et al. (2015).

Site Name	Island Rank	Overall Rank	Final RS	Raw RS	MA	BR	CR	CD	TV	HB	FA	NS
Haiña Point	1	14	1.00	0.88	1.00	0.74	1.00	1.00	0.78	0.21	0.14	0.95
West Harbor_MMT	2	16	0.99	0.87	0.99	0.72	0.89	0.94	0.89	0.22	0.36	0.71
As Dudo_MMT	3	8	0.98	0.87	0.94	0.85	0.64	0.92	0.89	0.40	0.00	0.67
Agatasi	4	31	0.95	0.84	1.00	0.73	0.58	0.95	0.78	0.45	0.17	0.67
Senhanom Wall	5	45	0.93	0.83	0.80	0.71	0.17	0.89	0.86	1.00	0.32	0.67
Coral Gardens_MMT	6	49	0.91	0.82	1.00	0.96	0.03	0.63	0.73	0.98	MPA	0.68
East Wedding Cake	7	39	0.90	0.81	0.96	0.82	0.11	0.89	0.89	0.59	0.33	0.70
Sunset Villa_MMT	8	53	0.89	0.79	0.75	0.64	0.78	0.91	0.92	0.18	0.27	0.73
Mochong	9	47	0.87	0.78	0.46	0.80	0.93	0.98	0.89	0.07	0.12	0.67
Coconut Village	10	51	0.86	0.78	0.63	0.76	0.50	0.98	0.92	0.29	0.22	0.70
Malilok Point	11	64	0.86	0.76	1.00	0.59	0.27	0.96	0.78	0.47	0.19	0.68
Sasanhaya_MMT	12	48	0.86	0.77	0.84	0.78	0.30	0.94	0.89	0.31	0.35	0.83
Teteto	13	67	0.84	0.74	0.94	0.53	0.47	0.88	0.92	0.23	0.23	0.68
Okgok_MMT	14	63	0.84	0.76	0.46	0.85	0.81	0.87	0.73	0.26	0.23	0.69
Honey Gardens	15	60	0.83	0.76	0.90	1.00	0.09	0.53	0.89	0.53	MPA	0.67
Iota Salvage_MMT	16	58	0.82	0.74	0.99	0.77	0.11	0.87	0.92	0.24	0.25	0.68
Harnom Point	17	68	0.80	0.73	0.45	0.78	0.37	0.87	0.86	0.48	0.31	0.67
Cave Museum_MMT	18	69	0.77	0.70	0.65	0.72	0.24	0.96	0.89	0.17	0.31	0.75
Talakhaya_MMT	19	71	0.75	0.68	0.31	0.86	0.58	0.93	0.73	0.12	0.22	0.67
Takta Sagua	20	70	0.74	0.68	0.60	0.85	0.07	0.81	0.89	0.26	MPA	0.67
South I Ch. Park	21	73	0.73	0.67	0.17	0.71	0.51	0.88	0.89	0.30	0.07	0.67
Joanne's Reef	22	72	0.71	0.66	0.71	0.80	0.00	0.77	0.89	0.22	0.33	0.73
Rota Resort_MMT	23	75	0.71	0.64	0.52	0.57	0.40	0.91	0.92	0.02	0.19	1.00
Sailigai Point	24	78	0.56	0.53	0.00	0.59	0.00	0.89	1.00	0.18	0.30	0.67

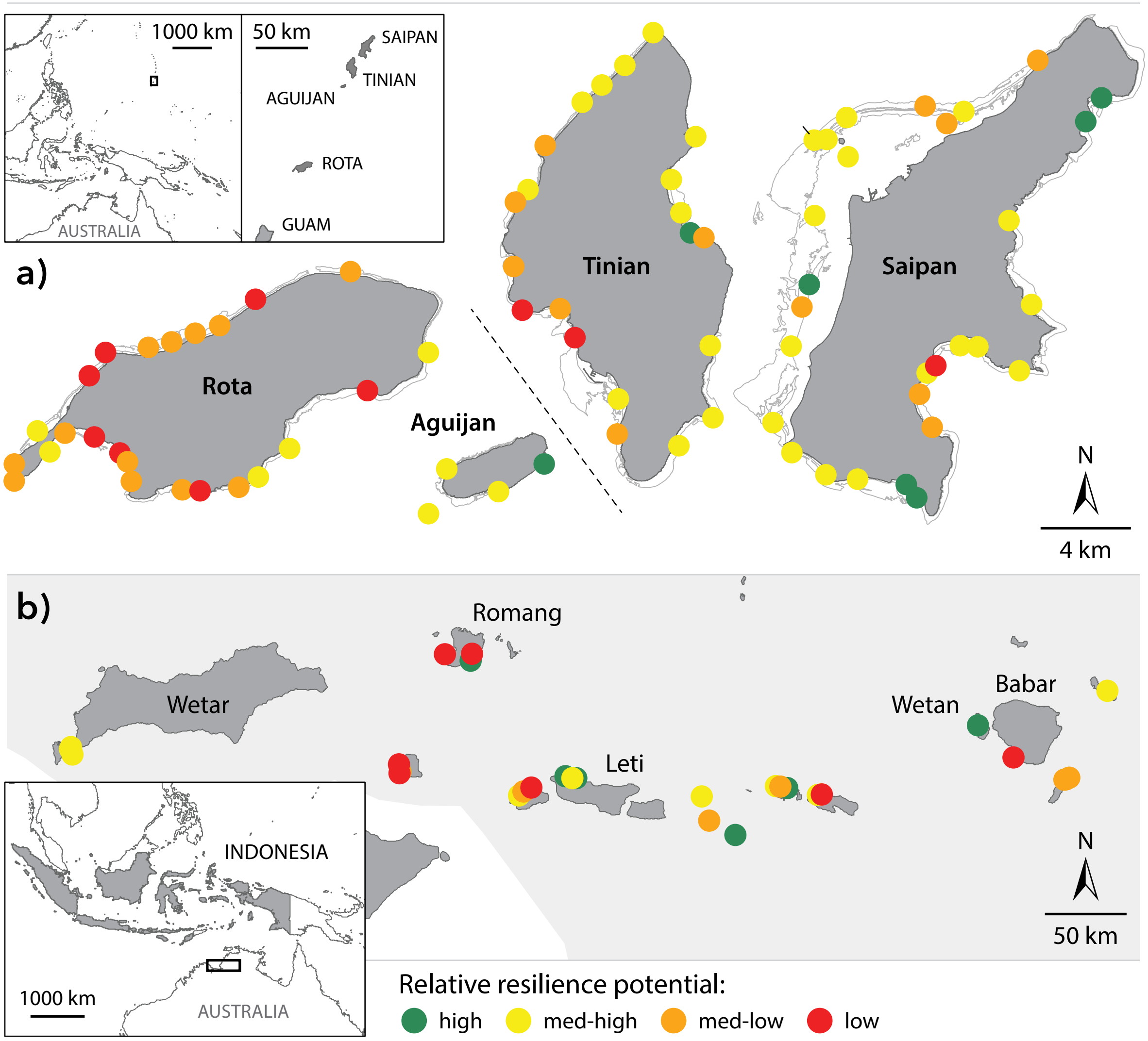


Figure 3. Example map outputs showing relative resilience for sites surveyed specifically for a resilience assessment in CNMI (a, from Maynard et al. 2015), and from data compiled from long-term monitoring (by WWF staff) at fringing reef sites in the Forgotten Islands of Indonesia (b). The normalized uni-directional scores for resilience indicators can be normalized by dividing by the maximum value for the indicator from any group of sites. Here, the 'group of sites' includes all sites surveyed at all islands. Scores can also be normalized to the values for indicators within smaller groups, such as around single islands (or in any other distinct area within a management area); see Table 2 for 'intra-island' scores and rankings for Rota.

Box 1 — Weighting indicators

Much evidence suggests that some resilience indicators have stronger links to resistance and recovery processes than others. For example, coral diversity will be a greater predictor of whether a coral community will resist and/or recover from disturbance than coral size-class distribution. We suggest the following three options to resolve indicator weighting. The first describes our recommendation of equally weighting indicators, which we also described in the section on selecting indicators, p 16. Two other approaches are described for consideration if you are interested in using differential weighting; these have equal merit, though the literature review method will be less resource-intensive.

Recommended – Equal weighting: During indicator selection, you select only those indicators considered in your area to be strong indicators of resistance or recovery potential. You may suspect some selected indicators are stronger indicators than others but may feel evidence is lacking either to support that suspicion or to enable you to quantify differences in relative importance.

For consideration – For both differential weighting options described below, the normalized uni-directional indicator scores (output of steps 1 and 2 of 8 in section above) are then multiplied by the weighting factors (or 'scaling factors') you calculate when deciding weighting.

Review literature – Combined perceived importance scores for the recommended indicators from McClanahan et al. (2012) (and other recognized articles that may be available) can be compared for indicators you select. For example, the perceived importance (to resilience) score for coral diversity is 12.43 and for coral size-class distribution is 10.08. 12.43 divided by 10.08 = 1.23 meaning that, according to this study, coral diversity is 1.23 times more important for resistance and recovery processes than coral size-class distribution is (see methods in Maynard et al. 2015).

Generate consensus view – You could survey close colleagues or experts involved in your assessment and/or a broader group, asking: which indicator(s) is the strongest indicator of resistance and/or recovery and which indicator(s) is the weakest? Then, with that decided, how much stronger of a resilience indicator is the strongest indicator than the weakest? The second question will give you your maximum multiplicative factor. You can then rank the other indicators and set out their multiplicative factors as between 1 and the highest multiplier you decided on (see Maynard et al. 2010). Keep in mind in deciding to weight the indicators that assessments of relative importance of resilience indicators are likely to be highly subjective. Further, views are likely to differ meaning it may be hard to reach a consensus.

5 Identify key drivers of differences in resilience scores

- → *Some indicators have greater and some lesser influence on resilience scores*
- → *If indicators are equally weighted, highly variable indicators have greater influence on differences in resilience scores*
- → *High variability indicators should be monitored regularly*
- → *Multivariate analyses can be used to determine which indicators are most strongly associated with high and low resilience*

A key benefit of normalizing the indicator scores is that we can examine variability in the scores on the same scale (i.e., 0-1) and undertake multivariate analyses. Such analyses help answer these questions: Which resilience indicators have greater and lesser influence on the final resilience scores? Do sites within a relative class of resilience (e.g., high resilience sites) have high scores for the same or different indicators? Do high resilience sites have high resilience for the same reasons?

Understanding which indicators vary most and which are most strongly associated with high and low resilience has multiple benefits. Managers should ensure high variability indicators are included within any regular monitoring programs.

If scores are equally weighted, the indicators with the greatest variability influence the resilience scores more than the indicators with low variability. An example is provided in Figure 4. In this case, variance in the temperature variability indicator is low. Since most sites have similar scores for that indicator, it has little influence on the final resilience rankings. In contrast, macroalgae cover varies greatly. Macroalgae cover is a greater driver of differences in resilience rankings than temperature variability. Multivariate ordination analyses can also be used to examine which indicators are driving differences in resilience across the relative resilience classifications (see Box 2 on p 26).

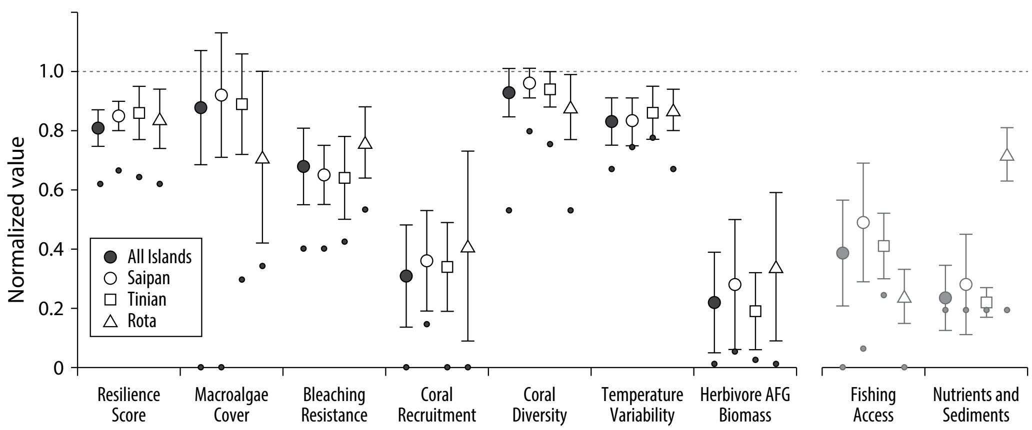
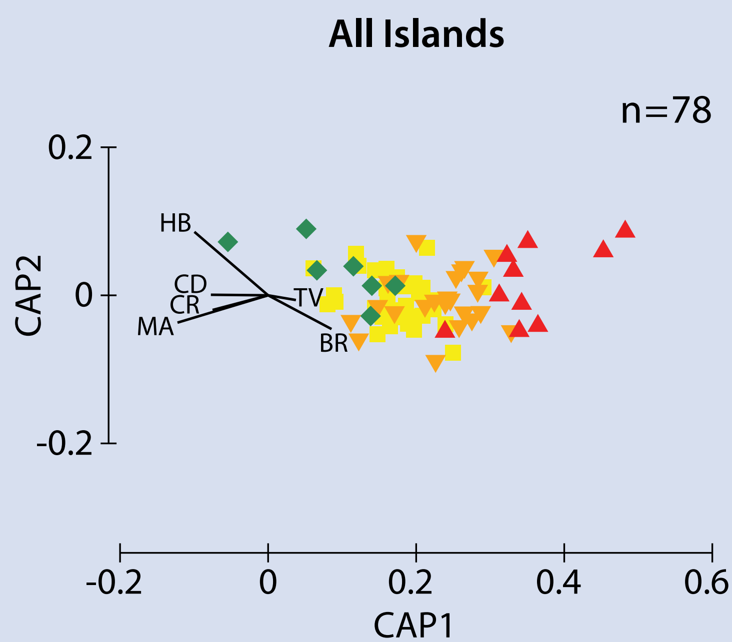


Figure 4. Distribution of normalized values for the resilience scores, indicators and anthropogenic stressors for the inter-island and intra-island analyses in CNMI (see also Figure 3). Shapes represent average values, the tails equal 1 standard deviation (sd), and the dots are the minimum values; maximum values are all 1.0 (dashed line). Relative classifications for resilience scores and resilience indicator scores are as follows: high (final scores that are >1 sd above average (avg.) and ≤ 1), medium-high (<avg.+1 sd and > avg.), medium-low (<avg. and >avg.–1 sd), and low (<avg.–1 sd). The range in scores meant that there are all four classifications among the survey sites in CNMI for 5 of 7 indicators. For macroalgae cover and coral diversity the value of the average+1 sd exceeds the maximum possible value of 1 so no sites are described as being relatively 'high' (macroalgae cover has been inversed so high scores mean low cover – see 2 in Section 4). Figure from Maynard et al. (2015).

Box 2 – Multivariate analyses

A canonical analysis of principal coordinates (CAP, Anderson and Willis, 2003) has been used in recent resilience assessments. The CAP results explain which resilience indicators are the biggest drivers of differences among sites in final resilience scores, and which resilience indicators are most strongly associated with high and low resilience sites.
For the stats-savvy, the CAP is based on Bray-Curtis similarity matrices where variables ('resilience indicators' in this case) that might be responsible for group differences are investigated by calculating the Spearman-rank correlations of canonical ordination axes (with the original variables). Users of the software package R can undertake a CAP analysis using the 'CAPdiscrim' functions found in the package 'Biodiversity R' (available at github). An example CAP output is shown below for the All-islands comparisons in the CNMI resilience assessment (Maynard et al. 2015; analyses conducted by GJ Williams).



Canonical analysis of principal coordinates showing the relative contribution of six resilience indicators (overlaid as vectors, codes are: HB – herbivore biomass, CD – coral diversity, CR – coral recruitment, MA – macroalgae cover, TV – temperature variability, BR – bleaching resistance) to the overall resilience of reef sites for the CNMI inter-island analysis, presented in Figure 3. Stats Notes - Squared canonical correlation values (δ^2) of the first and second ordination axes are 0.603 and 0.112 for all islands. These correlation values represent the amount of variation, as a proportion, in the dataset that each CAP explains; the axes are not fully independent, which is why the value exceeds 1 when the two are added. The CAP results indicate that high resilience sites generally had high values for herbivore AFG biomass, coral recruitment and coral diversity and low macroalgae cover; the opposite is true for sites with medium-low or low resilience. Figure adapted from Maynard et al. (2015).

6 Assess anthropogenic stress

→ *Anthropogenic stressors particularly important in a resilience assessment are nutrient pollution, sedimentation, physical human impacts and fishing pressure*

→ *Stressors can be assessed quantitatively or qualitatively using field and social surveys or existing monitoring data*

→ *500 m resolution data on overfishing, marine-based pollution and damage, coastal development and watershed-based pollution are available from the World Resources Institute*

→ *High scores equal high stress*

Anthropogenic stressors (e.g., nutrient pollution, sedimentation, physical human impacts, fishing pressure) are separated from the ecological indicators because they can be directly addressed through management actions (see next section). This ensures indicators of resilience processes are separate from stressors that reduce resilience. There are four approaches you can use to develop relative classifications (low to high, as for resilience) for anthropogenic stress at your survey sites. (1) Anthropogenic stressors can be directly assessed qualitatively and/or quantitatively using field and social surveys or existing monitoring data. Examples include regular water sampling and testing for monitoring water quality, using fisheries observers and landing surveys and surveys of targeted species biomass to assess fishing pressure, or belt transects for density of anchor and fin damage. These methods can yield rigorous data but directly measuring stressors will not be possible in many areas. Alternately, you can: (2) assess or measure proxies, (3) review publicly available datasets, or (4) survey experts. It is likely that a combination of two or more of the four approaches will yield the most robust datasets for anthropogenic stress.

In many cases, measuring or assessing a proxy for the stressor, rather than the stressor directly, will be more practical. For example, understanding spatial variation in water quality (nutrients and/or sediments) requires regular water sampling as well as testing. If data from regular water quality monitoring programs are not available, you could use a proxy for water quality. Distance from river or stream outlets that are the point of release of pollutants into coastal waters is one potential proxy for water quality. Alternately, if watersheds have been mapped, sites can be classified with respect to the watersheds that influence their water quality. Then, watersheds can be assessed for the likelihood of contributing to poor water quality near reefs, based on land-use activities, terrain, and presence of rivers and streams. Proxies can also be developed for fishing pressure, such as site accessibility and distance to markets.

You can also access spatial data (500 m resolution) on anthropogenic stressors from the World Resources Institute (WRI) Reefs at Risk Revisited webpages on local threats (Burke et al. 2011). Data are available on overfishing and destructive fishing, marine-based pollution and damage, watershed-based pollution, and coastal development. In many reef areas, the WRI data will be all that is available on spatial variation in anthropogenic stress. All 500 m pixels in reef areas have been classified as low, medium, high or very high for all four stressors. You can extract these classifications for your survey sites using GIS software, such as ArcGIS. You may also be able to access spatial data for one more anthropogenic stressors from regional programs that, for example, monitor water quality or fishing pressure.

You can also consider using an expert survey to rate all your survey sites from low-high for each stressor type you want to examine and can include known local experts, such as managers, scientists or stakeholders. Such surveys can have a high degree of subjectivity. However, you can review surveys from many respondents, see where there is good agreement in levels of stress and then use meetings or a workshop to classify sites where survey respondents disagree on levels of anthropogenic stress.

A description of the four anthropogenic stressors we recommend including in your resilience assessment is provided in Table 3, along with possible methods and units.

Table 3. A description of the recommended anthropogenic stressors, along with common units, and a list of potential field methods and proxies.

Anthropogenic stressors	Description	Possible methods	Common units
Nutrients (pollution)	Concentrations of nitrogen and phosphorous or loading information.	Regular water sampling and testing, or proxies, such as distance from river and stream outlets.	ug/L or Relative.
Sedimentation	Concentrations of heavy and fine sediments or loading information.	Regular water sampling and testing, or proxies, such as distance from river and stream outlets.	ug/L or Relative.
Physical human impacts	Abundance or density of injuries to reef-building corals caused by anchoring, fins, or boat/ship groundings.	Timed swims, quadrats, belt transects, point-intercept transects, or proxies such as 'frequency of visit'.	#/m^2 or Relative
Fishing pressure	Frequency and intensity of extraction of reef and reef-associated fishes.	Timed surveys of boat trips per unit area, or social surveys, or expert judgment, or proxies such as 'accessiblity'.	Trips per day or Relative

Though separated in the analysis, it can be helpful to present scores for stressors with the scores for the resilience indicators and final resilience scores (as in Table 2). For anthropogenic stressors, it is intuitive to have high scores equal high stress; i.e., there is no need to subtract stressor scores from 1 to make high scores a 'good score' as was described in step 2 of 8 in the Calculating relative resilience scores section. We suggest sticking with the intuitive stoplight color scheme described for resilience where green is 'good'. To visualize anthropogenic stressors, relative classes and colors can be: green – low, yellow – medium-low, orange – medium-high, and red – high (see Table 4).

Table 4. Results for the site 'Agatasi' near the island of Rota in CNMI (from Appendix B for Maynard et al. 2015). The stoplight color scheme is intuitive for resilience (left) and anthropogenic stress (right), though the corresponding values change; i.e., green for resilience means high scores and high resilience, and green for stress means low scores and low stress.

Analysis	Rank	Resilience Score	Macroalgae Cover	Bleaching Resistance	Coral Recruitment	Coral Diversity	Temperature Variability	Herbivore Biomass	Accessibility (wave exposure)	LBSP
Inter-Island	**31/78**	0.83	1.00	0.73	0.31	0.95	0.72	0.27	0.17	0.19
Intra-Island	**4/24**	0.95	1.00	0.73	0.58	0.95	0.78	0.45	0.17	0.67

Low (<avg - 1 SD) Med-Low (<avg and >avg - 1 SD) Med-High (>avg and <avg+1 SD) High (>avg+1 SD)

Low Med-High
Med-Low High

7 Review climate exposure information

- *Climate model projections for acidification and bleaching are publicly accessible*
- *Globally available acidification projections are currently too coarse to be useful in resilience assessments, excepting in very large reef systems.*
- *Projections for bleaching event frequency and severity have been downscaled to 4-km*
- *Bleaching projections can vary greatly on the scales over which resilience assessments are conducted*
- *Projected exposure to bleaching can be expressed in relative terms and sites categorized into relative classes*
- *Resilience and exposure relative classes can be combined to produce a vulnerability assessment*
- *Priority sites are those that are relative climate refugia, projected to bleach >10 years later than other sites in your area*

Resilience assessments enable us to discern strong from weak sites (Game et al. 2008), with respect to ability to resist and recover from disturbances, climate-related and otherwise. We then need to assess exposure to climate-related threats to ensure that limited management resources are applied to the reefs with the best survival prospects. Reviewing climate exposure information enables us to discern lucky from unlucky sites. Sites with lower or later projected future exposure are relatively lucky and sites with higher or earlier projected future exposure are unlucky. The reefs with the best survival prospects, and hence the most likely to continue to provide goods and services, are those that are both lucky and strong.

A resilience assessment can summarize all available information on current and potential future 'exposure' to climate change and ocean acidification. Such information is available from climate model projections. These projections are now available at 4-km resolution for future frequencies of thermal stress events severe enough to cause coral bleaching and at 1° (latitude/longitude) resolution for ocean acidification. The 1°-resolution projections for ocean acidification are unlikely to be useful at the scale over which most resilience assessments are conducted, but may be useful in regional-scale exposure analyses. In contrast, the higher-resolution coral bleaching projections may be useful. The timing of projected exposure to annual severe bleaching (ASB) varies greatly within countries and territories with coral reefs and may vary at the scale over which your resilience assessment will be conducted (e.g., in the central Philippines, see Box 3 on p 30, van Hooidonk et al. 2016). If projected ASB timing varies more than 10 years within the resilience assessment area, sites projected to bleach >10 years later than other sites in your area can be considered to be climate refugia in the context of your assessment. You can categorize the survey sites into relative classes for exposure based on the average and standard deviation, as was described for resilience (see p 21). The exposure and resilience classes can then be combined, via the matrix in Figure 5, to produce a 'vulnerability to coral bleaching' classification for each of the survey sites.

Exposure \ Resilience	High	Med-High	Med-Low	Med-High
Low	Low	Med-Low	Med-Low	Med-High
Med-Low	Med-Low	Med-Low	Med-High	High
Med-High	Med-Low	Med-High	High	High
High	Med-High	High	High	High

Figure 5. Vulnerability matrix relating resilience and exposure using four relative classes for the input (resilience and exposure) and output (vulnerability). See p 21 for methods on using the average and standard deviation to categorize survey sites into the resilience and exposure classes.

Box 3 — Downscaled projections of coral bleaching conditions

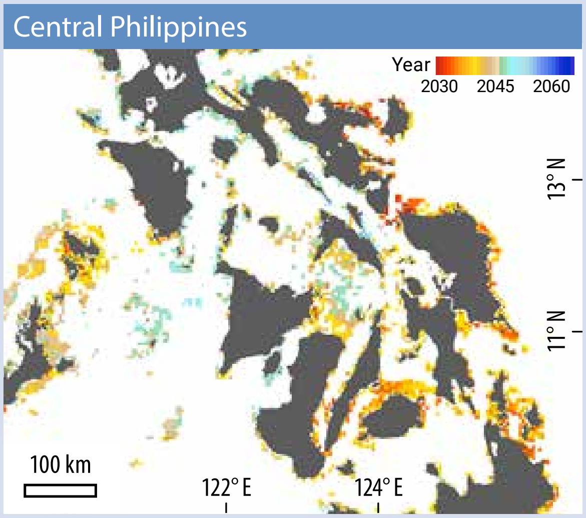
Summarized from van Hooidonk et al. (2016).

Increasingly frequent severe coral bleaching is among the greatest threats to coral reefs posed by climate change. Global climate models (GCMs) project great spatial variation in the timing of annual severe bleaching (ASB) conditions; a point at which reefs are certain to change and recovery will be limited. However, previous model-resolution projections (approximately 1x1°, van Hooidonk et al. 2013, and Maynard et al. 2015b) are too coarse to inform reef management planning. To meet the need for higher-resolution projections, we developed statistically downscaled projections (4-km resolution) for all the world's coral reefs using the newest generation of IPCC climate models (CMIP5). Methods for developing these projections are within the publications listed above.

Under a business-as-usual scenario (RCP8.5), ASB is projected to occur within this century for 99% of the world's coral reefs. The average projected year of ASB is 2043.

The downscaled projections can inform management decision-making where variation in projected ASB timing is more than 10 years between locations. Projected exposure to bleaching conditions is sufficiently different among these locations to potentially be a driver of differences in relative climate change vulnerability. Reefs projected to experience ASB 10 or more years later than other reefs in the same jurisdiction are relative refugia and are conservation priorities (i.e., these have lower relative exposure). The range in projected ASB timing is more than 10 years in 82% (71 of 87) of the countries and territories with at least 500 km² of coral reef.

The projections have been made publicly accessible via the Coral Reef Theme on UNEP-Live and under Research Activities on the NOAA Coral Reef Watch website. On both websites the projections are available as large image files, as *.kmz files viewable through Google Earth, and as a spatial data layer package that can be opened in ArcGIS versions 10 and above. 'About' pages on the websites describe the project background, methods and main findings, and provide an overview of applications.



Example of spatial variation in the downscaled projections for the onset of annual severe bleaching under RCP8.5. Reef areas in turquoise and blue are relative climate refugia that represent conservation priorities. Figure adapted from van Hooidonk et al. (2016).

8 Review connectivity information

- *High-resolution connectivity information is not always readily available*
- *Larvae sources contribute coral and fish larvae to other reefs; sources can help reefs and the reef system recover after major disturbances*
- *Sinks are larvae destinations; sinks have potential for recovery after disturbances, if sources are healthy and continue to provide larvae*
- *All coral reef areas are sources and sinks but the extent to which they are sources and sinks can vary greatly*
- *If available, connectivity information can be used to determine the extent to which each site is a larvae source or sink*
- *Priority sites are relatively greater sources that are not weak sinks*

Connectivity refers to the extent to which populations are linked by the exchange of eggs, larval recruits, juveniles or adults. It also refers to the ecological linkages associated with adjacent and distant habitats. Ecological connectivity among habitats (reefs, mangroves, and seagrasses) supports vital life stages of reef organisms, such as herbivores, so affects reef resilience.

Connectivity information is rarely available at the local scales over which resilience assessments are typically conducted. However, connectivity information may be available in your area, if not at the site scale then at the scale of the islands included within the assessment (as was the case for CNMI in Maynard et al. 2015).

Connectivity information typically comes from oceanographic models that examine currents and mixing patterns. The models run scenarios that calculate the number of larvae that arrived at each reef or reef area and determine where those larvae originated (Kendall and Poti 2015). The results express larvae numbers at sites or reef areas within matrices that quantify where larvae originated and their destinations. This enables us to determine the extent to which each site or reef area is a source and sink.

Larvae sources contribute coral and fish larvae to other reefs, so can help reefs and the reef system recover after major disturbances. Sinks are larvae destinations, so have potential for recovery after disturbances, if sources are healthy and continue to provide larvae. All coral reef areas are sources and sinks but the extent to which they are sources and sinks can vary greatly.

Sources are important to protect so will often be conservation priorities while sinks have greater chance of recovering and may recover faster, however this assumes sources continue to function (hence the need to conserve these). Sites that are relatively infrequent or rare destinations for larvae may struggle to recover as disturbance frequencies increase, meaning management actions may have little to no impact there.

Connectivity information, if available, is a data layer that can be considered when using resilience assessment results to formulate management recommendations, described next.

Management actions will have a greater positive influence on the ecological resilience of a reef system if implemented at sites that are relatively good sources and not weak sinks.

9 Formulate management recommendations

- *Recommendations are more likely to be implemented if made in local decision-making context*
- *Management recommendations should be developed with involvement of relevant management agencies and other stakeholders.*
- *Data layers resulting from a resilience assessment are likely to be used among many other information types in management priority setting*
- *Management recommendations may relate to MPA creation, zoning or targeted reduction of stress through other, sectoral actions as well as through multisectoral marine spatial planning*
- *The process for identifying and prioritizing target sites is the same for all action types*
- *Priority sites have higher relative resilience, or lower relative vulnerability, are greater relative sources and not weak sinks, and are exposed to a manageable anthropogenic stress*

With the resilience assessment complete, all of the following are data layers that can be included in management decision-making processes and planning: 1) resilience to climate change, 2) spatial variation in anthropogenic stress, 3) projections of future bleaching event frequency and severity, 4) vulnerability to bleaching, and 5) connectivity information (if available). At this stage, resilience assessments can involve management agencies and/or stakeholders to identify and prioritize options for management actions that will support site and system resilience. Depending on your decision-making authority, priority management actions may either be directly implemented, integrated into near or longer-term management or environmental planning, or posed to others as recommendations. Most resilience assessments will be done in collaboration with a range of management agencies and other partners to identify priority actions and recommendations.

Collaborating to identify the management recommendations may be most effective in a workshop setting. All prior steps in the resilience assessment process (1-8) can be reviewed with emphasis on sharing resultant spatial data layers as maps and tables. These data layers/maps, such as relative resilience to climate change, may be new to many, helping them to consider what actions to implement and where those actions should be targeted in a new way. In all areas, resilience assessment information will only represent a portion of the information that will be considered during marine spatial planning or when making targeted management decisions. Biodiversity, cultural values, commercial and recreational use, and presence of endangered or threatened species are all examples of other considerations (i.e., data layers) that may be available for prioritizing management options.

Increasingly, spatial planning processes use planning software, such as Marxan (Ball et al. 2009). Marxan develops spatial planning scenarios for multi-use MPAs. As examples, maximizing biodiversity within protected areas, and minimizing resource user conflict are two very popular conservation objectives during MPA planning processes. Marxan is increasingly being used to develop MPA plans that meet or partially meet those objectives while also accounting for resilience to climate change.

You will need to account for known local conservation objectives, consider trade-offs and opportunity costs (among conservation objectives), and know which entities would implement recommended actions.

Ideally, all relevant management entities are involved in the priority-setting process/workshop.

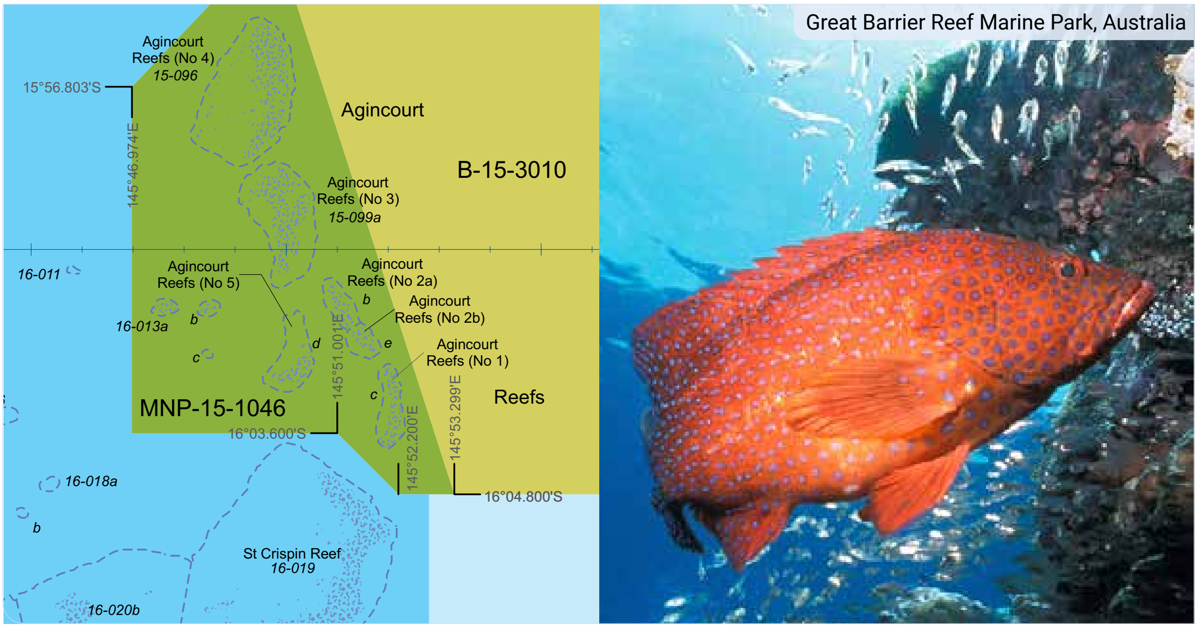
Representatives of these entities can then share how the recommendations will need to be supported or defended so that recommendations lead to decisions and, in turn, on-ground action. Resilience assessment leaders can then tailor reporting outputs (see section 10 below) to best meet the needs of decision-makers.

The recommended priority actions are the most critical output of resilience assessments.

Management recommendations that result from the resilience assessment process can either relate to: 1) including sites within MPAs or MPA networks zoned for various uses; or 2) targeting actions that reduce stressors related to human activities. Below, we provide give examples of potential management action for each of these action types and describe criteria you can use or modify to identify target sites in your management area for those actions. Essentially, the data layers that result from the resilience assessment process are 'queried' based on criteria you set to identify target sites for various management strategies. There is a focus in the example criteria provided below on the sites with medium-high and high relative resilience.

Disturbance frequencies are expected to increase in all coral reef areas in the coming decades, seriously challenging reef resilience.

Sites with higher relative resilience are more likely to continue to provide ecosystem goods and services and management actions can increase that likelihood (Mumby and Anthony 2015). Sites with lower relative resilience still warrant consideration in decision-making processes but are lesser priorities, requiring other data/information layers support their being management action targets (i.e., biodiversity, cultural values, or high use/dependence of nearby coastal communities).



Great Barrier Reef Marine Park, Australia

The management actions described below should be seen as examples rather than an exhaustive list. All five of these examples are likely to be relevant in all coral reef areas worldwide. You may have other actions that interest you. You can use the same logic and process described here for any other management actions you want the resilience assessment results to inform. Candidate sites for the action are identified using criteria for sub-set survey sites based on a combination of the five data layers that can result from the resilience assessment process.

Priority sites will typically: have higher relative resilience, or lower relative vulnerability (if you combined resilience with bleaching projections), be greater relative larvae sources and not weak sinks (if connectivity data are available), and have relatively high levels of a manageable anthropogenic stress.

Marine Protected Areas and MPA networks

Long-term conservation — You can identify sites that represent strategic priorities for conservation, either through co-management schemes or restriction of all extractive practices (i.e., no-take areas within MPAs). These conservation priority sites have high or medium-high relative resilience. These sites are more likely to resist and recover from climate and other disturbances and thus are most likely to continue to provide ecosystem goods and services in the decades ahead. A 'representation and replication' approach to risk-spreading may be used during MPA planning – the suggestion here is that the high resilience sites are more represented than the low resilience sites.

This example is aimed specifically at revisions in MPA zoning and/or development of new MPAs or MPA networks (see case study example on developing a management plan for Wakatobi National Park). If an MPA has already been established, you can determine the extent to which each relative resilience class (low – high) is represented within the various MPA zones (as in Maynard et al. 2015b). If/when zoning is reviewed scenarios can be set out and discussed that increase representation and replication of areas with greater relative resilience. If bleaching projections vary >10 years within your area of interest, you may have been able to combine resilience and exposure classes to classify sites based on their relative vulnerability (as in Figure 5 on p 29). If that is the case, everything stated here still applies, but you will be looking to include sites with lower relative vulnerability within MPAs.

Sites with greater relative resilience, climate refugia or, if you combined these, low vulnerability areas, should have greater replication within MPAs and MPA networks than low resilience sites.

If connectivity data is also available then you can prioritize from among the high resilience (or low vulnerability) sites by choosing sites that are greater relative sources and not weak sinks.

Targeting stress reduction through other (non-MPA) actions

Improve water quality – There are no global standard guidelines for critical levels of nutrients and sediments in coral reef waters, though many areas will have guidelines for acceptable levels of pollutants. Judgment will be required as to whether land-based sources of pollution (LBSP) levels at any sites in your area are sufficiently high to impact coral health.

Improving water quality will be important throughout almost every coral reef management area.

There is probably no other single type of action that can support the resilience at the greatest number of sites in areas where reefs are within a few kilometers of the coast. The resilience assessment results can aid in deciding where to undertake local or small-scale projects addressing particular problems, such as point sources of wastewater (see case study example on wastewater treatment in Bonaire). A case can also be made for reducing LBSP more broadly in watersheds. Such actions may be most urgently needed at low resilience sites. However, benefits may be greater, in terms of continued provision of ecosystem goods and services, at the Priority sites we describe above.

Sites that meet the criteria you set (be it for low or high relative resilience) that also have relatively high values for nutrient and sediment loading or concentrations are priority areas for improving water quality. Once priority sites are decided on, you can identify a range of actions to improve water quality that reflect your local context and that consider and account for the who and how of implementing those actions. As examples, recommendations could be made to: further regulate coastal development, shape or restrict beach nourishment activities, reduce or restrict fertilizer usage, reduce deforestation and other activities that lead to soil erosion, regulate or otherwise improve wastewater treatment (UN Environment 2017), and establish or re-design storm drainage routes. These are pertinent examples as they reflect that improving water quality can involve development, agriculture, and water treatment, each of which is often managed by a different agency or entity.

You should identify a range of action options and then prioritize from among those actions with collaborating managers based on what you see as best-case trade-offs between impact (on improving water quality) and feasibility.

Reduce fishing pressure – The impact of fishery management on resilience and the continued provision of ecosystem goods and services as the climate changes is likely to be greatest at sites that: 1) have medium-high or high relative resilience (or are climate refugia or, if you combined these, low relative vulnerability areas), and 2) have high fishing pressure. You may further create a sub-set from among the identified sites for sites that are greater relative sources and not weak sinks, if connectivity data is available. The key here is that actions to reduce fishing pressure on herbivorous fishes be targeted to the areas most likely to recover as climate disturbance frequencies increase. There is a large range of potential management actions that can reduce fishing pressure, including: restricting fishing in some areas (as in no-take MPAs), seasonal closures, gear restrictions, size restrictions, and quotas.

You will need to consider which action options for reducing fishing pressure exist and which from among your options are most politically and practically feasible.

As with improving water quality (see above), this is likely to involve creating a long list of action options and target sites first, and then prioritizing those options in collaboration with fisheries management agencies and stakeholders.

Support Marine Spatial Planning (MSP) – Countries increasingly use marine spatial planning (sometimes referred to as maritime spatial planning) to allocate use of marine space in order to promote economic growth while supporting environmental sustainability. Such planning is commonly applied across different sectors, and may build on or incorporate other more circumscribed tools and approaches such as: fisheries management, local or municipal land use plans, and area-based biodiversity measures such as siting of marine protected areas and networks. The management that flows from marine spatial planning therefore includes Integrated Coastal Management, MPA design and implementation, and the spatial allocation of maritime uses and sectors (e.g., shipping lanes, oil and gas leases, fisheries closures, scientific research sites, etc.).

MSP is increasingly used by countries to achieve economic development and environmental sustainability objectives. MSP provides opportunities to manage reefs as an asset for dependent people and businesses and addresses many pressures that threaten reef resilience, through a single process.

Coral reef resilience assessment findings can be directly applied in a MSP process, to identify: sites that warrant particular protection (e.g., closed sites/MPAs), areas where specific activities need to be restricted (certain types of fishing, infrastructure development or shipping), or areas where resilience to climate change or low vulnerability of coral reefs is likely to support economic activity, such as tourism. The mapping of institutional mandates and jurisdictions necessitated by marine spatial planning also helps in the formulation of management recommendations based on resilience assessments.

The long-term efficacy of marine spatial planning can be greatly enhanced by incorporating resilience assessment findings.

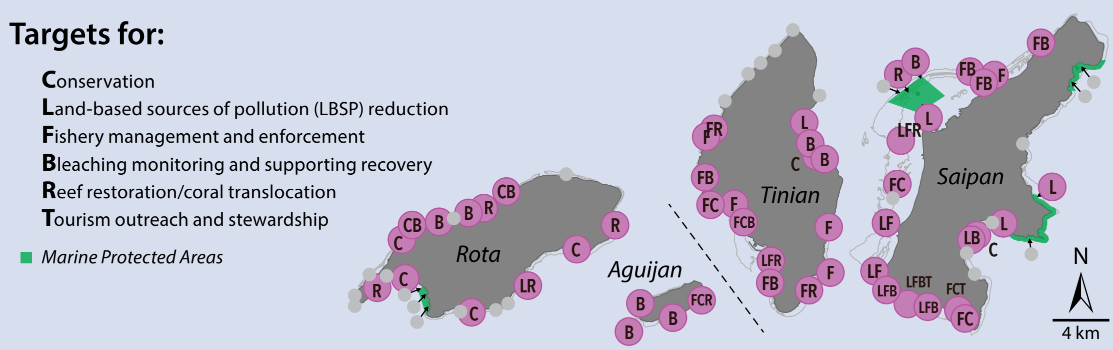
Marine spatial planning utilizes a wide range of spatial analysis tools, such as the planning software Marxan. Several data outputs from a resilience assessment can be included in a marine spatial planning process, including resilience scores for individual sites, anthropogenic stressor information, climate change projections and connectivity data, if available. Marxan can manage these disparate datasets, and can complete 'kriging' processes based on assumptions that you set such that site-based resilience data can be made spatially continuous. Consider whether your sampling intensity warrants kriging the site data; i.e., whether your sampling captures spatial variation in the resilience indicators in the entire area over which sites have been surveyed.

Box 4 — Targeting actions to support reef resilience in CNMI

Criteria were set and site targets were identified for all six of the management actions described in the guide text (conservation, LBSP reduction, reducing fishing pressure, bleaching monitoring and supporting recovery, coral translocation, and outreach) during the 2015 Commonwealth of the Northern Mariana Islands (CNMI) resilience assessment (see Figure 3 on p 23). Criteria for these management action queries of resilience assessment results are shown in the table below, which also contains lists of example actions. Summary maps can also be made that combine all assessment queries showing all candidate sites for the targeted management actions (see map below). It will be important to be clear that sites that did not meet any of your set criteria may warrant management attention for reasons distinct from the actions and associated criteria you develop. Bleaching projections do not vary >10 years where those surveys were conducted (see Box 3 on p 30) so bleaching vulnerability was not assessed in CNMI. However, island-scale connectivity information was available so sites identified as targets for the actions (see map below) were considered higher priorities if greater sources and not weak sinks (i.e., near Saipan and Tinian, see Maynard et al. 2015 for details).

Queries of resilience assessment results developed to inform management decision-making and planning processes in CNMI in 2015. Bracketed numbers under criteria indicate the number of sites that met the criteria. Lists of relevant management actions were not intended to be exhaustive. * indicates actions not planned in CNMI in 2015. The results are shown as a map below. Table from Maynard et al. (2015).

Query name	Criteria (n of 78)	Relevant management actions
Conservation	High or low resilience potential and are currently outside established no take MPAs (14)	Any of the actions described below (as appropriate)
Land-based sources of pollution reduction.	Above average scores for resilience potential and land-based sources of pollution (13)	Afforestation, stream bank stabilization, riparian restoration, and storm drain improvement, other erosion control practices, wetland enhancement and sewage treatment plant upgrades
Fishery management and enforcement	Above average resilience potential and accessability due to wave exposure (10) OR Below average herbivore AFG biomass and above average accessibility due to wave exposure (15) or both (6)	Increased enforcement, marine protected areas*, temporary closures*, LMMAs, size regulations and bag and catch limits, moorings and no-anchoring areas, fish stocking, marine debris removal
Bleaching monitoring and supporting recovey	Low bleaching resistance and low herbivore AFG biomass (20)	Increased monitoring during warm seasons, shading or other cooling measures, supporting recovery processes using any other actions described in this table
Reef restoration/coral translocation	Above average resilience potential and low coral diversity or coral cover (10)	Priority coral nursery and transplantation area, artificial reef installation
Tourism outreach and stewardship	Above average coral diversity and above average fish species richness and biomass above average accessibility due to wave exposure (2)	Establish moorings, undertake targeted outreach, develop stewardship and/or citizen science programs, marine debris removal



Results of 6 queries used to identify targets for different types of management actions that can support site or system resilience in CNMI in 2015. Criteria for the queries and relevant suggested management actions are described within the table above. Sites in gray meet none of the 6 set criteria but may warrant some of these same kinds of management actions for reasons distinct from the resilience assessment results.

By using resilience assessment findings, MSP can enhance the prospects for sustained ecosystem service provision. MSP can then also reduce the risks of widespread damage to the ecosystem due to climate change, and support economic activity based on the ecosystem services provided by coral reefs.

Informing other kinds of management actions

Resilience assessment results can be used to inform a range of other management actions beyond establishing or revising MPAs, improving water quality, and reducing fishing pressure (see Box 4 on p 38 for an example from the west Pacific). As examples, you can identify sites where bleaching susceptibility is greatest, i.e., where the proportion of the community made up by bleaching-resistant species is lowest. These are priorities for monitoring bleaching prevalence and severity during thermal stress events and may benefit from actions that support recovery (e.g., temporary closures) when bleaching events occur (see Box 4 on p 38). Resilience assessment results can also be used to identify locations for transplanting corals from nurseries, translocating corals or restoring reefs. You may decide to outplant corals from nurseries to locations where anthropogenic stress is low that are also relatively weak sinks and/or that have low coral diversity or cover. Resilience assessments may also be used to identify locations to promote education and outreach, such as through citizen-based monitoring of reef recovery in highly impacted areas (i.e., as a way of teaching resilience concepts).

For all potential management actions that could support site and system resilience, the process of using the resilience assessment results is the same.

First, query the resilience assessment results to identify potential target sites. Again, priority sites have medium-high or high resilience, are climate refugia or, if you combined these, have lower relative vulnerability and are greater relative larvae sources and not weak sinks.

Among priority sites, actions will be targeted to sites that are exposed to an anthropogenic stress that can be influenced through management or policy actions.

Next, prioritize from among those target sites in collaboration with relevant management agencies and stakeholders. You need to use the local decision-making context to determine what is feasible that will have the greatest positive impact on supporting resilience and reducing vulnerability. Remember, meaningful engagement with management agencies and stakeholders is a key ingredient in a successful resilience assessment process. The last step in the resilience assessment process, and also a critical ingredient in the process being successful, is producing clear data and reporting products and making these accessible. Such reporting ensures the management recommendations are well understood and can be easily defended, and therefore increases the use and impact of the findings.

10 Provide data and share results

- *Developing data outputs and reporting products should be an ongoing effort during the resilience assessment process*
- *Data and reporting products will need to be tailored to the target audience and able to support all intended uses*
- *Most assessment leaders will generate a range of data and reporting products including spatial data, tables, maps, summaries for decision makers, technical reports and potentially fact sheets or posters*
- *Broad communication of project results can increase compliance and promote stewardship*
- *Resilience assessments have a longer-lasting legacy if access to data and reports is maintained*
- *A large range of different outputs and reporting products can be generated during the resilience assessment process.*

Generating data outputs and preparing to develop and deliver reporting products requires investment of time and resources throughout the resilience assessment process.

Formalizing all of your outputs into communications products or making data layers publicly accessible will typically occur after you have formulated the management recommendations. Importantly, steps 9 and 10 are highly complementary and are best implemented as linked steps.

Data and reporting products will need to be tailored to the target audience (management or regulatory agencies as well as other stakeholders such as community members, businesses and the scientific community).

The language, format and presentation style, file type, data types and format all need to suit the intended audience and support any intended uses or application. For most resilience assessments, this will mean developing and sharing all or most of the following: spatial data files compatible with ArcGIS (such as zipped layer packages '*.lpk' with all gridded data), databases that can easily be queried such as in MS Excel or Access, tables, maps, technical reports for the scientific and management community, shorter summaries for decision-makers (executive summaries of project reports), summaries that concisely describe management recommendations and their justification, and public summaries such as 'fact sheets' or posters.

Leaders of resilience assessments may broadly share these data and reporting products (beyond the planned managers workshops) through presentations at community meetings or town halls, as well as through relevant national and regional processes for environmental planning and management.

Broadly communicating results of the resilience assessment process to community members and stakeholders can increase compliance with management actions once implemented and promote stewardship.

Stewardship is a way of empowering local communities to take a more active role in sustaining the natural resources on which they depend. Stakeholders that are stewards are more likely to comply with management actions and engage in and promote a range of other environmentally friendly practices and behaviors (see case study example of building reef stewardship in Belize). A Reef Manager's Guide to Fostering Community Stewardship has been developed to help you promote stewardship.

Keep in mind that the resilience assessment process will have a longer-lasting legacy if the data and reporting products are regularly discussed in meetings with management agencies and other end users of the findings and if ongoing accessibility is ensured (e.g., through creating a web area on a local management agency website).

Conducting resilience assessments regularly

The resilience assessment process supports adaptive management of coral reefs to address the threat of climate change combined with local human impacts.

During any resilience assessment, research gaps and sources of uncertainty will be identified along with parts of the process that could be strengthened or refined. Those research gaps being filled, new information becoming available (e.g., high-resolution connectivity data or new climate model projections) or a new decision-making process or opportunity arising (e.g., revision of existing MPAs) are all reasons to conduct the process again. Further, where possible, we recommend conducting a resilience assessment every 5 years to keep assessment results up to date and support adaptive management. Since the resilience assessment process will be repeated and iteratively refined, Step 10 of formalizing data and reporting products is followed, usually 3-5 years later, by repeating Step 1 and deciding whether to re-undertake the process. This ensures assessments are representative of current spatial variation in resilience indicators and anthropogenic stress and are reported on in ways that inform current and near-term decision-making.

References

Anthony, K., Marshall, P. A., Abdulla, A., Beeden, R., Bergh, C., Black, R., ... & Green, A. (2015). Operationalizing resilience for adaptive coral reef management under global environmental change. ***Global change biology***, 21(1), 48-61.

Ball, I. R., Possingham, H. P., & Watts, M. (2009). Marxan and relatives: software for spatial conservation prioritisation. ***Spatial conservation prioritisation: quantitative methods and computational tools***. Oxford University Press, Oxford, 185-195.

Burke, L., Reytar, K., Spalding, M., & Perry, A. (2011). ***Reefs at risk revisited***.

Depczynski, M., Gilmour, J. P., Ridgway, T., Barnes, H., Heyward, A. J., Holmes, T. H., ... & Wilson, S. K. (2013). Bleaching, coral mortality and subsequent survivorship on a West Australian fringing reef. ***Coral Reefs***, 32(1), 233-238.

Game, E. T., McDonald-Madden, E. V. E., Puotinen, M. L., & Possingham, H. P. (2008). Should we protect the strong or the weak? Risk, resilience, and the selection of marine protected areas. ***Conservation Biology***, 22(6), 1619-1629.

Graham, N. A., Jennings, S., MacNeil, M. A., Mouillot, D., & Wilson, S. K. (2015). Predicting climate-driven regime shifts versus rebound potential in coral reefs. ***Nature***, 518(7537), 94-97.

Graham, N. A., Pratchett, M. S., McClanahan, T. R., & Wilson, S. K. (2013). The status of coral reef fish assemblages in the Chagos Archipelago, with implications for protected area management and climate change. In ***Coral reefs of the United Kingdom overseas territories*** (pp. 253-270). Springer Netherlands.

Golbuu, Y., Victor, S., Penland, L., Idip, D., Emaurois, C., Okaji, K., ... & Van Woesik, R. (2007). Palau's coral reefs show differential habitat recovery following the 1998-bleaching event. ***Coral Reefs***, 26(2), 319-332.

Heron SF, Maynard JA, van Hooidonk R, Eakin CM (2016) Warming trends and bleaching stress of the world's coral reefs 1985-2012. ***Nature Scientific Reports***. DOI: 10.1038/srep38402

Marshall, N. A., & Marshall, P. A. (2007). Conceptualizing and operationalizing social resilience within commercial fisheries in northern Australia. ***Ecology and Society***, 12(1), 1.

Marshall, P. A., & Baird, A. H. (2000). Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. ***Coral Reefs***, 19(2), 155-163.

Maynard, J. A., Beeden, R., Puotinen, M., Johnson, J. E., Marshall, P., Hooidonk, R., ... & Ban, N. (2015). Great Barrier Reef no-take areas include a range of disturbance regimes. ***Conservation Letters***.

Maynard, J. A., Mckagan, S., Raymundo, L., Johnson, S., Ahmadia, G. N., Johnston, L., ... & Van Hooidonk, R. (2015b). Assessing relative resilience potential of coral reefs to inform management. ***Biological Conservation***, 192, 109-119.

Maynard, J., Van Hooidonk, R., Eakin, C. M., Puotinen, M., Garren, M., Williams, G., ... & Harvell, C. D. (2015c). Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. ***Nature Climate Change***, 5(7), 688-694.

McClanahan, T. R., Baird, A. H., Marshall, P. A., & Toscano, M. A. (2004). Comparing bleaching and mortality responses of hard corals between southern Kenya and the Great Barrier Reef, Australia. ***Marine Pollution Bulletin***, 48(3), 327-335.

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), e42884.

Mumby, P. J., & Anthony, K. (2015). Resilience metrics to inform ecosystem management under global change with application to coral reefs. ***Methods in Ecology and Evolution***, 6(9), 1088-1096.

Mumby, P. J., Hastings, A., & Edwards, H. J. (2007). Thresholds and the resilience of Caribbean coral reefs. ***Nature***, 450(7166), 98-101.

Obura, D., & Grimsditch, G. (2009). ***Resilience assessment of coral reefs: assessment protocol for coral reefs, focusing on coral bleaching and thermal stress***. Gland: IUCN.

Sheppard, C. R., Bowen, B. W., Chen, A. C., Craig, M. T., Eble, J., Fitzsimmons, N., ... & Koldewey, H. (2013). British Indian Ocean Territory (the Chagos Archipelago): setting, connections and the marine protected area. In ***Coral Reefs of the United Kingdom Overseas Territories*** (pp. 223-240). Springer Netherlands.

Transport Pathways of Marine Larvae Around the Mariana Archipelago. In: Kendall, M.S., Poti, M. (Eds.), ***NOAA Technical Memorandum NOS NCCOS 193***. Silver Spring, Maryland, USA (130 pp.).

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., ... & Polsky, C. (2003). A framework for vulnerability analysis in sustainability science. ***Proceedings of the National Academy of Sciences***, 100(14), 8074-8079.

UN Environment (2017) ***Wastewater Pollution and Coral Reefs: Science-to-Policy Brief***

van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadia, G., Raymundo, L., ... & Planes, S. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. ***Scientific Reports***, 6, 39666.

West, J. M., & Salm, R. V. (2003). Resistance and resilience to coral bleaching: implications for coral reef conservation and management. ***Conservation Biology***, 17(4), 956-967.

Additional resources

Data sources mentioned in this Guide

Reefs at Risk Revisited Local Threats: Data are available at 500-m resolution from the World Resources Institute for these anthropogenic stressors: sedimentation and nutrients associated with coastal development, watershed-based pollution, marine-based pollution and damage, and injuries associated with fishing activities. These are assessed for all coral reef areas as low, medium, high or very high.

Link to Data:

http://www.wri.org/publication/reefs-risk-revisited

Downscaled (4-km) projections of coral bleaching conditions: Climate model projections of the timing of the onset of twice per decade and annual severe bleaching conditions under emissions scenarios RCP8.5 (business as usual) and RCP4.5 (suggests major climate policy is enacted and complied with). Projections are available as static images, Google Earth files, and an ArcGIS layer package:

Links to Data:

http://environmentlive.unep.org/theme/index/19

http://coralreefwatch.noaa.gov/climate/projections/downscaled_bleaching_4km/index.php

Ocean acidification: Climate model projections (1x1° resolution, latitude and longitude) are available of the absolute and percentage change in aragonite saturation state between 2006 and 2050, between 2006 and 2100, and between 2016 and the projected timing of the onset of annual severe bleaching. Projections are available as static images, and a Google Earth file. Spatial data can be requested (see contact at link).

Link to Data:

http://coralreefwatch.noaa.gov/climate/projections/piccc_oa_and_bleaching/index.php

CNMI resilience assessment technical report and appendices

A resilience assessment was completed in the Commonwealth of the Northern Mariana Islands (CNMI) between 2012 and 2014, following the methodology and process presented within this Guide. The assessment results are presented within Maynard et al. (2015) in Biological Conservation. This open access paper includes appendices that describe all analysis steps and 1-page Site Summaries. This journal article and the associated supplementary material appendices can serve as a valuable reference for those considering resilience assessments and, while you are conducting an assessment, provide ideas on how to share and present assessment results.

MS-Excel tutorial on Analyzing data for a resilience assessment (process Step 4).

A tutorial is available from the UN Environment website that describes all 8 analysis steps. The tutorial is an Excel workbook that has a spreadsheet for each analysis step. Working through the tutorial will familiarize you with the analysis steps, ensuring you can complete an analysis of your data without missing steps or making mistakes.

The tutorial is also valuable as a reference. You can copy formulas from within the spreadsheets into your own analysis workbooks and can refer to the descriptions of the required task sequence for each step. You can also access virtual assistance with the data analysis through the Reef Resilience Network Forum (see next section).

TNC Reef Resilience Toolkit and Network

The Reef Resilience Network is a partnership effort led by the Nature Conservancy that builds the capacity of reef managers and practitioners around the world to better address the impacts on coral reefs from climate change and other stressors.

The Reef Resilience Network has the following main components:

- Access to new coral reef science and management strategies for coral reef practitioners through the following online modules: Resilience, Coral Reef, Coral Reef Fisheries, and Community-Based Climate Adaptation.
- Communication to coral reef managers worldwide on new resources and tools for managing for resilience
- Virtual capacity-building that is implemented through the Reef Resilience online course, a webinar series, and the Reef Resilience Network Forum.
- Intensive, in-person trainings and experiences for coral reef managers in order to improve management techniques on the ground, through Training of Trainers Workshops and learning exchanges. This includes seed funding for on-the-ground trainings led by workshop participants.

The online content and course provide detailed information and tutorials on conducting resilience assessments and provide case study examples of resilience assessments and managing reefs to support resilience from around the world.

A Guide to Assessing **Coral Reef Resilience**

FOR DECISION SUPPORT