IMPLEMENTING 50 REEFS:
A Climate-Smart Solution to Saving Coral Reefs

Coral Reef Conservation Solution-Scape White Paper

50 REEFS™

Wildlife Conservation Society

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Table of Contents

List of Acronyms and Abbreviations ..... **ii**

Executive Summary ..... **iii**

Introduction: Urgency for Coral Reefs **1**

What is Success for Coral Reef Conservation? **2**

Enabling Conditions for Conservation and Management Success **4**

What's New for Climate-Smart Coral Reef Conservation? **5**

Technical Tools for Coral Reef Conservation **7**

Marine Protected Areas 1

Rights-Based Management of Marine Resources 3

Gear Modifications and Restrictions 4

Reducing Watershed-Based Pollution 4

Managing Wastewater Pollution 6

Managing Coastal Development 6

Managing Shipping 7

Managing Invasive Species and Population Outbreaks of Predators 8

Tools to Enhance Recovery 9

Future Frontiers: Treating Coral Disease and Promoting Assisted Evolution of Corals to Climate Change 10

Conservation in Action: Integrating Social Values, Economics, Uncertainty, Equity, and Timeframes **11**

Enabling Conditions **14**

Policy and Legislative Approaches 14

Compliance and Enforcement 16

Financial Mechanisms 17

Toward Success: Monitoring the Social and Ecological Impact of Investments and Implementing Adaptive Management **21**

Conclusions: Summary of Recommendations **21**

References **23**

Appendix **42**

Appendix A. List of Practitioner Guidelines, Toolkits, Frameworks, and Other Resources 42

List of Acronyms and Abbreviations

AUD	Australian dollar
COTS	Crown-of-thorns starfish
CTFs	Conservation Trust Funds
LMMAs	Locally managed marine areas
MPA(s)	Marine protected area(s)
MSC	Marine Stewardship Council
NGO(s)	Non-governmental organization(s)
PES	Payment for ecosystem services
PHCs	Periodically harvested closures
PIPA	Phoenix Islands Protected Area
TNC	The Nature Conservancy
TURFs	Territorial use rights for fisheries
USD	U.S. dollar

Coral Reef Solution-Scape: A Summary of Approaches to Coral Reef Conservation

Executive Summary

In the face of climate change, warming oceans, and repeated mass coral bleaching, coral reef conservation is at a timely crossroads. There is a new urgency to support and strengthen a rich history of conservation partnerships and actions, while also building toward new actions to meet unparalleled global threats. The goal of this white paper is to synthesize and summarize the diversity of tools, approaches and solutions for coral reef conservation implemented to date and to understand the enabling conditions that lead to successful coral reef conservation. Framed as a "solution-scape," this white paper seeks to support ongoing decisions to strengthen existing assets and build new investments into portfolios of global coral reef conservation that are equitable and aligned with diverse cultures and worldviews. This white paper addresses the following main themes:

- **What is success for coral reef conservation?** This white paper defines success in both ecological and social terms, and success can be achieved through strategies that promote biodiversity and ecological functioning, social equity, and food and livelihood security. Table 1 identifies social and ecological metrics that are commonly used to define "success" in coral reef conservation, including coral cover and structural reef complexity, species richness of coral reef organisms, high abundance and biomass of coral reef fishes, human wellbeing and economic development, livelihoods, and poverty alleviation.
- **Enabling conditions for conservation and management success.** Active participation in decision-making, local leadership, recognition of the knowledge and rights of local stakeholders, nested institutions, and targeted educational activities have all been consistently and globally observed to be some of the main drivers of conservation and management success and sustainability (Table 2). This white paper also includes detailed summaries of policy and legislative approaches to support conservation outcomes, compliance and enforcement of policies, and financial mechanisms for the sustainable delivery of resources.
- **Technical tools for coral reef conservation.** Protection of coral reefs requires an understanding of what strategies can be implemented to achieve coral reef conservation goals. This document describes a range of approaches including marine protected areas, rights-based management of marine resources, fishing gear modifications and restrictions, watershed management, management of coastal development and shipping, invasive species and population outbreaks of predators, tools to enhance habitat recovery, and future frontiers of coral disease treatments and assisted evolution. We also highlight the critical role of rigorous social and ecological monitoring to evaluate the effectiveness of management actions, making evidence-based decisions, and supporting adaptive management.
- **What's new for climate-smart coral reef conservation?** Prioritization of conservation strategies toward "climate refuges" may include locations exposed to deeper reefs and channels, shallow lagoons that have long been exposed to variable temperatures and where corals continue to survive, and areas of cool-water upwelling driven by gyres or eddies. Reefs that experience chronic and acute thermal exposure over time may be critically important for maintaining a diversity of species capable of resistance and recovery. Assisted evolution, networks of marine reserves to enhance recovery, reduced local impacts from fishing, coastal

development, and land-based stressors may enhance resistance and/or recovery to the impacts of climate change, notably mass coral bleaching.

We conclude with 10 recommendations that focus on equitable conservation practices that will align successful interventions with diverse cultures and worldviews, help ensure that the right decisions are made, and strengthen investments into conservation portfolios that will lead to successful coral reef conservation.

Solution-Scape White Paper

Introduction: Urgency for Coral Reefs

Tropical coral reefs are the most biodiverse marine ecosystem in the world (Fisher et al. 2015); they support millions of people in food security, cultural practices and livelihoods, and provide ecosystem services that generate billions of dollars for the global economy through benefits such as fisheries, tourism, and coastal protection (Moberg and Folke 1999, Cesar et al. 2003, De Groot et al. 2012). Yet the rapid growth in human populations and coastal development, climate change, and the unsustainable extraction of reef resources have led to increasing pressures on living corals, the three-dimensional underwater architects of tropical reef systems (Gardner et al. 2005, Bruno and Selig 2007, Carpenter et al. 2008, De'ath et al. 2012, Jackson et al. 2014).

Coral reefs are subjected to local and global impacts, including overfishing, destructive fishing practices, pollution, invasive species, and extreme weather events such as destructive storms and temperature anomalies, all of which have been implicated in their precipitous decline (Jackson et al. 2001, McClanahan et al. 2007, Cramer et al. 2012, De'ath et al. 2012, Jackson et al. 2014, Hughes et al. 2017b, McClanahan 2017). Conservation and management interventions over previous decades have attempted to slow and reverse their decline, while trying to ensure that essential activities and resource use by local communities can be maintained. Engagement with and financial investment by local stakeholders, non-governmental organizations (NGOs), governments, aid organizations, and intergovernmental groups have led to some locally successful results (Russ et al. 2008, Cinner et al. 2012, Birkeland et al. 2013, Edgar et al. 2014, Bahr et al. 2015, Gill et al. 2017). Yet, despite these best efforts, globally coral reefs are still in decline. As climate change and coastal development become more pronounced, the long-term survival of coral reefs is threatened (Hughes et al. 2007, Hughes et al. 2017b). It is through this lens that we must ask the question: ***How can we strengthen and develop practical solutions toward coral reef conservation and management to ensure the persistence of coral reefs in a changing world?***

Persistence and resilience in the face of environmental and climate change fundamentally relies on two different processes: the extent to which coral reefs can resist changing when impacted by pressures (i.e., resistance) and the ability of coral reefs to recover following a disturbance (i.e., recovery (Côté and Darling 2010). Both processes are important and can be achieved through different mechanisms (McClanahan et al. 2007, Kennedy et al. 2013, Graham et al. 2015, Oliver et al. 2015). It is thus critical to identify the technical management interventions that can adequately mitigate threatening processes and promote recovery for coral reef ecosystems. Equally important is the need to ensure that, along with conservation and management actions at specific locations, carbon dioxide emissions are reduced at the global level, given that as warming ocean temperatures and increasing ocean acidification are global stressors that do not stop at the borders of conserved or managed areas (Hoegh-Guldberg et al. 2007, Kennedy et al. 2013, Anthony 2016, Hughes et al. 2017b).

In addition to understanding the biological, ecological, and oceanographic conditions of a reef in order to guide conservation and management decisions, management must involve those who use and depend on coral reefs. Local stakeholders have unique visions and worldviews of conservation that are critical to achieve long-term project effectiveness and sustainability (Jupiter 2017). Further, for many people living close to coral reefs, food and livelihood security is directly tied to coral reef resources; this means that conservation must be aligned with the desired social and development outcomes for the community (Christie 2004, Camargo et al. 2009, Christie et al. 2009, Eisma-Osorio et al. 2009, Brewer 2013, Hicks and Cinner 2014, Jupiter 2017).

This white paper synthesizes and summarizes the diversity of tools, approaches, practices, and solutions for coral reef conservation implemented to date. Our goal is to assess the evidence base for the effectiveness, costs, and feasibility of coral reef conservation solutions across multiple scales, bridging local, regional, and global practices of conservation and management. In the following sections, we examine the technical approaches, enabling conditions, and financial mechanisms that have been and are being used in coral reef conservation. We use this information to propose ways forward to strengthen existing initiatives and develop new practical solutions to achieve climate change resilience for global coral reefs. Ultimately, investments in portfolios of global coral reef conservation must be equitable and aligned with diverse cultures and worldviews to achieve long-term social and ecological success.

What is Success for Coral Reef Conservation?

One of the challenges in assessing the success of conservation interventions is that different communities and contexts define success in different ways. It is the position of this white paper that success should be defined in both ecological and social terms, and can be achieved through strategies that promote biodiversity and ecological functioning, social equity, and food and livelihood security (Cardinale et al. 2012, Sandifer et al. 2015). Furthermore, consideration of socio-economic and development goals can lead to better conservation and development outcomes (Gurney et al. 2015, Mangubhai et al. 2015). Ultimately, any strategy for marine conservation requires the full participation and consideration of local stakeholders to ensure that fair and ethical practices are followed (Bennett et al. 2017).

There is now a large body of literature on social and ecological indicators for “management and conservation success.” Table 1 lists the ones most relevant to coral reefs. When considering conservation to achieve biodiversity goals, high coral cover and reef macrostructural complexity, species richness of coral reef organisms, and high abundance and biomass of coral reef fishes are the most common indicators of success (Table 1). High coral cover and reef structural complexity support high levels of coral reef fish abundance, biomass, and species richness (Darling et al. 2017). Increased biomass and abundance of targeted fish are critical for the maintenance and replenishment of fish stocks (Harrison et al. 2012). Key social indicators of success include greater economic development, more employment opportunities, and poverty alleviation, among others (Table 1). Success for an indicator can be measured in terms of a lower rate of decline, maintenance in the same state, or an improvement. As has been well discussed elsewhere, identifying clear objectives for conservation interventions are imperative, and an adaptive monitoring strategy must include control reference points and realistic timeframes for expected changes (Fox et al. 2017, Mascia et al. 2017).

Table 1: A Selection of Social and Ecological Indicators Relevant to Coral Reefs

Type of Success	Metric of Success	Reference
Ecological	Increased/maintained average size of target fish species	Cinner et al. 2005, McClanahan et al. 2006
Ecological	Increased/maintained coral species richness	Hoffmann 2002, Cinner et al. 2005, McClanahan et al. 2006
Ecological	Increased/maintained fish abundance	Cinner et al. 2005, McClanahan et al. 2006, Gutierrez et al. 2011, Kaplan et al. 2015
Ecological	Increased/maintained fish biomass	Cinner et al. 2005, McClanahan et al. 2006, Kaplan et al. 2015, MacNeil et al. 2015
Ecological	Increased/maintained fish species richness	Cinner et al. 2005, McClanahan et al. 2006, Camargo et al. 2009, McClanahan et al. 2011b
Ecological	Reduced/maintained macroalgae cover	McClanahan et al. 2011b
Ecological	Low ratio of macroalgae to coral cover	Camargo et al. 2009, McClanahan et al. 2011b
Ecological	Increased/maintained herbivorous fish as % of total fishable biomass	McClanahan et al. 2011b
Ecological	Increased/maintained calcifying substrate	McClanahan et al. 2011b
Ecological	Increased/maintained live hard coral cover	Hoffmann 2002, Cinner et al. 2005, McClanahan et al. 2006, Camargo et al. 2009, Hargreaves-Allen et al. 2011, McClanahan et al. 2011b
Ecological	Reduced/maintained number of corals affected by predators, parasites, and pathogens	Hoffmann 2002, Lamb et al. 2015
Social	Greater economic development	Hargreaves-Allen et al. 2011
Social	More employment opportunities	Hargreaves-Allen et al. 2011
Social	Improved social welfare	Gutierrez et al. 2011

Type of Success	Metric of Success	Reference
Social	Poverty alleviation (including, but not limited to, number of different occupations, fisheries dependence, well-being, wealth, and marine resource control)	Gurney et al. 2014
Social	Lower levels of conflict	Camargo et al. 2009; Hargreaves-Allan et al. 2011
Social	Decreased rate of destructive fishing	Hargreaves-Allen et al. 2011
Social	Decreased rate of mangrove extraction	Hargreaves-Allen et al. 2011
Social	Improved diet and nutrition	Gjertsen 2005, Alva et al. 2016

Enabling Conditions for Conservation and Management Success

In conjunction with the development of indicators of success, there has been extensive effort undertaken to identify enabling conditions that lead to uptake of management initiatives (Table 2). Several consistent trends emerge that can provide a framework for the initiation of new projects. ***Active participation in decision-making, local leadership***, ***recognition of the knowledge and rights of local stakeholders***, ***nested institutions***, and ***targeted educational activities*** have all been observed to be some of the main drivers of conservation and management success and sustainability (Table 2). Participatory decision-making arrangements also tend to enhance the perceived legitimacy of decisions that are made. In places where there are strong customary or co-management systems, formally recognized community rights provide an enabling framework that empowers communities to manage their own resources (Hoffmann 2002, Lauer and Aswani 2009, Weeks et al. 2010, Cohen et al. 2012, Gurney et al. 2015). Conservation is not a one-size-fits-all approach and it is critical to understand the social, political, and environmental conditions at each location. However, the diverse lessons learned from the accumulated experiences of practitioners provide a template for best practice management and can aid in identifying strategies and potential barriers to conservation that may be in place (Katikiro et al. 2015).

At the local scale, some of the main factors for successful uptake of management initiatives are a clear legal mandate, local involvement in decision-making, recognition of local knowledge and ownership, and enforcement mechanisms (Russ and Alcala 1999, Balgos 2005, Christie and White 2007, Cinner et al. 2012, Gurney et al. 2015, Jupiter et al. 2017). However, it is vitally important to understand the local and national context. In Indonesia, while individual participation in decision-making and marine protected area (MPA) management strongly relates to community expectations, community-level participation is more likely to occur if MPA management groups are supported by external institutions, including NGOs (Gurney et al. 2016). In the Philippines, Pollnac et al. (2001) found that a high level of community participation in decision-making, combined with continuing support from the implementing organization and the municipal government, were strong factors in predicting MPA success. The importance of nested institutions, including NGOs, is widely recognized (Ostrom 1990), highlighting that engagement with community-based management should be accompanied by a strategy for continued, long-term community buy-in, else risking the loss of accrued ecological and social benefits (Gurney et al. 2014).

Table 2. Enabling Conditions for Conservation and Management Success

Enabling Conditions	Specific Enabling Conditions	Reference
Effective enforcement	Enforcement mechanisms in place	The WorldFish Center 2008; Jupiter et al. 2017; Pomeroy et al. 2005; Cinner et al. 2012; Kaplan et al. 2015
Effective enforcement	Well defined and recognized boundaries and rules	Ostrom 1990; Aswani and Hamilton 2004
Effective governance	Respected leaders	Cinner et al. 2012; Frey and Berkes 2014; Gutierrez et al. 2011; Pietri et al. 2009
Market forces	Distance away from markets	Cinner et al. 2012
Public support/buy-in	Educational outreach	Leisher et al. 2012; Frey and Berkes 2014
Public support/buy-in	Participation in decision making	Arias et al. 2015; Balgos 2005; GEF-lessons learnt; Gurney et al. 2016; Pollnac and Pomeroy 2005; Pomeroy et al. 2005; Russ and Alcala 1999; Arias et al. 2015; Camargo et al. 2009; Ostrom 1990
Public support/buy-in	Perception of realized or potential tangible outcomes	Cho 2005; Pollnac and Pomeroy 2005; Pomeroy et al. 2005
Resourcing	Adequate human and financial resources	Cho 2005; Gill et al. 2017
Supportive legal and policy environment	Clear legal mandate	Christie and White 2007
Supportive legal and policy environment	Consistency and recognition of management and rules across governance scales	Christie 2005; White et al. 2005; GEF-lessons learnt; Jupiter et al. 2017; Pollnac et al. 2001; Aswani and Hamilton 2004; Balgos 2005; Cinner et al. 2016; White et al. 2005; Eisma et al. 2005; Lowry et al. 2005; Pomeroy et al. 2005; Ostrom 1990

What's New for Climate-Smart Coral Reef Conservation?

With recurrent mass bleaching as a result of climate-change-induced ocean warming (Hughes et al. 2017b) and potentially limited windows for slow-growing corals to recover (Côté and Darling 2010), what new tools and interventions are needed to ensure that reef conservation interventions are climate smart? There are two positive aspects to the responses of corals to raised water temperatures: first, there is increasing evidence that not all coral species or locations bleach equally (McClanahan et al. 2007, McClanahan et al. 2011a, Darling et al. 2013, Hughes et al. 2017b, McClanahan and Muthiga 2017), and second, surviving corals can, in some contexts, adapt to repeated bleaching events (Guest et al. 2012, Howells et al. 2012, McClanahan 2017). Climate-smart conservation can leverage these diverse responses and use a variety of management strategies and technical tools that would allow "nature to pick the winners" in any particular location (Webster et al. 2017). Such an approach involves protecting and managing, with a suite of technical tools, connected and diverse reef-scapes across gradients of climate exposure, human impacts, and habitat diversity in order to increase the potential for "evolutionary rescue," whereby beneficial mutations or adaptations can arise naturally and spread, helping coral populations to acclimate or adapt to rapidly changing environments. A climate-smart conservation approach for coral reefs might include the following:

- Known “climate refuges”—places where slow-growing corals are known either to be able adapt to ocean warming or not exposed to it—can be protected and carefully managed. These locations may include access to deeper reefs and channels, shallow lagoons that have long been exposed to variable temperatures and where corals continue to survive, and areas of cool-water upwelling driven by gyres or eddies (Oliver and Palumbi 2011, Ainsworth et al. 2016, McClanahan and Muthiga 2017). Reefs that experience chronic and acute thermal exposure over time may be critically important for maintaining a diversity of species that are capable of resistance and recovery (Mumby et al. 2011, Webster et al. 2017).
- Assisted evolution of the coral host, symbiont guild, or microbiome may produce new combinations of adaptations that can reseed reefs facing unprecedented climate impacts (van Oppen et al. 2015, van Oppen et al. 2017, Ziegler et al. 2017).
- Time scales can be given better consideration, recognizing that benefits are realized over much longer scales (e.g., decades) than previously understood (Poiani et al. 2011). Nevertheless, over the short and medium term, networks of MPAs and no-take marine reserves that consider larval connectivity and maximizes the protection of diverse habitats may improve resistance and enhance recovery following unpredictable of extreme events associated with climate change (Baskett et al. 2010, McClanahan et al. 2011a, Abelson et al. 2016, Krueck et al. 2017, Webster et al. 2017).
- Networks of MPAs should ensure that connectivity is maintained between protected reef communities, which may improve the chances of recovery if corals and other sensitive species are negatively affected by a temperature anomaly event (Mumby et al. 2011, Selig et al. 2012). MPA networks should also protect habitat diversity across different coral reef habitats and depths, as well as adjacent seagrass beds and mangrove forests. Different habitats may provide some refuge for corals. For example, mangroves reduce light stress often associated with thermal stress and coral bleaching, and potentially alter seawater chemistry to buffer against ocean acidification (Yates et al. 2014); mangroves can enhance reef fish biomass (Mumby et al. 2004b); and seagrass beds can reduce pathogen levels and rates of disease on coral reefs (Lamb et al. 2017).
- Well-protected MPAs that minimize the effect of other non-climate stressors may provide opportunities for populations to recover from the impacts of climate change (Green et al. 2015, Lamb et al. 2015, Lamb et al. 2016).
- Since coral reef organisms are often sensitive to changes in water quality, maintenance of water quality and reduction and mitigation of pollution are vitally important both in preventing reef deterioration (Lamb et al. 2016, Wenger et al. 2016) and in improving recovery rates of coral reefs following bleaching events or destructive storms (Carilli et al. 2009, Lamb et al. 2016). Reductions in nutrient levels can lower bleaching susceptibility, increase coral calcification rates, and reduce bioeroding organisms, making corals more resistant to thermal stress and ocean acidification (Edinger et al. 2000, Le Grand and Fabricius 2011, Wiedenmann et al. 2013).
- Fishery gear restrictions designed to selectively harvest more climate-tolerant species can reduce pressure on species that are vulnerable to climate change and/or important for coral reef recovery, e.g., herbivores (Cinner et al. 2009).
- Explicit recognition of separate objectives for coral resistance to and recovery from climate change impacts, for example that different ecological and oceanographic factors, will allow

coral reefs to either resist or recover from climate stress (Côté and Darling 2010, McClanahan et al. 2012b).

Technical Tools for Coral Reef Conservation

Protection of coral reefs requires an understanding of what strategies can be implemented to achieve coral reef conservation goals. Many large-scale drivers of coral reef state, including market access, governance structure, or human population growth (Cinner et al. 2016, Hughes et al. 2017a), act on scales often beyond the control of local and regional managers. However, local and regional managers and stakeholders have an important role to play in ensuring manageable drivers of coral reef decline, such as over-fishing or pollution, are effectively mitigated. Many approaches that have been undertaken to improve coral reef health, as we describe below. Some of these approaches have demonstrated success in achieving conservation goals, while others have not yet been field-tested and represent the next frontier in coral reef management (Figure 1). The management strategies described below vary substantially in terms of scale of implementation and potential costs (Figure 1). Further, although this white paper is primarily focused on coral reef conservation, management of adjacent ecosystems such as seagrass beds and mangrove forests can play a large role in coral reef functioning and productivity and these ecosystems are also briefly considered throughout the document.

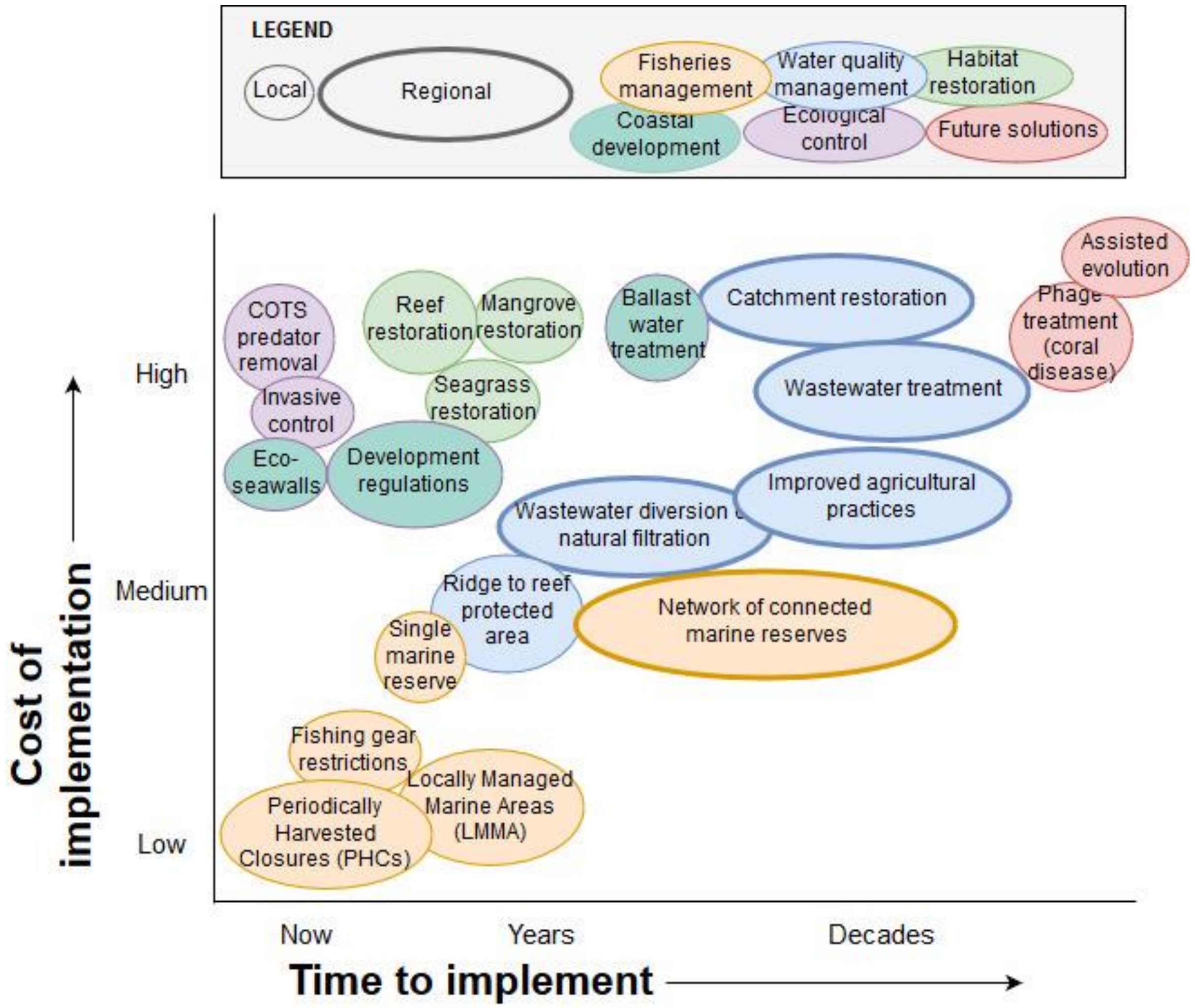

Figure 1. Summary of Technical Tools for Coral Reef Conservation Across Spatial, Temporal, and Cost Scales

Marine Protected Areas

One of the primary management strategies used to conserve and enhance coral reef biodiversity and fisheries is the implementation of MPAs, defined as "…clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Day et al. 2012). MPAs can also include no-take marine reserves, where no exploitation is allowed. MPAs can lead to successful outcomes when specific ecological and social conditions are met (Edgar et al. 2014, Gill et al. 2017): their outcomes can include increases in targeted and non-targeted species (Babcock et al. 2010), restoration of trophic function (Mumby et al. 2007, Boaden and Kingsford 2015), and lower levels of coral disease (Lamb et al. 2015). A global assessment of conservation benefits arising from MPAs identified five key traits of their success (Edgar et al. 2014):

- No take.
- Well-enforced.
- Old (>10 years).

- Large (>100 square kilometer).
- Isolated by deep water or sand.

However, benefits from MPAs are not guaranteed and can depend on local conditions and additional external threats that diminish MPA protection (Jones et al. 2004, Lamb et al. 2016, Wenger et al. 2016, Williams et al. 2016, Arias-González et al. 2017, Cox et al. 2017). For example, the majority of global MPAs do not meet adequate staff or budget capacity, which has been shown to jeopardize ecological outcomes (Gill et al. 2017). Given our understanding of the potential benefits that can accrue and the circumstances that promote MPA success (Edgar et al. 2014), several factors should be considered in MPA design to ensure that they can act as a tool to promote climate change resilience:

- Strategic creation of networks of MPAs and no-take marine reserves should consider larval connectivity and stakeholder use under changing environmental conditions, and maximize the protection of diverse habitats as a way to enhance recovery following disturbances and safeguard against the unpredictability of extreme weather events (Baskett et al. 2010, McClanahan et al. 2011a, Abelson et al. 2016, Krueck et al. 2017, Webster et al. 2017).
- Networks of MPAs should be larger than the average size of acute thermal events to improve the chances of recovery via connectivity with areas of MPA network that were not exposed to the thermal event (Mumby et al. 2011, Selig et al. 2012).
- The incorporation of habitat diversity should not only include different coral reef types, but also adjacent mangroves and seagrass meadows, which can enhance the biomass of coral reef fish communities and reduce coral disease levels through pathogen mitigation (Mumby et al. 2004a, Olds et al. 2012, Lamb et al. 2017).
- Likewise, to ensure that fisheries benefits are maximized in conjunction with climate change resilience, MPA designs should ensure that protected area size is adequate for species of conservation or management concern, thereby providing them a place to recover from the impacts of climate change (Green et al. 2015).

While a robust network of MPAs and no-take marine reserves is likely to provide the greatest benefit from both a biodiversity and fisheries perspective (Cinner et al. 2012, Harrison et al. 2012, Gill et al. 2017), this approach may be infeasible in many coral reef countries, owing to local-scale commons management and a strong reliance on coral reef resources for food security and livelihoods (Cinner et al. 2012, Gruby and Basurto 2013, Afflerbach et al. 2014). In these contexts, strategies toward community-based management and co-management have been implemented to incorporate locally identified objectives, particularly regarding fisheries management (Jupiter et al. 2014b), in order promote more sustainable use and greater levels of compliance.

One of the most common coral reef management strategies within locally managed marine areas (LMMAs) is the use of periodically harvested closures (PHCs). PHCs are locations that are opened and closed to exploitation based on community decisions—for example, harvested to provide food for celebrations or funerals—and are a well-documented traditional practice across many countries, particularly in contexts of strong marine tenure and traditional governance (Cinner et al. 2006, Cohen and Foale 2013). Although PHCs have widely been promoted as a conservation and fisheries management tool that blends traditional ecological knowledge with more technical tools, the realized benefits are variable (Goetze et al. 2016). Resources are often overexploited when PHCs are open, thus negating positive impacts from closures (Williams et al. 2006, Jupiter et al. 2012b, Cohen and

Foale 2013). Given the variation in demographics of targeted species, it is likely that PHCs are most effective as a conservation and fisheries tool when the species targeted are fast-growing and the time between harvests is at least a few years (Cohen and Foale 2013, Goetze et al. 2016).

Seasonal closures are a variant on PHCs, used to enhance protection of important fishery species usually during important spawning time windows when populations are particularly vulnerable to overexploitation (Hamilton et al. 2011, Friedlander et al. 2013). In Papua New Guinea, the closure of spawning aggregations of grouper species led to a significant increase in abundance of groupers over a four-year period (Hamilton et al. 2011). Seasonal closures of octopus in Madagascar have been documented to meet social and ecological objectives (Oliver et al. 2015). Seasonal restrictions can be more feasible to implement than trying to protect the entire area where fishers target catch (Waldie et al. 2016).

Rights-Based Management of Marine Resources

LMMAs are areas of nearshore waters being actively managed by local communities or resource-owning groups that have formal or informally recognized rights to negotiate and implement management rules to meet their local objectives (Weeks et al. 2010, Jupiter et al. 2014b, Horigue et al. 2015). The objectives of LMMAs can vary substantially and may compete—such as maintenance of stocks and maximizing yields, for which there must be management tradeoffs (Jupiter et al. 2014b). LMMAs encompass a wide range of specific management measures, including fisheries closures, gear restrictions, species restrictions, access restrictions, watershed management, and livelihood diversification strategies (Jupiter et al. 2014b). However, local-scale management is unlikely to adequately sustain fish populations and fisheries and achieve conservation goals.

Local management should be supplemented with focused investments in addressing fishing threats through management opportunities. The potential for success in fisheries management at scale ought to feed back into site selection, since successful fisheries management will directly affect the likely persistence of your target reefs. The magnitude of fishing (and other higher-order) threats, and their tractability in terms of improved management, should be an essential site selection criterion. In each case, the relative risk from offsite effects—including fisheries management—should also be assessed before any management plan is developed, and then addressed in the plan. ***Nesting sites (or even networks of sites) within tractable fisheries management jurisdictions will be an important strategy to achieve broader conservation goals.***

One fisheries management strategy that could complement local MPA management to adequately protect coral reef ecosystems is to focus on a few key coral-dependent multispecies finfish fisheries that can show results quickly. The benefits of management could be leveraged to get government to set and implement new policies that bring other fisheries and coral reefs into compliance with conservation goals. This need not be a community-by-community approach, which can be slow and costly; it could instead be a first-adopter-to-scale strategy.

Different management strategies vary in support by local stakeholders, emphasizing the need for full participation of diverse local stakeholders to ensure their concerns are met (Jupiter et al. 2014b). In some coral reef countries, rights-based fishing initiatives have been formalized within territorial use rights for fisheries (TURFs) schemes, which gives fishers access to specific fishing grounds (Afflerbach et al. 2014). In many TURFs, there are also some fishery regulations, including catch quotas, size limits, seasonal closures, and gear restrictions (Afflerbach et al. 2014). A TURFs approach was piloted in Belize in 2011 at Glovers Reef Marine Reserve by the Belize Fisheries Department, supported by the Environmental Defense Fund and Wildlife Conservation Society (Foley 2012). Based on the success of this pilot project (reduction in illegal infractions by approximately 90% and increased stewardship of the area by fishers), there are now TURFs across all Belizean national waters since 2016. However, for many coral reef regions, it is unlikely that TURFs will work in the absence of other elements of a fishery management plan to prevent overfishing.

Gear Modifications and Restrictions

Restrictions or modifications of fishing gear provide another way to manage catch and exploitation of coral reef resources and thus maintain reef health. Gear restrictions attempt to reduce unsustainable or destructive fisheries practices, such as very small mesh sizes or the use of dynamite or poison. In some places, fishery yields can be maintained with gear restrictions, in addition to restrictions on access (e.g., MPAs) or target species (MacNeil et al. 2015). Gear restrictions are often indicated as the preferred management strategy by fishers and other resource users (McClanahan et al. 2012a). However, management preferences are context-specific (Waldie et al. 2016), underscoring the importance of stakeholder engagement in decision making around resource use. Gear modifications, such as gated “escape traps” used in Kenya, are also effective fisheries management approaches that can reduce the bycatch of smaller juvenile fish while increasing catch quality (e.g., fish size) and income, even in heavily fished systems (Mbaru and McClanahan 2013, Gomes et al. 2014, Condy et al. 2015). Gear modification has also been applied in the Caribbean, for example in Curaçao, where traps, one of the predominant fishing tools, were fitted with bycatch reduction devices to significantly reduce the amount of bycatch while maintaining catch rates of targeted species (Johnson 2010). Gear restrictions and gear modifications improve the resilience of a coral reef to climate change. In Kenya and Papua New Guinea, where spear guns and traps target species that are vulnerable to coral mortality and important for coral reef recovery, it may be wise to persuade fishers to switch to line fishing, which catches a low proportion of these species (Cinner et al. 2009). McClanahan and Cinner (2008) propose a framework for gear restrictions for multi-gear coral reef fisheries in Papua New Guinea that could be applied to other regions with similar gear use. Namely, they propose:

- Restrictions on gill nets when coral cover is low, in order to reduce damage to coral.
- Restrictions on line fishing when large-bodied predators are depleted.
- Restrictions on spear fishing when algal cover is high, in order to reduce the catch of herbivorous fish, which are important for controlling algal growth.

Ultimately, a suite of different coral reef fishery management strategies should be implemented that will provide for both sustainable harvests and biodiversity conservation benefits (Day 2002, Afflerbach et al. 2014, Mangubhai et al. 2015).

Reducing Watershed-Based Pollution

The impacts to coral reefs from declining water quality due to land-based sources of pollution, including sediments, nutrients, and pesticides, are well documented, and at least 30% of coral reefs are at medium to high risk from reduced water quality (Dikou and van Woesik 2006, Cramer et al. 2012, Lamb et al. 2016, Wenger et al. 2016, Burke et al. 2011).

A range of solutions can be implemented to improve water quality and the health of coral reefs. However, although ridge to reef or integrated coastal zone planning are increasingly being considered and implemented, beyond two examples of coral reef improvement following diversion of sewage effluent to deeper water (Birkeland et al. 2013, Bahr et al. 2015), there are no published examples of water quality improvements and *subsequent recovery* of coral reef ecosystems. Further, although watershed pollution is considered one of the main threats to coral reef environments, conservation budgets disproportionately underfund pollution mitigation strategies (Wear 2016). Thus, the management recommendations described below are based on successful practices implemented in non-reef environments and strategies that have reduced pollution levels but have been implemented too recently for results to show.

Studies comparing the nearshore coral reefs subjected to runoff with control locations can help inform conservation strategies (Fabricius et al. 2005, Rodgers et al. 2012, Hamilton et al. 2017). Given the lag time between the introduction of good land-use management and the appearance of improvements in water quality, and the additional lag time between changes in water quality and improvements to the ecosystem (Meals et al. 2010, Bartley et al. 2014a)***, the precautionary approach of protecting ridge to reef systems that have not yet been modified is strongly recommended*** (Fabricius et al. 2005, Rodgers et al. 2012, Hamilton et al. 2017, Quiros et al. 2017). This is the approach being suggested in the Bua Regional Integrated Coastal Zone Management Plan in Fiji (S. Mangubhai and S. Jupiter, pers. comm).

When protection of entire intact catchments is not feasible due to the history of land use and land cover change and the importance of agriculture, globally recognized best land-use management practices should be implemented, including:

- Adjusting stocking rates and rotational grazing (to increase vegetation cover and reduce soil erosion: Bartley et al. 2014b).
- Avoidance of steep slopes (Douglas 1967).
- Fencing to exclude livestock from wetlands (to protect riparian vegetation buffers and avoid river bank erosion: Agouridis et al. 2005).
- Improving fertilizer use (to reduce nutrient runoff: Thorburn et al. 2013).
- Reducing pesticide use (Oliver et al. 2014).
- With existing agricultural activities, pesticide and fertilizer reduction strategies can be implemented in concert with groundcover or understory re-vegetation to reduce soil erosion (Thorburn and Wilkinson 2013, Thorburn et al. 2013, Bah et al. 2014, Oliver et al. 2014, Tarigan et al. 2016).

Additionally, many countries have logging and mining codes of practices, in an attempt to mitigate water quality impacts on coral reefs from the release of sediments, chemicals, or tailings. In instances where these activities are occurring, enforcement of these codes will help to mitigate impacts. In many coral reef countries, erosion from dirt roads is a major concern, as they act as both sediment sources and conduits for sediment. In steep tropical environment's, even low-density unpaved road networks can lead to high levels of sediment runoff and relatively simple drainage designs have improved sediment runoff in the Caribbean (Ramos-Scharrón 2012, Ramos-Scharrón and LaFevor 2016). Finally, although restoration activities can be costly and labor-intensive, the restoration of gullies and riparian zones (Brooks et al. 2015) may be necessary in some circumstances when threats to marine ecosystems from water quality are severe (Brodie et al. 2013). Given the limited information available about the effectiveness of water quality improvement strategies in promoting the resilience of coral reefs, monitoring and reporting procedures must be put into place at the same time.

Managing Wastewater Pollution

Even in areas without extensive development activity, human communities living adjacent to coral reefs will generate sewage pollution (Wear and Thurber 2015) and the majority of coral reef countries have documented wastewater pollution problems (Wear and Thurber 2015). Sewage runoff has many impacts, including increased coral mortality; increased bleaching; increased coral, fish, and human pathogens; increased coral disease prevalence; decreased coral skeletal integrity; and decreased growth rates (Wear and Thurber 2015, Wear 2016, Lamb et al. 2017). As the problem of wastewater discharge has become more recognized, several coastal regions adopted wastewater treatment plans, including the United States and Australia. The Australian government embarked on an ambitious $188 million Australian dollars (AUD) project to upgrade major wastewater treatment plants, called the Cleaner Seas Project, which ensures an 80% reduction in the amount of nitrogen, phosphorus, and ammonia being discharged onto the Great Barrier Reef annually. ***Australia's Cleaner Seas project can serve as an important standard for wastewater management in places where wastewater treatment plants exist.***

In many countries with coral reefs, the construction of wastewater infrastructure and advanced wastewater treatment plants will be infeasible. For countries that can control the output of wastewater, diversion into deeper water can lead to significant improvements in coral reef condition (Birkeland et al. 2013, Bahr et al. 2015). In regions where wastewater cannot be diverted, the creation of filtration systems using natural filtration mechanisms has been proposed as a way to mitigate some of the impacts associated with sewage runoff (Rose et al. 2014, Lamb et al. 2017).

Managing Coastal Development

Coastal development is expanding at a rapid rate and has been identified as one of the main threats to coral reefs, as perceived by coral reef practitioners (Wear 2016). One of the main management strategies for ensuring that coastal development is conducted sustainably is to require robust environmental impact assessments (EIAs) (Morrisey 1993). Furthermore, it is essential that there be a thorough review process that considers the mitigation hierarchy and, if development approvals are granted, ensures that any conditions in approvals are monitored and the companies are held to legislative requirements (Foster et al. 2010). However, for many coral reef countries, even when laws requiring EIAs are in place, the capacity and resources required to conduct them is limited (Jupiter et al. 2014a) or economic development takes precedence (Manap and Voulvoulis 2015). Furthermore, even when the capacity and required resources are in place, unintended consequences can occur. For example, two different coastal development projects in Australia resulted in high levels of coral disease at one site (Pollock et al. 2014) and high levels of disease in important fisheries species, resulting in the closure of the fishery (Landos 2012). It is unclear why these impacts were not predicted, but EIAs often allow from some level of unavoidable damage to coral reefs (Foster et al. 2010). ***In these instances, additional management strategies should be put in place to reduce the impacts of coastal development, including seasonal restrictions on development activity during peak timing for vulnerable life history stages or events, such as***

during coral spawning, seagrass flowering, or fish recruitment periods (Erftemeijer et al. 2012, Erftemeijer et al. 2013, Wenger et al. in review).

Coastal development activities lead to coastal hardening, which can affect nearshore coral reefs. As the impacts of sea level rise continue to be felt, coastal hardening will further increase to slow erosion rates (Dafforn et al. 2015). As a result, ecological and engineering research has focused on ways to better design coastal infrastructure to support marine ecosystems (Firth et al. 2016). ***One proposed technique is the creation of varying artificial habitat types within permanent structures*** (Chapman and Underwood 2011, Dafforn et al. 2015). There are limited examples of eco-engineered seawalls being effective at large scales, but the incorporation of artificial habitats during the initial placement of seawalls is likely to mitigate some of the damage that would otherwise occur during their construction. ***Another technique used to mitigate some of the negative impacts of coastal marine infrastructure has been transplantation of habitat-forming species onto artificial structures*** (Ng et al. 2015). In Singapore, nursery-reared corals that were transplanted onto a seawall were found to support coral reef fish and gastropods after 24 months (Ng et al. 2015).

Managing Shipping

Accompanying the development of coastal infrastructure is the increase in shipping. Over 80 percent of traded goods currently travel by ship (Tsolaki and Diamadopoulos 2010) and this number is expected to increase, with a threefold increase forecast worldwide by 2060 (UNTCAD 2011). The increase in shipping comes with several concerns, including the introduction of invasive species and the increased risk of ship groundings. In 2017, a ship grounding occurred in Raja Ampat, one of the most biodiverse coral reefs and an important site for tourism. ***In an effort to manage impacts or potential impacts from shipping, the International Maritime Organization (IMO) has established Particularly Sensitive Sea Areas (PSSA) following recognition that specific marine areas are particularly vulnerable to shipping activities. Due to PSSAs' unique features, each one carries its own protection regime, including measures such as compulsory ship routing, reporting and no-go areas (IMO 2006).*** However, there is a mismatch between the need for designation and placement of these areas. For example, the eight busiest ports with container terminals worldwide are in China, Singapore, Hong Kong, and South Korea (World Shipping Council 2017). PSSAs have not been designated around any Asian country, even though numerous shipping routes transit the Coral Triangle (extending from the Philippines to the Solomon Islands), a global marine biodiversity "hotspot" representing 75% of marine species (Veron et al. 2009).

Not only do ship groundings cause direct damage to coral reefs, they can release invasive species into the marine environment. Ships relocate approximately 3,000 to 4,000 species each day, which can destabilize and rapidly degrade coral reef environments (Gollasch et al. 2002, Molnar et al. 2008). Since the implementation of the International Convention for the Control and Management of Ships' Ballast Water and Sediments in 2004, several technologies have been approved to treat harmful aquatic organisms or pathogens on board vessels, reviewed in Tsolaki and Diamadopoulos (2010). ***The current recommended method for controlling the introduction of non-native species is open ocean exchange of ballast water at a distance of 200 nautical miles from land and a depth of 200 meters. Open ocean exchange is not always effective; in certain instances, more organisms were found in the ballast water following exchange (e.g., Macdonald and***

Davidson 1998). This is especially the case when such water exchanges were undertaken during algal blooms. Additionally, vessels operating in coastal regions are not likely to meet the distance from land and depth requirements for open ocean exchange***. In these instances, ballast water treatment systems (BWTS) both onboard vessels and in port (reviewed in Tsolaki and Diamadopoulos 2010) may augment spatial management strategies and international legislation for protecting marine biodiversity.*** However, shore-based treatment systems may not be economically feasible for developing countries (Pereira and Brinati 2012), and retrofitting existing fleets with vessel-based systems carry economic costs and are of varying efficacy (Jee and Lee 2017).

Managing Invasive Species and Population Outbreaks of Predators

Non-native species and native species that have population outbreaks can rapidly degrade marine ecosystems (Molnar et al. 2008, Williams and Grosholz 2008), and are a particular concern for coral reefs (Smith et al. 2002, Lapointe and Bedford 2010, Frazer et al. 2012, Giddens et al. 2014, Williams et al. 2014). Here, we highlight two control initiatives that illustrate the social and financial commitments involved.

Crown-of-Thorns Starfish

Population outbreaks of the coral-eating crown-of-thorns starfish (COTS) are a major cause of live coral loss on Indo-Pacific coral reefs (Bruno and Selig 2007, De'ath et al. 2012). Outbreaks on reefs can be devastating and widespread, sometimes reducing live coral cover by 90% or more (Kayal et al. 2012). There are many factors that lead to population outbreaks, such as nutrient enrichment, that should be managed through preventative interventions (Wooldridge and Brodie 2015). Once an outbreak occurs, the only way to minimize the impact is through direct control. Many direct control methods have been attempted, including removal of the starfish and injection with points. ***The use of vinegar and lime juice to kill COTS has proven highly effective on local scales, helping to restore some level of ecosystem function*** (Dumas et al. 2015, Boström-Einarsson and Rivera-Posada 2016). In Vanuatu, after a six-month community removal initiative, women and children were able to resume normal activities in the area, including fishing and swimming (Dumas et al. 2015). Vinegar has been used in at least 10 countries and has been approved by the Great Barrier Reef Marine Park Authority as the primary treatment tool for outbreaks. Although the use of vinegar may only be feasible on small scales, direct control of predator outbreaks could positive affect locally important coral reefs.

Lionfish and Peacock Groupers

Intensive control efforts are underway to control lionfish in the Caribbean and the Atlantic and the peacock grouper (roi) in Hawaii (de León et al. 2013, Giddens et al. 2014). The removal of both lionfish and roi from reefs has been shown to be locally successful provided that removal is maintained and recommended techniques are used (Frazer et al. 2012, de León et al. 2013, Côté et al. 2014, Giddens et al. 2014, Green et al. 2014). ***Recommend techniques include culling through spearfishing and hand-netting by concerned divers and through organized lionfish derbies and tournaments (Akins 2012).*** Removal efforts involve hundreds of trained volunteer divers, and thus require extensive community engagement and cooperation. Community involvement in invasive species management might provide an opportunity to discuss other environmental issues with communities (Giddens et al. 2014). Another strategy for eradicating lionfish involves creating a market for human consumption and thus creating an incentive for harvesting, but this could lead to economic dependence on the invasive species (Morris Jr and Whitfield 2009), and also to impacts on other fisheries. For example, there is evidence from Florida of declining lobster catch in traps that are occupied by lionfish. Similar impacts are beginning to occur in Belize, which has prompted the development of a lionfish management plan (see Appendix 1). Ultimately, although effective control can occur at local scales, the labor required for control of invasive species precludes this technique from being used beyond the scale of local communities, tourist facilities, or easily accessible locations (Morris Jr and Whitfield 2009, de León et al. 2013).

Tools to Enhance Recovery

Coral Reef Restoration

Coral reef restoration is a management tool promoted to enhance recovery on degraded reefs (Rinkevich 2008, Rinkevich 2014), but successful evidence of its use on large scales is limited and costs can be prohibitively high compared to other management interventions (Haisfield et al. 2010). Coral reef restoration projects can be implemented for a variety of reasons, including conservation, restoring fisheries, and economic benefits, and it is important to be explicit about the goals. For instance, in developed countries with high capacity, such as the United States, restoration projects are currently underway for *Acropora cervicornis,* which is federally listed under the U.S. Endangered Species Act (Young et al. 2012). In 2017, a global coral reef restoration project was launched, supported by SECORE International, the California Academy of Sciences and The Nature Conservancy. This project represents the first global endeavor to restore coral reefs on a large scale and highlights the role that technology can play in coral reef conservation. In both of these programs, the primary goal is conservation.

In order for coral reef restoration to be successful, practitioners need to consider whether the cause of degradation still exists (Baums 2008): ongoing degradation will jeopardize restoration outcomes. In many cases, it may be more cost-effective and beneficial to biodiversity and ecosystem functioning to enact measures that reduce the pressure on existing coral reefs, rather than resorting to restoration (Haisfield et al. 2010, Moreno-Mateos et al. 2012). However, in some cases where the degradation has stopped (e.g., dynamite-fished rubble fields that are now protected within a marine park), low-cost restoration of structure complexity can support new recruitment and growth by corals over time as an effective long-term conservation strategy (Clark and Edwards 1995).

Restoration and propagation techniques can also be used to support aquarium and coral export industries. For example, Indonesia is one of the largest exporters of coral and the primary reason for propagating corals is to sell them (Rhyne et al. 2012). As part of the industry, the Indonesian government requires 10% of the coral grown to be used for reef restoration (Barton et al. 2015). ***Creating economic incentives that combine mariculture with reef restoration can promote both increased coral propagation and economic opportunities for communities. However, it is important to maintain a balance where mariculture does not dominate reef restoration. This is particularly true for places where*** **ex situ** ***propagation is used, as the economic incentive to maintain good*** **in situ** ***conditions for restored reefs might decline (Barton et al. 2015)*****.** Propagation has also been used to alleviate pressures from natural populations where corals are harvested for other uses. For instance, communities in Manus Island, Papua New Guinea, have successfully grown corals to be harvested to produce lime for chewing betel nut, however, the approach has not yet reached a point of sustainability.

For coral reef communities engaging in reef restoration, the costs involved can be high (Chamberland et al. 2015), with the median cost per hectare estimated to be between $162,000 and $283,000 U.S. dollar (USD) in developing and developed countries, respectively (Bayraktarov et al. 2016). In Indonesia's Komodo National Park, even simple rehabilitation (e.g., by installing locally quarried rocks on blasted rubble fields) can be expensive (~$4.80 USD per square meter) (Haisfield et al. 2010). Local restoration can provide high value for tourism, making it an attractive option for resorts with adjacent coral reefs (Guest et al. 2014). At this stage, given the costs and the labor requirements, coral reef restoration is not viable as a large-scale conservation, fisheries, or coastal defense strategy.

In the context of climate change, restoration and translocation strategies may be useful for corals that have either survived a stress event or live in more extreme conditions and may be better adapted to cope with future stress events (Coles and Riegl 2013, Rinkevich 2014). For example, restoration of climate-smart corals can involve local transplantation of coral "survivors" between nearby habitats (Palumbi et al. 2014). However, recent evidence suggests that coral reefs as a whole (as opposed to individual corals) undergoing a bleaching event are not necessarily better adapted to survive another event (Hughes et al. 2017b). See also the section below on "assisted evolution."

For coral reef communities that want to proceed with restoration, there are new approaches that can offer promise. ***For instance, micro-fragging of small fragments placed over artificial substrates can encrust and fuse to grow corals faster than normal nubbin approaches (Forsman et al. 2015). There are also several published guides on how to accomplish coral reef restoration (see Appendix 1).*** It is necessary to understand why past restoration efforts have failed to ensure future success (Clark and Edwards 1995, Fox et al. 2005, Ferse 2010, Griffin et al. 2012).

Future Frontiers: Treating Coral Disease and Promoting Assisted Evolution of Corals to Climate Change

Coral Disease

Coral disease is an underreported cause of global coral loss and is exacerbated by warming oceans (Harvell et al. 2007, Maynard et al. 2015). The causes of coral disease are complex and varied, often operating on much larger scales than coral reef managers can control. Nonetheless, there have been conservation efforts to control the spread of disease and loss of corals within colonies (Beeden et al. 2012). These techniques range from simple interventions to complex strategies.

Techniques for the treatment of marine diseases range from simple to incredibly complex. Several studies have used simple interventions, such as separating healthy coral tissue from diseased tissue with a physical barrier (Miller et al. 2014), aspirating diseased coral tissue from colonies (Hudson 2000), and even excising the tips of healthy coral from diseased colonies and transplanting them (Miller et al. 2014) or removing the diseased margin from healthy coral (Dalton et al. 2010). However, these techniques have showed variable responses. Furthermore, although they may not be expensive due to their relative simplicity, it is unlikely that they could be further developed to be a feasible strategy beyond a small spatial scale, owing to the labor intensity required. Still, local mitigation could be effective in small locally managed MPAs, such as those supporting adjacent communities or tourist facilities.

As some of the large scale drivers of coral disease, such as sewage discharge (Redding et al. 2013), nutrient runoff (Lamb et al. 2016), and high temperatures (Maynard et al. 2015), continue to intensify, it may be increasingly important to develop therapeutic methods that can treat coral disease outbreaks on larger spatial scales than can currently be treated. Phage therapy, the therapeutic use of bacteriophages, is at the frontier of coral disease treatment and is one potential option for treating coral disease *in situ*. Atad et al. (2012) found that phage-treated corals only experienced an additional 5% tissue loss, whereas non-treated corals lost 65% of live tissue after 28 days, and that disease transmission rates to surrounding healthy coral colonies were reduced. As a conservation strategy, costs and feasibility are currently highly prohibitive and effectiveness remains largely unknown. Therefore, while this technique may have the potential to “treat” larger areas of coral reefs beyond the simple interventions described above, as a management strategy it largely unrealistic in many remote coral reef communities given the demands for access to laboratory facilities, commercial infrastructure, and reliable power (Efrony et al. 2007).

Assisted Evolution

To help corals cope with rising ocean temperatures and widespread bleaching, a new management approach being considered is one that encourages assisted evolution through laboratory-evolved stress-tolerant zooxanthellae (van Oppen et al. 2015, van Oppen et al. 2017). Zooxanthellae are photosynthetic micro-organisms that live inside coral tissue and provide sustenance to it. When ocean temperature increases, the coral tissue expels them, resulting in coral bleaching. Without their food source, corals will die (van Oppen et al. 2015). Such an approach is incredibly novel and not field tested. It is likely to be very cost-prohibitive and effective only on local scales. Similarly, as a future conservation or management strategy, the demands for access to laboratory facilities, commercial infrastructure, and reliable power currently makes this largely unrealistic at larger scales. However, assisted evolution toward the restoration of heat-tolerant corals grown in laboratories may represent a future frontier of active intervention to conserve coral reef biodiversity within the next 10–15 years (Aswani et al. 2015).

Conservation in Action: Integrating Social Values, Economics, Uncertainty, Equity, and Timeframes

A challenge in conserving coral reefs is the uncertainty associated with the interactions between various stressors and the management interventions used to mitigate them. For example, amplifying feedbacks and can provoke unpredictable “ecological surprises” that can accelerate negative impacts through synergies, where the combined effect of multiple stressors exceeds the sum of individual stressor effect (Brook et al. 2008). However, synergies are only one of several types of interactions between stressors, including additive, multiplicative, dominant, antagonistic, or “supersynergies”; the outcomes of stressors’ interactions may soon be predictable in some cases, but will largely remain unknowable (Côté et al. 2016).

To address the uncertainty in stressor interactions, several strategies have been proposed. One strategy is to explicitly accommodate risk and uncertainty via investing in management of coral reefs across a range of local climatic conditions, reef habitat types, and reef states in order to maximize phenotypic and genetic diversity, which may harbor more stress-tolerant species and allow for "evolutionary rescue" to share adaptive genes throughout connected seascapes (Abelson et al. 2016, Webster et al. 2017). For example, creating a network of MPAs that promotes connectivity, while accounting for potential changes that could occur in larval distribution patterns due to climate change, will ensure that gene flow between areas persists, thus promoting adaptation and recovery potential (Mumby et al. 2011, Webster et al. 2017). Additionally, the creation of MPA networks that achieve diverse management objectives, including conservation, fisheries, and socio-economic objectives, will likely garner more support (Mangubhai et al. 2015, Krueck et al. 2017). Finally, given the uncertainty surrounding the timing and location of extreme weather events, it is critical that protected areas encompass a network of coral in order to augment the potential for recovery from extreme climate events. A second approach considers management plans in the context of climate change. Several frameworks have been developed to address the need for multiple management interventions and diverse conservation and socio-economic objectives, including marine spatial planning, ecosystem-based management, and integrated coastal zone management (Cicin-Sain and Belfiore 2005, Arkema et al. 2006, Halpern et al. 2008, Norse 2010, Mangubhai et al. 2015). In essence, all of these frameworks acknowledge that there are multiple threats to coral reefs that need to be managed in concert in order to achieve conservation objectives. This meets the observations that rarely will a single management strategy address more than one or two threats impacting coral reefs; instead multiple management strategies are needed to act at the same time and place (Figure 2).

Wenger et al. (in review) propose that multiple management interventions can be layered over each other in space and time to maximize their efficiency. For example, Zaneveld et al. (2016) found higher levels of coral mortality during elevated temperature events when corals were exposed to nutrient enrichment and algal growth due to overfishing. Therefore, creating a layered approach to fisheries management and water quality might enable enhanced coral survival to bleaching events, or faster recovery following disturbances. In addition, there may be an optimal combination of management strategies such that they can enhance the benefits of each other that may take longer to realize on their own (Possingham et al. 2015, Gilby et al. 2016). In this way, the implementation of multiple management strategies that target different stressors across multiple spatial and temporal scales is likely to provide the best outcome possible within the current climate state.

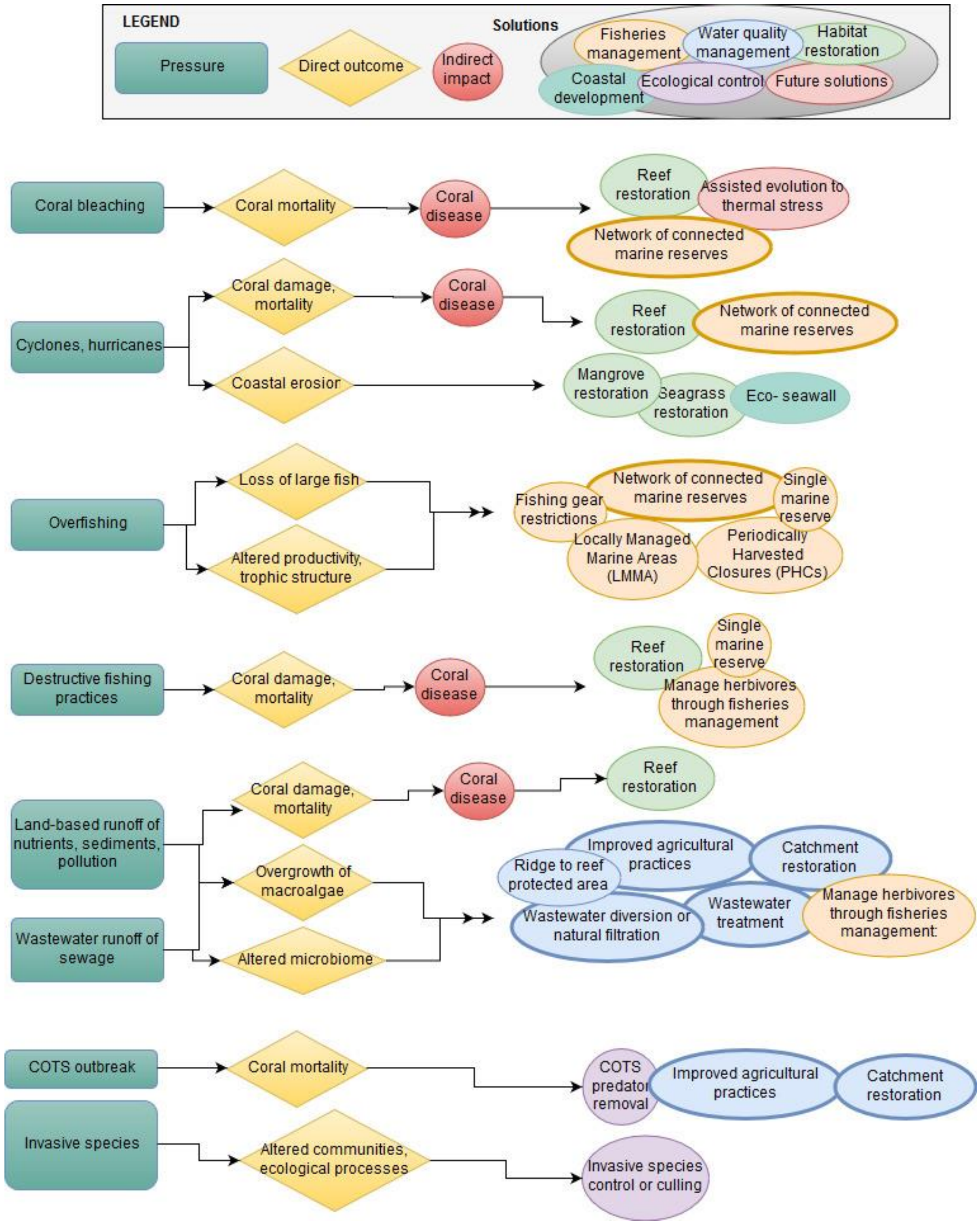

Figure 2. How to Choose Portfolios of Conservation and Management Interventions Specifically Targeted to Address Key Conservation Threats

Enabling Conditions

Policy and Legislative Approaches

Successful implementation and achievement of technical approaches to meet conservation, food security, and livelihood goals will not occur without enabling conditions in place. Fundamentally, there need to be mechanisms that recognize, deliver, and enforce different conservation interventions at multiple scales. This section highlights some considerations for different types of policies, legislated rules, and multi-lateral agreements to provide a favorable legal and policy environment for coral reef conservation.

In places where traditional management is strong and legally recognized, there is an increasing focus on supporting natural resource management and enforcement by local communities. As an example, a community in the Solomon Islands was able to peacefully negotiate a substantial fine from an illegal logging vessel that entered their managed area (Jupiter et al. 2017). On the other hand, prominent people might make decisions on management and development without consulting the broader population, which may create conflict or exclude people from full resource access (Gurney et al. 2016, Jupiter et al. 2017).

At the national level, many countries have environmental protection laws in place, although enforcement of them may vary. It may be that a legal framework is already in place to enact conservation measures. For example, through the Great Barrier Reef Marine Park Act 1975, a suite of policies have been developed and enacted to manage cruise ship activity, tourism operators, mooring locations, scientific research, dredging, and sewage discharging around the marine park (http://www.gbrmpa.gov.au/about-us/legislation-regulations-and-policies/policies-and-position-statements). The efficacy of such policies, however, depends on the ability of management to address exogenous threats beyond the local jurisdiction (Wenger et al. 2016). For instance, neither the Great Barrier Reef Marine Park Act nor the Great Barrier Reef Water Quality Protection Plan (which is a policy document) give any jurisdiction to the Great Barrier Reef Marine Park Authority to regulate catchment activities that affect water quality, thus limiting their ability to effectively manage exogenous threats.

National policy can provide considerable support to local management. In the United States, Executive Order 13089 established the interagency U.S. Coral Reef Task Force, whose mandate includes research and monitoring of coral reefs and associated threats, and serving as a coordinator and advisor for federal, state, and territorial agencies (http://www.coralreef.gov/about/docs.html). National laws can also ensure that resource extraction is meeting a set of national standards. In the United States, the Magnuson-Stevens Fishery Conservation and Management Act provides a policy framework to prevent overfishing, rebuild fish stocks, and ensure a sustainable supply of seafood. However, this act has been criticized for its failure to adopt an ecosystem-based management approach over single species management (Richmond et al. 2007). Some species-specific regulations can be beneficial. The Endangered Species Act has been successfully triggered to respond to the critical state of *Acropora cervicornis* (Hogarth 2006). Importantly, when a species is listed under the Endangered Species Act, recovery plans must be identified and listings can halt development. However, restoration attempts have been variable (Lohr et al. 2017).

When national and provincial laws and policies reflect and support community-level management, threatening processes can be managed on larger spatial scales that can more accurately reflect the ecological scale of impact. For instance, the development of province-level integrated coastal zone management plans in Fiji scales up district-level integrated coastal zone management plans with the aim of coordinating management implementation to mitigate threats at appropriate scales (i.e., at the provincial level instead of the district level). The provincial-level planning is being overseen by the Department of the Environment, which adds further legitimacy to the process (Jupiter et al. 2012a). However, when community level plans are scaled up, there is the risk that local support will weaken as the decision-making power is diluted (Gruby and Basurto 2013). National laws are likely to be followed when there is bottom-up momentum for change. In Belize, local fishers petitioned for a ban on fishing herbivores after the importance of herbivorous fishes for coral reef health and their livelihoods was conveyed to them. This led to a national law, with high compliance levels (Depondt 2014). However, there may be local backlash to these top-down decisions if there was not community-level engagement or support; this may lead to non-compliance (Fabinyi and Dalabajan 2011).

Non-legally-binding frameworks may exist for environmental management, which could provide important protections for coral reefs if followed, but are subject to the discretion of resource users. For instance, in Fiji, although there is a logging code of practice that provides guidance to forestry officers, landowners, contractors, and the forest industry on how forest harvesting should be conducted to reduce the amount of sediment runoff, communities can ultimately override guidelines in favor of development; this can lead to larger pollution impacts to nearshore coral reefs. Similarly, the Australian government has invested almost one billion dollars (AUD) into water quality improvement in Australia. However, because the best management practice guidelines that have been proposed for land use are voluntary schemes, the uptake rate has been too low to be effective (Kroon et al. 2016). The low uptake rates of best management practices in Australia demonstrate that even in a well-funded setting, coral reef management is unlikely to occur without appropriate legislative mechanisms in place.

At the international scale, there are many multi-lateral agreements and conventions that have been developed to regulate pressures on coral reefs. These include, but are not limited to, the United Nation Convention on Biological Diversity and the corresponding Aichi targets; the Convention on International Trade in Endangered Species of Wild Fauna and Flora; The Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security; The Micronesia Challenge; United Nations Sustainable Development Goals; The World Heritage Convention, and the United Nations Framework Convention on Climate Change and the Paris Agreement. These can help set national policy and are often implemented at the national or sub-national scale. However, they generally do not have legally binding commitments and many of them rely on relevant existing forums to implement actions. There are well-known issues that have resulted from international mandates—especially the designations of “residual reserves,” areas that are *de facto* protected because they have little extractive potential (Pressey et al. 2015).

Countries can strengthen their ability to meet various international commitments via multiple pathways. Importantly, countries should give greater consideration to non-conservation legal tools, such as land use planning and development control laws as well as laws on public finance. Additionally, the creation of economic incentives and disincentives, and the use of innovative market mechanisms can strengthen support of policy and legislative frameworks (Jonas and Lucas 2013).

Compliance and Enforcement

Non-compliance is one of the major barriers to effective coral reef conservation. For example, it is one of the main determining factors in MPA effectiveness (Bergseth et al. 2015); it is estimated that less than 10% of marine reserves are sufficiently managing compliance (Mora et al. 2006). As mentioned previously and in Table 2, active engagement of local stakeholders in decision-making around conservation interventions is likely to lead to greater support and compliance of management rules. Additionally, assessing the degree to which social norms drive participation and compliance or non-compliance activities may clarify how likely compliance is to occur (Gurney et al. 2016). Further, it is essential that non-compliance does not erode overall support for conservation interventions, which can happen when compliant individuals feel they are missing out on benefits (Arias et al. 2015). On the other hand, when communities are fully empowered, they can enforce management rules, leading to better compliance and support of management (Pomeroy et al. 2005, Cinner et al. 2012). ***Targeting the ultimate drivers of non-compliance may be more effective than targeting offenders themselves, but the reasoning behind non-compliance is important to understand.*** For instance, in the Philippines, the use of cyanide, even when banned, was driven by the high market of live exported reef fish (Fabinyi and Dalabajan 2011). However, in a different part of the Philippines, illegal fishing was typically carried out by young men and seen as a way to assert their masculinity and gain social status (Fabinyi 2007). In this example, market driven approaches are unlikely to change this behavior.

Incentives have also been used to try to encourage compliance, through awards, public recognitions, information and training, and financial mechanisms (Arias 2015). In the Caribbean, there was a significant, positive correlation between the number of incentives in place, including environmental education, skills training, exchange of equipment, purchase of equipment, and employment, and the biomass of commercially important fish (Kaplan et al. 2015), but the relationships of individual indicators and ecological indicators were not uniform. The introduction of incentives can have unintended consequences that need to be fully assessed prior to implementation. A number of studies have drawn attention to how providing material incentives, including payment for ecosystem services (PES), can “crowd out” or erode intrinsic pro-social and pro-environmental motivations (Frey and Jegen 2001, Narloch et al. 2012, Gurney et al. 2016). Similarly, the development of alternative livelihood schemes may bring about unintended consequences. For instance, seaweed farming in the Philippines was introduced to reduce fishing pressure. Yet they led to poor environmental outcomes, including increased pollution flowing onto reefs (Sievanen et al. 2005). Additionally, although tourism is a key source of income for many coral reef communities, consideration must be taken when promoting it as an alternative livelihood scheme. For instance, tourism development not done properly can actually driver further exploitation of fisheries because of the demand for fish from tourists (Rodrigues and Villasante 2016).

When voluntary compliance is unlikely or when outsiders fail to comply with regulations, enforcement can be necessary, but it is often costly to overall management costs. For instance, in the Great Barrier Reef Marine Park, enforcement accounts for roughly 30% of the management costs (McCook et al. 2010). Furthermore, compliance is expected to increase as the perceived legitimacy of enforcement mechanisms increases (Kaplan et al. 2015). It is thus not surprising that one of the main recipes for success is the presence of proper enforcement mechanisms (Table 2). In the

Caribbean, there was an overall positive relationship between biomass of commercially important species and the number of penalties in place, including verbal or written warnings, fines, loss of access to natural resource, confiscation of equipment, and incarceration (Kaplan et al. 2015). For co-management, Cinner et al. (2012) also found that, across several countries, graduated sanctions were an effective tool to boost compliance. Understanding the patterns of non-compliance can improve the efficiency of enforcement activities. Arias et al. (2016) observed that illegal fishing had distinct temporal patterns, related to lunar cycles, which has enabled patrols to optimize control efforts. Tracking technologies like Global Fishing Watch (www.globalfishingwatch.org) or the Spatial Management and Reporting Tool, SMART (http://smartconservationtools.org/), can provide information toward tracking compliance with conservation interventions and investing in appropriate enforcement strategies.

Financial Mechanisms

Financial support for sustainable and long-term coral reef conservation activities is critical to success. For example, in a global meta-analysis of MPAs, financial support for staff and management capacity were the strongest indicators of the conservation impact (Gill et al. 2017). For all conservation interventions, financial support is needed for a variety of activities, including day-to-day management costs (e.g., staff, fuel, offices, etc.), monitoring and reporting, enforcement, and in some cases, payments to communities and stakeholders for released financial benefits otherwise generated from resource use. Generating financial capacity should focus on two main themes: the generation of funds and the mobilization strategy for said funds. Currently, there are several strategies for fund generation that have been implemented in the coral reef conservation activities, including debt-for-nature swaps, public-private partnerships, and payments for ecosystem services. Here, we provide a brief synopsis on different finance schemes, acknowledging that when developing plans for specific locations, there are several practitioner's guides that can be followed to aid in the development of location-specific finance strategies (see Appendix 1).

Debt-for-Nature Swaps

Debt-for-nature swaps, or debt restructuring schemes, involve investment that buys a country's foreign debt at a discounted price, in return for which the country's government agrees to enact some level of protection for a terrestrial or marine area and pay for management activities of the protected area. The investor who buys the debt, and effectively invests in the protection of nature, does not own any equity or real estate and does not seek profit from the purchase of the debt. The Nature Conservancy has executed the first such debt restructuring in oceans, buying a portion of the foreign debt of the Seychelles; in essence, the debt is refinanced with a mix of investments and grants. The Nature Conservancy provided $15.2 million USD in impact capital loans and $5 million in grants to buy back $21.6 million of Seychelles' debt. The cash flow is then managed by a public-private trust fund called the Seychelles Conservation and Climate Adaptation Trust which is established specifically for this purpose. The fund will lead various streams of activities including working on the ground to improve management of coastal and marine ecosystems through a marine spatial planning process and establishment of an MPA network. Continued evidence of the potential for debt-for-nature swaps to meet ecological and socio-economic success metrics of coral reef conservation require continued monitoring and evaluation.

Payments for Ecosystem Services

PES is one of many types of marine conservation agreements used globally to generate capital and incentivize protection of resources. PES for coral reef resources can be defined by several components: 1) voluntary transactions; 2) well-defined ecosystem services, such as a marine area that would secure the service (or benefit); 3) bought by at least one buyer; 4) sold by at least one provider (seller); 5) conditionally maintained only if the provider continues to supply service (Wunder 2005). Payments can take on various forms, including 1) direct financial payments, which are usually made as compensation for opportunity cost due to forgone income; 2) financial support for community development and infrastructure; 3) in-kind payments, including goods, knowledge transfer, capacity-building in exchange for conservation; 4) rights recognition, fishing access rights, quota allocation, etc. (Hawkins et al. 2010, Muradian et al. 2010). These mechanisms account for the value of ES and the benefits they provide to people and are designed to channel ES information into decision-making processes with positive outcomes for environmental and social goals (Ingram et al. 2014).

Direct PES has most commonly been implemented with dive tourism, wherein tourists pay an extra fee to dive operators or a local community organization, and the funding finances maintenance costs of the local MPA that serves as the dive site (Lucas and Kirit 2009, Brunnschweiler 2010, Terk and Knowlton 2010). This concept has been successfully used to help create the Shark Reef Marine Reserve in Fiji (Brunnschweiler 2010). The local communities engage in a participatory business planning approach with an ecotourism operation to generate income for the local villages from diver user fees in exchange for establishment of a marine reserve completely closed to fishing within the villagers' traditional fisheries management area. In another example, Fiji's largest MPA, Namena Marine Reserve, was established through diver use fees that funded community development projects and educational scholarships for villages in the Kubulau community, where the fund is managed by the Kubulau Resource Management Committee (Clarke and Jupiter 2010). These examples from Fiji have distinctly resulted in marine biodiversity preservation, helping meet local conservation goals of increased fish biomass and sustained coral reef health (Jupiter and Egli 2010, Goetze and Fullwood 2013). PES schemes have also been proposed as a way for downstream resource users to incentivize upstream resources users to manage water quality (Goldman-Benner et al. 2012, Peng and Oleson 2017).

Payments for ecosystem services, however, are not without substantial critiques. Critics have challenged the win-win PES narrative (Muradian et al. 2013), highlighting for example that market-based interventions 1) are often unable to address underlying drivers of resource degradation such as uneven land tenure and lack of local participation in conservation (McElwee 2012); 2) may not provide "environmental additionality" (i.e., payments go toward protecting areas at low risk of being developed or exploited) (Muradian et al. 2013); and 3) are often inequitable, which can compromise other social and biological goals (Oracion et al. 2005, Lucas and Kirit 2009, Pascual et al. 2014). Further, a number of studies have drawn attention to how providing material incentives, including PES, can "crowd out" (i.e., erode) intrinsic pro-social and pro-environmental motivations (Frey and Jegen 2001, Narloch et al. 2012, Gurney et al. 2016).The mismanagement of funds or lack of tangible environmental outcomes can also undermine the process. For instance, in the Philippines, fishers agreed to give up fishing grounds for MPA establishment based on the assurance that MPAs would result in improvements in catches outside the boundaries. When this did not come into fruition, fishers began to fish in the MPA, thus weakening its effectiveness. Further complicating this situation was the frustration of repeat tourists who felt that 1) tourist fees were not being properly spent on MPA management and 2) that the coral reefs were not improving (Lucas and Kirit 2009).

The implementation of financial schemes requires the careful attention to potential hurdles. Firstly, the importance of having full stakeholder participation in decision-making is paramount. Secondly, the threatening processes causing coral reef decline must be properly addressed; otherwise coral reef recovery is unlikely, which will undermine support for existing and future conservation schemes. Thus, an investigation into whether enabling factors for success—ecological, socioeconomic, political, and cultural—are present is essential before a PES scheme is implemented (Muradian et al. 2013). These enabling conditions can include:

- Experience of local organizations with project management and finance management.
- Presence of community leadership.
- A diverse representation of voices within the community.
- Community-level decision-making and buy-in.
- Equitable distribution of benefits.

Furthermore, PES agreements toward coral reef conservation may need to define the roles and responsibilities of sellers/providers, buyers, payment fund managers, etc.; performance indicators upon which payment amounts can fluctuate; the frequency and duration of payments under the PES deal; and contingency scenarios and risk management.

Conservation Trust Funds

Conservation trust funds (CTFs) are being increasingly employed as a vehicle to mobilize funds for conservation (Bladon et al. 2014). These funds are legally independent institutions that can be used to provide sustainable, long-term financing for coral reef conservation (Balmford and Whitten 2003) and have been advocated as a beneficial tool to accumulate and re-distribute funding from diverse sources, including payments for ecosystem services, debt-for-nature swaps, and public-private partnerships (Goldman-Benner et al. 2012, Bladon et al. 2014). The distribution of funds can be structured in multiple ways, so it is important that the intent of the funding is clear (Bladon et al. 2014). Some of the main examples include the following:

- **Endowment funds,** which keep capital invested and use the interest to finance activities, may be most appropriate for the funding protect area management, due to the need for continuous, long-term funding.
- **Sinking funds** operate on a draw-down method, by directly investing the capital into conservation activities. Such a fund, often driven by philanthropic donors, may be more appropriate for conservation strategies that require larger, finite investments, such as land acquisition or large land or marine restoration activities.
- **Revolving funds** are continually replenished from sources such as continuous payments for ecosystem services, taxes/levies, developer payments, and public moneys allocated from central government budgets (Bladon et al. 2014).

There are several examples of CTFs that have been set up to conserve coral reefs. They range from funds to protect specific areas of a country to multi-national schemes, with resources being delivered in a variety of ways. The recently announced Blue Abadi Fund focuses on the protection of the Bird's

Head Seascape in West Papua. The Fund, a public-private partnership between the Indonesian government and donors, will provide grants to local communities and agencies so they can sustainably manage their marine resources. As a trust fund, the Blue Abadi Fund creates an annuity that will annually fund MPA management and capacity development for local fishers and government managers. The fund will provide 30% of the financial resources needed, with the rest being funded by the Indonesian government. In contrast, the Phoenix Islands Protected Area (PIPA) Trust Endowment Fund works by compensating the government for the fishing licenses that would have been sold to foreign fishing operations if the PIPA were not protected. The fund has enabled all of the PIPA to be a no-take marine reserve (Obura et al. 2016). There are multiple regional funds that operate in the Caribbean. The Caribbean Biodiversity Fund provides funding to the National Protected Area Trust Funds established in each of the eight participating countries to support activities that contribute substantially to the conservation, protection, and maintenance of biodiversity. The Mesoamerican Reef Fund funds projects on a competitive basis that focus on clearly defined priority protected area sites. A thorough review of CTFs can be found in Bladon et al. (2014). Bladon et al. (2014) provide insight into lessons learned that should improve future conservation fund endeavors. They highlight the need for a clear vision shared among a diverse group of stakeholders, a legal and financial framework for developing a fund, and government buy-in. At this point in time, it is difficult to assess the evidence for the success of CTFs in terms of conservation impact. Many of the funds are young and may not yet show any positive benefits. More importantly, there have been limited monitoring and evaluation strategies implemented alongside funding, which makes impact assessment challenging (Bladon et al. 2014). Thus, it is absolutely imperative that any conservation intervention implemented should require monitoring and impact evaluation.

Market Mechanisms

Several market mechanisms are currently in place to incentivize sustainable development with relevance to coral reef conservation. In particular, the Marine Stewardship Council (MSC) and the Forest Stewardship Council provide certifications for sustainably harvested fisheries and forests. The aim is to foster more sustainable natural resource extraction through promotion of more “eco-friendly” products on the market. Several countries with coral reefs have both types of certification, though the MSC certification is in in place for their tuna fisheries as opposed to coral reef fisheries, highlighting the need to examine if this type of certification is feasible or advisable for coral reef fisheries. Coral reef fisheries are multi-species, multi-gear fisheries, and so the assessment process for stocks and fishery sustainability has previously been a challenge, which is why there are not really any coral reef fisheries certified. Advocates of MSC certification point to evidence that shows certified fisheries are above biomass levels that would produce maximum sustainable yield compared to non-certified fisheries (Gutiérrez et al. 2012). However, the MSC certification scheme has been criticized for the “price of admission” favoring larger fisheries and creating perverse incentives (Jacquet et al. 2010, Pérez-Ramírez et al. 2016). There may be opportunities to provide financial support to small-scale fisheries to help them gain MSC certification (Pérez-Ramírez et al. 2016). Ultimately, unless compliance, enforcement, and monitoring measures are in place, it will difficult to ensure the effectiveness of different policy approaches across all scales.

Toward Success: Monitoring the Social and Ecological Impact of Investments and Implementing Adaptive Management

Rigorous monitoring is essential for evaluating the effectiveness of management actions to conserve coral reefs and enabling adaptive management. Monitoring is a crucial component of an informed process for making decisions, and design should be driven by the decisions context, and associated risks and uncertainties (Lyons et al. 2008); this is especially important when the efficacy or magnitude of impact of management actions is uncertain (Converse et al. 2013, Cook et al. 2016). There are published standards for recovery or maintenance targets for coral reef fish biomass needed to maintain reef health (McClanahan et al. 2012b, Karr et al. 2015, MacNeil et al. 2015). Similar standards should be developed for recovery from non-fishing-related stressors in order to effectively quantify the impact of management actions.

Costs of monitoring can be high in relation to program budgets, so it is critical to design monitoring efforts to ensure a high return on investment. Insufficient rigor can mean that data fail to translate into information that can support decisions like planning, and management investments and priorities. Given that many coral reefs are in developing countries, building local scientific capacity to undertake the full cycle of monitoring is key to developing informed decision-making. Collecting baseline data before a management intervention is vital. In a recent study, investing in the capacity of local staff to manage, analyze, interpret, and communicate about data proved the most cost-effective approach in the long term, though this approach to monitoring has tradeoffs (Fox et al. 2017). Most critically, it can result in a poor baseline as participants develop skills. Consequently, to inform management decisions, it is pivotal for trained experts work with local staff at the beginning to collect high-rigor data. This may require staggered investment, weighted toward program initiation to support both collection of high-value baseline information and skill development.

Conclusions: Summary of Recommendations

The goal of this white paper is to synthesize and summarize a range of coral reef conservation strategies. The following recommendations focus on equitable conservation practices that will help to align successful interventions with diverse cultures and worldviews, will contribute to ensuring the right decisions are made, and will help build greater investment into conservation portfolios that will lead to successful reef conservation:

1. Community-driven conservation initiatives are likely to have the greatest buy-in. They can be strategically supported and scaled up through nested institutions, including NGOs, governments, and donors.
2. Networks of spatially managed coral reefs, supported by fisheries gear restrictions, can provide both conservation and fishery outcomes at multiple scales. This approach accounts for different home ranges and larval dispersal patterns of coral reef species, and prioritizes connectivity across patches and habitats to increase the probability of “evolutionary rescue,” whereby adaptive genes may spread across meta-populations, increasing the resilience of reefs to climate change (Webster et al. 2017).
3. Managing water quality at the ridge to reef scale can reduce the impacts from soil runoff, nutrient enrichment, and other forms of pollution. The protection of riparian and coastal vegetation and the introduction of erosion control measures where land use cannot be prevented on steep slopes is essential. Wastewater management through treatment facilities,

diversion, or natural filtration mechanisms is essential to reduce marine pollution and its subsequent impacts on both reefs and humans.

4. Active restoration of reefs and the local control of invasive species can be costly, but where these interventions can be undertaken in a cost-effective manner they may significantly enhance the conservation of small local areas of coral reefs.
5. In cases of acute disturbances, local-scale active restoration may promote recovery, but emphasis should be placed on prevention of damage. Recurrent impacts shrink the available window of recovery for slow-growing ecosystems, such as reef corals.
6. Strategies matched in space and time should be designed to address the impacts of multiple stressors and their potential interactions; strategies focusing on single stressors may ultimately fail.
7. Successful policy approaches will depend on local contexts. Complementary policies across governance levels that support and strengthen each other will likely lead to the achievement of both conservation and development goals.
8. Financial mechanisms should be thoroughly vetted to ensure their appropriateness to the given context and determine time requirements of financial needs to support conservation and management interventions.
9. Voluntary compliance through strong local support is ideal. In cases where enforcement is necessary, understanding the drivers and patterns of non-compliance will allow for more effective countermeasures.

Robust monitoring and evaluation strategies are necessary to assess the effectiveness of management actions in order to strengthen the evidence base of coral reef conservation and inform adaptive management.

References

Abelson, A., P. A. Nelson, G. J. Edgar, N. Shashar, D. C. Reed, J. Belmaker, G. Krause, M. W. Beck, E. Brokovich, R. France, and S. D. Gaines. 2016. Expanding marine protected areas to include degraded coral reefs. Conservation Biology **30**:1182-1191.

Afflerbach, J. C., S. E. Lester, D. T. Dougherty, and S. E. Poon. 2014. A global survey of "TURF-reserves", Territorial Use Rights for Fisheries coupled with marine reserves. Global Ecology and Conservation **2**:97-106.

Agouridis, C. T., S. R. Workman, R. C. Warner, and G. D. Jennings. 2005. Livestock grazing management impacts on stream water quality: a review. JAWRA Journal of the American Water Resources Association **41**:591-606.

Ainsworth, T. D., S. F. Heron, J. C. Ortiz, P. J. Mumby, A. Grech, D. Ogawa, C. M. Eakin, and W. Leggat. 2016. Climate change disables coral bleaching protection on the Great Barrier Reef. Science **352**:338-342.

Akins, L. 2012. Best practices and strategies for lionfish control. Invasive lionfish: a guide to control and management. Gulf and Fisheries Institute Press, Fort Pierce.

Alva, S., K. Johnson, A. Jacob, H. D'Agnes, R. Mantovani, and T. Evans. 2016. Marine protected areas and children's dietary diversity in the Philippines. Population and environment **37**:341-361.

Anthony, K. R. 2016. Coral reefs under climate change and ocean acidification: challenges and opportunities for management and policy.

Arias-González, J. E., T. Fung, R. M. Seymour, J. R. Garza-Pérez, G. Acosta-González, Y.-M. Bozec, and C. R. Johnson. 2017. A coral-algal phase shift in Mesoamerica not driven by changes in herbivorous fish abundance. PLoS ONE **12**:e0174855.

Arias, A. 2015. Understanding and managing compliance in the nature conservation context. Journal of Environmental Management **153**:134-143.

Arias, A., J. E. Cinner, R. E. Jones, and R. L. Pressey. 2015. Levels and drivers of fishers' compliance with marine protected areas. Ecology and Society **20**:1-14.

Arias, A., R. L. Pressey, R. E. Jones, J. Álvarez-Romero, and J. E. Cinner. 2016. Optimizing enforcement and compliance in offshore marine protected areas: A case study from Cocos Island, Costa Rica. Oryx.

Arkema, K. K., S. C. Abramson, and B. M. Dewsbury. 2006. Marine ecosystem-based management: from characterization to implementation. Frontiers in Ecology and the Environment **4**:525-532.

Aswani, S., P. J. Mumby, A. C. Baker, P. Christie, L. J. McCook, R. S. Steneck, and R. H. Richmond. 2015. Scientific frontiers in the management of coral reefs. Frontiers in Marine Science **2**:50.

Aswani, S. and R. Hamilton. 2004. The value of many small vs. few large marine protected areas in the Western Solomon Islands. Available: http://westernsolomons.uib.no/docs/Aswani,%20Shankar/Aswan%20and%20Hamilton%20(2004)%20Marine%20protected%20areas%20in%20Western%20Solomon%20Islands%20(article).pdf. Accessed 27 September 2017.

Atad, I., A. Zvuloni, Y. Loya, and E. Rosenberg. 2012. Phage therapy of the white plague-like disease of Favia favus in the Red Sea. Coral Reefs **31**:665-670.

Babcock, R., N. Shears, A. Alcala, N. Barrett, G. Edgar, K. Lafferty, T. McClanahan, and G. Russ. 2010. Decadal trends in marine reserves reveal differential rates of change in direct and indirect effects. Proceedings of the National Academy of Sciences **107**:18256-18261.

Bah, A., M. Husni, C. Teh, M. Rafii, S. Syed Omar, and O. Ahmed. 2014. Reducing Runoff Loss of Applied Nutrients in Oil Palm Cultivation Using Controlled-Release Fertilizers. Advances in Agriculture **2014**.

Bahr, K. D., P. L. Jokiel, and R. J. Toonen. 2015. The unnatural history of Kāne ʻohe Bay: coral reef resilience in the face of centuries of anthropogenic impacts. PeerJ **3**:e950.

Balgos, M. C. 2005. Integrated coastal management and marine protected areas in the Philippines: concurrent developments. Ocean & Coastal Management **48**:972-995.

Balmford, A., and T. Whitten. 2003. Who should pay for tropical conservation, and how could the costs be met? Oryx **37**:238-250.

Bartley, R., Z. T. Bainbridge, S. E. Lewis, F. J. Kroon, S. N. Wilkinson, J. E. Brodie, and D. M. Silburn. 2014a. Relating sediment impacts on coral reefs to watershed sources, processes and management: A review. Science of the Total Environment **468**:1138-1153.

Bartley, R., J. P. Corfield, A. A. Hawdon, A. E. Kinsey-Henderson, B. N. Abbott, S. N. Wilkinson, and R. J. Keen. 2014b. Can changes to pasture management reduce runoff and sediment loss to the Great Barrier Reef? The results of a 10-year study in the Burdekin catchment, Australia. The Rangeland Journal **36**:67-84.

Barton, J. A., B. L. Willis, and K. S. Hutson. 2015. Coral propagation: a review of techniques for ornamental trade and reef restoration. Reviews in Aquaculture.

Baskett, M. L., R. M. Nisbet, C. V. Kappel, P. J. Mumby, and S. D. Gaines. 2010. Conservation management approaches to protecting the capacity for corals to respond to climate change: a theoretical comparison. Global Change Biology **16**:1229-1246.

Baums, I. B. 2008. A restoration genetics guide for coral reef conservation. Molecular ecology **17**:2796-2811.

Bayraktarov, E., M. I. Saunders, S. Abdullah, M. Mills, J. Beher, H. P. Possingham, P. J. Mumby, and C. E. Lovelock. 2016. The cost and feasibility of marine coastal restoration. Ecological Applications **26**:1055-1074.

Beeden, R., J. A. Maynard, P. A. Marshall, S. F. Heron, and B. L. Willis. 2012. A framework for responding to coral disease outbreaks that facilitates adaptive management. Environmental management **49**:1-13.

Bennett, N. J., L. Teh, Y. Ota, P. Christie, A. Ayers, J. C. Day, P. Franks, D. Gill, R. L. Gruby, J. N. Kittinger, J. Z. Koehn, N. a. Lewis, J. Parks, M. Vierros, T. S. Whitty, A. Wilhelm, K. Wright, J. A. Aburto, E. M. Finkbeiner, C. F. Gaymer, H. Govan, N. Gray, R. M. Jarvis, M. Kaplan-Hallam, and T. Satterfield. 2017. An appeal for a code of conduct for marine conservation. Marine Policy **81**:411-418.

Bergseth, B. J., G. R. Russ, and J. E. Cinner. 2015. Measuring and monitoring compliance in no-take marine reserves. Fish and fisheries **16**:240-258.

Birkeland, C., A. Green, D. Fenner, C. Squair, and A. Dahl. 2013. Substratum stability and coral reef resilience: insights from 90 years of disturbances on a reef in American Samoa1. Micronesica **6**:1-16.

Bladon, A., E. Mohammed, and E. MILNER GULLAND. 2014. A Review of Conservation Trust

Funds for Sustainable Marine Resources Management: Conditions for Success. Documento de trabajo de IIED. Londres: IIED.

Boaden, A., and M. Kingsford. 2015. Predators drive community structure in coral reef fish assemblages. Ecosphere **6**:1-33.

Boström-Einarsson, L., and J. Rivera-Posada. 2016. Controlling outbreaks of the coral-eating crown-of-thorns starfish using a single injection of common household vinegar. Coral Reefs **35**:223-228.

Brewer, T. 2013. Dominant discourses, among fishers and middlemen, of the factors affecting coral reef fish distributions in Solomon Islands. Marine Policy **37**:245-253.

Brodie, J. E., J. Waterhouse, B. Schaffelke, M.Furnas, J. Maynard, C. Collier, S. Lewis, M. Warne, K. Fabricius, M. Devlin, L. McKenzie, H. Yorkston, L. Randall, and J. Bennett. 2013. Relative risks to the Great Barrier Reef from degraded water quality. Department of the Premier and Cabinet, Queensland Government, Brisbane.

Brook, B. W., N. S. Sodhi, and C. J. Bradshaw. 2008. Synergies among extinction drivers under global change. Trends in Ecology & Evolution **23**:453-460.

Brooks, A. P., J. Spencer, J. Olley, T. Pietsch, F. Iwashita, D. Borombovits, and G. Curwen. 2015. The importance of managing riparian zones for saving the Great Barrier Reef.*in* Proceedings of the 7th Australian Stream Management Conference, Townsville, QLD.

Brunnschweiler, J. M. 2010. The Shark Reef Marine Reserve: a marine tourism project in Fiji involving local communities. Journal of Sustainable Tourism **18**:29-42.

Bruno, J. F., and E. R. Selig. 2007. Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. PLoS ONE **2**:e711.

Burke, L., K. Reytar, M. Spalding, and A. Perry. 2011. Reefs at risk revisited. World Resources Institute, Washington, D.C.

Camargo, C., J. H. Maldonado, E. Alvarado, R. Moreno-Sánchez, S. Mendoza, N. Manrique, A. Mogollón, J. D. Osorio, A. Grajales, and J. A. Sánchez. 2009. Community involvement in management for maintaining coral reef resilience and biodiversity in southern Caribbean marine protected areas. Biodiversity and Conservation **18**:935-956.

Cardinale, B. J., J. E. Duffy, A. Gonzalez, D. U. Hooper, C. Perrings, P. Venail, A. Narwani, G. M. Mace, D. Tilman, and D. A. Wardle. 2012. Biodiversity loss and its impact on humanity. Nature **486**:59.

Carilli, J. E., R. D. Norris, B. A. Black, S. M. Walsh, and M. McField. 2009. Local stressors reduce coral resilience to bleaching. PLoS ONE **4**:e6324.

Carpenter, K. E., M. Abrar, G. Aeby, R. B. Aronson, S. Banks, A. Bruckner, A. Chiriboga, J. Cortés, J. C. Delbeek, L. DeVantier, G. J. Edgar, A. J. Edwards, D. Fenner, H. M. Guzmán, B. W. Hoeksema, G. Hodgson, O. Johan, W. Y. Licuanan, S. R. Livingstone, E. R. Lovell, J. A. Moore, D. O. Obura, D. Ochavillo, B. A. Polidoro, W. F. Precht, M. C. Quibilan, C. Reboton, Z. T. Richards, A. D. Rogers, J. Sanciangco, A. Sheppard, C. Sheppard, J. Smith, S. Stuart, E. Turak, J. E. N. Veron, C. Wallace, E. Weil, and E. Wood. 2008. One-Third of Reef-Building Corals Face Elevated Extinction Risk from Climate Change and Local Impacts. Science **321**:560-563.

Cesar, H., L. Burke, and L. Pet-Soede. 2003. The economics of worldwide coral reef degradation. Cesar environmental economics consulting (CEEC).

Chamberland, V. F., M. J. Vermeij, M. Brittsan, M. Carl, M. Schick, S. Snowden, A. Schrier, and D. Petersen. 2015. Restoration of critically endangered elkhorn coral (Acropora palmata) populations using larvae reared from wild-caught gametes. Global Ecology and Conservation **4**:526-537.

Chapman, M., and A. Underwood. 2011. Evaluation of ecological engineering of “armoured” shorelines to improve their value as habitat. Journal of Experimental Marine Biology and Ecology **400**:302-313.

Cho, L. 2005. Marine protected areas: a tool for integrated coastal management in Belize. Ocean and Coastal Management **48**: 932-947.

Christie, P. 2005. Is Integrated Coastal Management Sustainable? Ocean and Coastal Management **48**: 208-232.

Christie, P. 2004. Marine protected areas as biological successes and social failures in Southeast Asia. Pages 155-164 *in* American Fisheries Society Symposium. Citeseer.

Christie, P., R. B. Pollnac, E. G. Oracion, A. Sabonsolin, R. Diaz, and D. Pietri. 2009. Back to basics: an empirical study demonstrating the importance of local-level dynamics for the success of tropical marine ecosystem-based management. Coastal Management **37**:349-373.

Christie, P., and A. T. White. 2007. Best practices for improved governance of coral reef marine protected areas. Coral Reefs **26**:1047-1056.

Cicin-Sain, B., and S. Belfiore. 2005. Linking marine protected areas to integrated coastal and ocean management: A review of theory and practice. Ocean & Coastal Management **48**:847-868.

Cinner, J., M. Marnane, T. McClanahan, and G. Almany. 2006. Periodic closures as adaptive coral reef management in the Indo-Pacific. Ecology and Society **11**.

Cinner, J. E., C. Huchery, M. A. MacNeil, N. A. J. Graham, T. R. McClanahan, J. Maina, E. Maire, J. N. Kittinger, C. C. Hicks, C. Mora, E. H. Allison, S. D’Agata, A. Hoey, D. A. Feary, L. Crowder, I. D. Williams, M. Kulbicki, L. Vigliola, L. Wantiez, G. Edgar, R. D. Stuart-Smith, S. A. Sandin, A. L. Green, M. J. Hardt, M. Beger, A. Friedlander, S. J. Campbell, K. E. Holmes, S. K. Wilson, E. Brokovich, A. J. Brooks, J. J. Cruz-Motta, D. J. Booth, P. Chabanet, C. Gough, M. Tupper, S. C. A. Ferse, U. R. Sumaila, and D. Mouillot. 2016. Bright spots among the world’s coral reefs. Nature **535**:416-419.

Cinner, J. E., M. J. Marnane, and T. McCLANAHAN. 2005. Conservation and community benefits from traditional coral reef management at Ahus Island, Papua New Guinea. Conservation Biology **19**:1714-1723.

Cinner, J. E., T. R. McClanahan, N. A. J. Graham, M. S. Pratchett, S. K. Wilson, and J.-B. Raina. 2009. Gear-based fisheries management as a potential adaptive response to climate change and coral mortality. Journal of Applied Ecology **46**:724-732.

Cinner, J. E., T. R. McClanahan, M. A. MacNeil, N. A. J. Graham, T. M. Daw, A. Mukminin, D. A. Feary, A. L. Rabearisoa, A. Wamukota, N. Jiddawi, S. J. Campbell, A. H. Baird, F. A. Januchowski-Hartley, S. Hamed, R. Lahari, T. Morove, and J. Kuange. 2012. Comanagement of coral reef social-ecological systems. Proceedings of the National Academy of Sciences **109**:5219-5222.

Clark, S., and A. J. Edwards. 1995. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. Coral Reefs **14**:201-213.

Clarke, P., and S. D. Jupiter. 2010. Law, custom and community-based natural resource management in Kubulau District(Fiji). Environmental Conservation **37**:98-106.

Cohen, P. J., L. S. Evans, and M. Mills. 2012. Social networks supporting governance of coastal ecosystems in Solomon Islands. Conservation Letters **5**:376-386.

Cohen, P. J., and S. J. Foale. 2013. Sustaining small-scale fisheries with periodically harvested marine reserves. Marine Policy **37**:278-287.

Coles, S. L., and B. M. Riegl. 2013. Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. Marine Pollution Bulletin **72**:323-332.

Condy, M., J. E. Cinner, T. R. McClanahan, and D. R. Bellwood. 2015. Projections of the impacts of gear-modification on the recovery of fish catches and ecosystem function in an impoverished fishery. Aquatic Conservation: Marine and Freshwater Ecosystems **25**:396-410.

Converse, S. J., C. T. Moore, M. J. Folk, and M. C. Runge. 2013. A matter of tradeoffs: reintroduction as a multiple objective decision. The Journal of Wildlife Management **77**:1145-1156.

Cook, C. N., K. de Bie, D. A. Keith, and P. F. Addison. 2016. Decision triggers are a critical part of evidence-based conservation. Biological Conservation **195**:46-51.

Côté, I. M., L. Akins, E. Underwood, J. Curtis-Quick, and S. J. Green. 2014. Setting the record straight on invasive lionfish control: Culling works. 2167-9843, PeerJ PrePrints.

Côté, I. M., and E. S. Darling. 2010. Rethinking ecosystem resilience in the face of climate change. PLoS Biol **8**:e1000438.

Côté, I. M., E. S. Darling, and C. J. Brown. 2016. Interactions among ecosystem stressors and their importance in conservation. Page 20152592 *in* Proc. R. Soc. B. The Royal Society.

Cox, C., A. Valdivia, M. McField, K. Castillo, and J. F. Bruno. 2017. Establishment of marine protected areas alone does not restore coral reef communities in Belize. Marine ecology progress series **563**:65-79.

Cramer, K. L., J. B. Jackson, C. V. Angioletti, J. Leonard-Pingel, and T. P. Guilderson. 2012. Anthropogenic mortality on coral reefs in Caribbean Panama predates coral disease and bleaching. Ecology letters **15**:561-567.

Dafforn, K. A., M. Mayer-Pinto, R. L. Morris, and N. J. Waltham. 2015. Application of management tools to integrate ecological principles with the design of marine infrastructure. Journal of Environmental Management **158**:61-73.

Dalton, S., S. Godwin, S. Smith, and L. Pereg. 2010. Australian subtropical white syndrome: a transmissible, temperature-dependent coral disease. Marine and freshwater research **61**:342-350.

Darling, E. S., N. A. J. Graham, F. A. Januchowski-Hartley, K. L. Nash, M. S. Pratchett, and S. K. Wilson. 2017. Relationships between structural complexity, coral traits, and reef fish assemblages. Coral Reefs:1-15.

Darling, E. S., T. R. McClanahan, and I. M. Côté. 2013. Life histories predict coral community disassembly under multiple stressors. Global Change Biology **19**:1930-1940.

Day, J., N. Dudley, M. Hockings, G. Holmes, D. d. A. Laffoley, S. Stolton, and S. M. Wells. 2012. Guidelines for applying the IUCN protected area management categories to marine protected areas. IUCN.

Day, J. C. 2002. Zoning—lessons from the Great Barrier Reef marine park. Ocean & Coastal Management **45**:139-156.

De'ath, G., K. E. Fabricius, H. Sweatman, and M. Puotinen. 2012. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proc Nat Acad Sci **109**:17995-17999.

De Groot, R., L. Brander, S. Van Der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, N. Crossman, A. Ghermandi, and L. Hein. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services **1**:50-61.

de León, R., K. Vane, P. Bertuol, V. C. Chamberland, F. Simal, E. Imms, and M. J. Vermeij. 2013. Effectiveness of lionfish removal efforts in the southern Caribbean. Endangered Species Research **22**:175-182.

Depondt, F. 2014. Protecting Reef Grazers to Enable Coral Reef Recovery: An Innovative Coral Reef Management Approach in Belize. Reef Resilience.

Dikou, A., and R. van Woesik. 2006. Survival under chronic stress from sediment load: Spatial patterns of hard coral communities in the southern islands of Singapore. Marine Pollution Bulletin **52**:7-21.

Douglas, I. 1967. Man, vegetation and the sediment yields of rivers. Nature **215**:925-928.

Dumas, P., S. Gereva, M. Moutardier, J. Ham, and R. Kaku. 2015. Collective action and lime juice fight crown-of-thorns starfish outbreaks in Vanuatu. SPC Fisheries newsletter **146**:47-52.

Edgar, G. J., R. D. Stuart-Smith, T. J. Willis, S. Kininmonth, S. C. Baker, S. Banks, N. S. Barrett, M. A. Becerro, A. T. Bernard, and J. Berkhout. 2014. Global conservation outcomes depend on marine protected areas with five key features. Nature **506**:216-220.

Edinger, E. N., G. V. Limmon, J. Jompa, W. Widjatmoko, J. M. Heikoop, and M. J. Risk. 2000. Normal coral growth rates on dying reefs: Are coral growth rates good indicators of reef health? Mar Pollut Bull **40**:404-425.

Efrony, R., Y. Loya, E. Bacharach, and E. Rosenberg. 2007. Phage therapy of coral disease. Coral Reefs **26**:7-13.

Eisma-Osorio, R.-L., R. C. Amolo, A. P. Maypa, A. T. White, and P. Christie. 2009. Scaling up local government initiatives toward ecosystem-based fisheries management in Southeast Cebu Island, Philippines. Coastal Management **37**:291-307.

Erftemeijer, P. L., M. J. Jury, B. Gabe, J. T. Dijkstra, D. Leggett, T. M. Foster, and D. J. Shafer. 2013. Dredging, port-and waterway construction near coastal plant habitats. Page 280 *in* Coasts and Ports 2013: 21st Australasian Coastal and Ocean Engineering Conference and the 14th Australasian Port and Harbour Conference. Engineers Australia.

Erftemeijer, P. L. A., B. Riegl, B. W. Hoeksema, and P. A. Todd. 2012. Environmental impacts of dredging and other sediment disturbances on corals: A review. Marine Pollution Bulletin **64**:1737-1765.

Fabinyi, M. 2007. Illegal fishing and masculinity in the Philippines a look at the Calamianes Islands in Palawan. Philippine studies:509-529.

Fabinyi, M., and D. Dalabajan. 2011. Policy and practice in the live reef fish for food trade: A case study from Palawan, Philippines. Marine Policy **35**:371-378.

Fabricius, K., G. De'ath, L. McCook, E. Turak, and D. M. c. B. Williams. 2005. Changes in algal, coral, and fish assemblages along water quality gradients on the inshore Great Barrier Reef. Mar Pollut Bull **51**:384-398.

Ferse, S. C. A. 2010. Poor Performance of Corals Transplanted onto Substrates of Short Durability. Restoration Ecology **18**:399-407.

Firth, L. B., K. A. Browne, A. M. Knights, S. J. Hawkins, and R. Nash. 2016. Eco-engineered rock pools: a concrete solution to biodiversity loss and urban sprawl in the marine environment. Environmental Research Letters **11**:094015.

Fisher, R., R. A. O'Leary, S. Low-Choy, K. Mengersen, N. Knowlton, R. E. Brainard, and M. J. Caley. 2015. Species richness on coral reefs and the pursuit of convergent global estimates. Current Biology **25**:500-505.

Foley, J. R. 2012. Managed access: moving towards collaborative fisheries sustainability in Belize.*in* Proceedings of the 12th International Coral Reef Symposium.

Forsman, Z. H., C. A. Page, R. J. Toonen, and D. Vaughan. 2015. Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover. PeerJ **3**:e1313.

Foster, T., E. Corcoran, P. Erftemeijer, C. Fletcher, K. Peirs, C. Dolmans, A. Smith, H. Yamamoto, and M. Jury. 2010. Dredging and port construction around coral reefs. The World Association for Waterborne Transport Infrastructure.

Fox, H. E., M. D. Barnes, G. N. Ahmadia, G. Kao, L. Glew, K. Haisfield, N. I. Hidayat, C. L. Huffard, L. Katz, and S. Mangubhai. 2017. Generating actionable data for evidence-based conservation: The global center of marine biodiversity as a case study. Biological Conservation **210**:299-309.

Fox, H. E., P. J. Mous, J. S. Pet, A. H. Muljadi, and R. L. Caldwell. 2005. Experimental Assessment of Coral Reef Rehabilitation Following Blast Fishing

Evaluación Experimental de la Rehabilitación de Arrecifes de Coral Después de Pêsca con Explosivos. Conservation Biology **19**:98-107.

Frazer, T. K., C. A. Jacoby, M. A. Edwards, S. C. Barry, and C. M. Manfrino. 2012. Coping with the lionfish invasion: can targeted removals yield beneficial effects? Reviews in Fisheries Science **20**:185-191.

Frey, J. B. and F. Berkes. 2014. Can partnerships and community-based conservation reverse the decline of coral reef social-ecological systems? International Journal of the Commons **8**: 26-46.

Frey, B. S., and R. Jegen. 2001. Motivation crowding theory. Journal of economic surveys **15**:589-611.

Friedlander, A. M., J. M. Shackeroff, and J. N. Kittinger. 2013. Customary marine resource knowledge and use in contemporary Hawai 'i 1. Pacific Science **67**:441-460.

Gardner, T. A., I. M. Côté, J. A. Gill, A. Grant, and A. R. Watkinson. 2005. HURRICANES AND CARIBBEAN CORAL REEFS: IMPACTS, RECOVERY PATTERNS, AND ROLE IN LONG-TERM DECLINE. Ecology **86**:174-184.

Giddens, J., A. M. Friedlander, E. Conklin, C. Wiggins, K. Stamoulis, and M. K. Donovan. 2014. Experimental removal of the invasive peacock hind (roi) Cephalopholis argus, in Puako, Hawai 'i: methods for assessing and managing marine invasive species. Mar Ecol Prog Ser **511**:209-221.

Gilby, B. L., A. D. Olds, R. M. Connolly, T. Stevens, C. J. Henderson, P. S. Maxwell, I. R. Tibbetts, D. S. Schoeman, D. Rissik, and T. A. Schlacher. 2016. Optimising Land-Sea Management for Inshore Coral Reefs. PLoS ONE **11**:e0164934.

Gill, D. A., M. B. Mascia, G. N. Ahmadia, L. Glew, S. E. Lester, M. Barnes, I. Craigie, E. S. Darling, C. M. Free, and J. Geldmann. 2017. Capacity shortfalls hinder the performance of marine protected areas globally. Nature.

Gjertsen, H. 2005. Can habitat protection lead to improvements in human well-being? Evidence from marine protected areas in the Philippines. World Development **33**:199-217.

Goetze, J., and L. Fullwood. 2013. Fiji's largest marine reserve benefits reef sharks. Coral Reefs **32**:121-125.

Goetze, J., T. Langlois, J. Claudet, F. Januchowski-Hartley, and S. D. Jupiter. 2016. Periodically harvested closures require full protection of vulnerable species and longer closure periods. Biological Conservation **203**:67-74.

Goldman-Benner, R. L., S. Benitez, T. Boucher, A. Calvache, G. Daily, P. Kareiva, T. Kroeger, and A. Ramos. 2012. Water funds and payments for ecosystem services: practice learns from theory and theory can learn from practice. Oryx **46**:55.

Gollasch, S., E. MacDonald, S. Belson, H. Botnen, J. T. Christensen, J. P. Hamer, G. Houvenaghel, A. Jelmert, I. Lucas, and D. Masson. 2002. Life in ballast tanks. Pages 217-231 Invasive aquatic species of Europe. Distribution, impacts and management. Springer.

Gomes, I., K. Erzini, and T. R. McClanahan. 2014. Trap modification opens new gates to achieve sustainable coral reef fisheries. Aquatic Conservation: Marine and Freshwater Ecosystems **24**:680-695.

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

Green, A. L., A. P. Maypa, G. R. Almany, K. L. Rhodes, R. Weeks, R. A. Abesamis, M. G. Gleason, P. J. Mumby, and A. T. White. 2015. Larval dispersal and movement patterns of coral reef fishes, and implications for marine reserve network design. Biological Reviews **90**:1215-1247.

Green, S. J., N. K. Dulvy, A. M. Brooks, J. L. Akins, A. B. Cooper, S. Miller, and I. M. Côté. 2014. Linking removal targets to the ecological effects of invaders: a predictive model and field test. Ecological Applications **24**:1311-1322.

Griffin, S., H. Spathias, T. Moore, I. Baums, and B. Griffin. 2012. Scaling up Acropora nurseries in the Caribbean and improving techniques. Pages 1-5 *in* Proceedings of the 12th International Coral Reef Symposium. ARC Centre of Excellence for Coral Reef Studies Townsville.

Gruby, R. L., and X. Basurto. 2013. Multi-level governance for large marine commons: politics and polycentricity in Palau's protected area network. Environmental Science & Policy **33**:260-272.

Guest, J. R., A. H. Baird, J. A. Maynard, E. Muttaqin, A. J. Edwards, S. J. Campbell, K. Yewdall, Y. A. Affendi, and L. M. Chou. 2012. Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. PLoS ONE **7**:e33353.

Guest, J. R., M. V. Baria, E. D. Gomez, A. J. Heyward, and A. J. Edwards. 2014. Closing the circle: is it feasible to rehabilitate reefs with sexually propagated corals? Coral Reefs **33**:45-55.

Gurney, G., J. Cinner, J. Sartin, R. Pressey, N. Ban, N. Marshall, and D. Prabuning. 2016. Participation in devolved commons management: Multiscale socioeconomic factors related to individuals' participation in community-based management of marine protected areas in Indonesia. Environmental Science & Policy **61**:212-220.

Gurney, G. G., J. Cinner, N. C. Ban, R. L. Pressey, R. Pollnac, S. J. Campbell, S. Tasidjawa, and F. Setiawan. 2014. Poverty and protected areas: An evaluation of a marine integrated conservation and development project in Indonesia. Global Environmental Change **26**:98-107.

Gurney, G. G., R. L. Pressey, N. C. Ban, J. G. Álvarez-Romero, S. Jupiter, and V. M. Adams. 2015. Efficient and equitable design of marine protected areas in Fiji through inclusion of stakeholder-specific objectives in conservation planning. Conservation Biology **29**:1378-1389.

Gutierrez, N. L., R. Hilborn, and O. Defeo. 2011. Leadership, social capital and incentives promote successful fisheries. Nature **470**:386-389.

Gutiérrez, N. L., S. R. Valencia, T. A. Branch, D. J. Agnew, J. K. Baum, P. L. Bianchi, J. Cornejo-Donoso, C. Costello, O. Defeo, T. E. Essington, R. Hilborn, D. D. Hoggarth, A. E. Larsen, C. Ninnes, K. Sainsbury, R. L. Selden, S. Sistla, A. D. M. Smith, A. Stern-Pirlot, S. J. Teck, J. T. Thorson, and N. E. Williams. 2012. Eco-Label Conveys Reliable Information on Fish Stock Health to Seafood Consumers. PLoS ONE **7**:e43765.

Haisfield, K. M., H. E. Fox, S. Yen, S. Mangubhai, and P. J. Mous. 2010. An ounce of prevention: cost-effectiveness of coral reef rehabilitation relative to enforcement. Conservation Letters **3**:243-250.

Halpern, B. S., K. L. McLeod, A. A. Rosenberg, and L. B. Crowder. 2008. Managing for cumulative impacts in ecosystem-based management through ocean zoning. Ocean & Coastal Management **51**:203-211.

Hamilton, R., T. Potuku, and J. Montambault. 2011. Community-based conservation results in the recovery of reef fish spawning aggregations in the Coral Triangle. Biological Conservation **144**:1850-1858.

Hamilton, R. J., G. R. Almany, C. J. Brown, J. Pita, N. A. Peterson, and J. Howard Choat. 2017. Logging degrades nursery habitat for an iconic coral reef fish. Biological Conservation **210, Part A**:273-280.

Hargreaves-Allen, V., S. Mourato, and E. J. Milner-Gulland. 2011. A global evaluation of coral reef management performance: are MPAs producing conservation and socio-economic improvements? Environmental management **47**:684-700.

Harrison, H. B., D. H. Williamson, R. D. Evans, G. R. Almany, S. R. Thorrold, G. R. Russ, K. A. Feldheim, L. Van Herwerden, S. Planes, and M. Srinivasan. 2012. Larval export from marine reserves and the recruitment benefit for fish and fisheries. Current Biology **22**:1023-1028.

Harvell, D., E. Jordán-Dahlgren, S. Merkel, E. Rosenberg, L. Raymundo, G. Smith, E. Weil, and B. Willis. 2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. Oceanography **20**:172-195.

Hawkins, S., P. X. To, P.X. Phuong, P. T. Thuy, N. D. Tu, C. V. Cuong, S. Brown, P. Dart, S. Robertson, N. Vu, and R. McNally. 2010. Roots in the Water: Legal Frameworks for Mangrove PES in Vietnam. Katoomba Group's Legal Initiative Country Study Series. Forest Trends: Washington, DC. Available: http://www.forest-trends.org/documents/files/doc_2561.pdf

Hicks, C. C., and J. E. Cinner. 2014. Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs. Proceedings of the National Academy of Sciences **111**:17791-17796.

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, and K. Caldeira. 2007. Coral reefs under rapid climate change and ocean acidification. Science **318**:1737-1742.

Hoffmann, T. C. 2002. The reimplementation of the Ra'ui: Coral reef management in Rarotonga, Cook Islands. Coastal Management **30**:401-418.

Hogarth, W. 2006. Endangered and threatened species: final listing determinations for elkhorn coral and staghorn coral. Federal Register **71**:26852-26861.

Horigue, V., R. L. Pressey, M. Mills, J. Brotánková, R. Cabral, and S. Andréfouët. 2015. Benefits and challenges of scaling up expansion of marine protected area networks in the Verde Island Passage, Central Philippines. PLoS ONE **10**:e0135789.

Howells, E., V. Beltran, N. Larsen, L. Bay, B. Willis, and M. Van Oppen. 2012. Coral thermal tolerance shaped by local adaptation of photosymbionts. Nature Climate Change **2**:116-120.

Hudson, J. H. 2000. First aid for massive corals infected with black band disease, Phormidium corallyticum: An underwater aspirator and post-treatment sealant to curtail reinfection.

Hughes, T. P., M. L. Barnes, D. R. Bellwood, J. E. Cinner, G. S. Cumming, J. B. C. Jackson, J. Kleypas, I. A. van de Leemput, J. M. Lough, T. H. Morrison, S. R. Palumbi, E. H. van Nes, and M. Scheffer. 2017a. Coral reefs in the Anthropocene. Nature **546**:82-90.

Hughes, T. P., J. T. Kerry, M. Álvarez-Noriega, J. G. Álvarez-Romero, K. D. Anderson, A. H. Baird, R. C. Babcock, M. Beger, D. R. Bellwood, and R. Berkelmans. 2017b. Global warming and recurrent mass bleaching of corals. Nature **543**:373-377.

Hughes, T. P., M. J. Rodrigues, D. R. Bellwood, D. Ceccarelli, O. Hoegh-Guldberg, L. McCook, N. Moltschaniwskyj, M. S. Pratchett, R. S. Steneck, and B. Willis. 2007. Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current Biology **17**:360-365.

International Maritime Organization (IMO). 2006. Revised Guidelines For the Identification and Designation of Particularly Sensitive Sea Areas.*in* I. M. Organization, editor., London.

Ingram, J. C., D. Wilkie, T. Clements, R. B. McNab, F. Nelson, E. H. Baur, H. T. Sachedina, D. D. Peterson, and C. A. H. Foley. 2014. Evidence of Payments for Ecosystem Services as a mechanism for supporting biodiversity conservation and rural livelihoods. Ecosystem Services **7**:10-21.

Jackson, J., M. Donovan, K. Cramer, and V. Lam. 2014. Status and trends of Caribbean coral reefs: 1970-2012. Global Coral Reef Monitoring Network.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, and R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science **293**:629-638.

Jacquet, J., D. Pauly, D. Ainley, S. Holt, P. Dayton, and J. Jackson. 2010. Seafood stewardship in crisis. Nature **467**:28-29.

Jee, J., and S. Lee. 2017. Comparative feasibility study on retrofitting ballast water treatment system for a bulk carrier. Marine pollution bulletin **119**:17-22.

Johnson, A. E. 2010. Reducing bycatch in coral reef trap fisheries: escape gaps as a step towards sustainability. Marine ecology progress series **415**:201-209.

Jonas, H., and S. Lucas. 2013. Legal aspects of the Aichi biodiversity target 11: a scoping paper. International Development Law Organization, Rome.

Jones, G., M. McCormick, M. Srinivasan, and J. V. Eagle. 2004. Coral Decline Threatens Fish Biodiversity in Marine Reserves. Proc Nat Acad Sci **101**:8251-8253.

Jupiter, S. 2017. Culture, kastom and conservation in Melanesia: what happens when worldviews collide? Pacific Conservation Biology.

Jupiter, S., A. S. Wenger, C. J. Klein, S. Albert, S. Mangubhai, J. L. Nelson, L. Teneva, V. J. Tulloch, A. T. White, and J. E. M. Watson. 2017. Opportunities and constraints for implementing integrated land-sea management on islands. Environmental Conservation **44(3)**: 254-266.

Jupiter, S., M. Fox, A. Cakacaka, A. Caginitoba, N. Askew, I. Qauqau, R. Weeks, and S. Prasad. 2012a. Building provincial-level integrated coastal management plans: Outcomes from the Vatu-i-Ra Seascape Stakeholders Workshop. Wildlife Conservation Society Fiji, Suva.

Jupiter, S., S. Mangubhai, and R. T. Kingsford. 2014a. Conservation of biodiversity in the Pacific Islands of Oceania: challenges and opportunities. Pacific Conservation Biology **20**:206-220.

Jupiter, S., R. Weeks, A. Jenkins, D. Egli, and A. Cakacaka. 2012b. Effects of a single intensive harvest event on fish populations inside a customary marine closure. Coral Reefs **31**:321-334.

Jupiter, S. D., P. J. Cohen, R. Weeks, A. Tawake, and H. Govan. 2014b. Locally-managed marine areas: multiple objectives and diverse strategies. Pacific Conservation Biology **20**:165-179.

Jupiter, S. D., and D. P. Egli. 2010. Ecosystem-based management in Fiji: successes and challenges after five years of implementation. Journal of Marine Biology **2011**.

Jupiter, S. D., A. Wenger, C. J. Klein, S. Albert, S. Mangubhai, J. Nelson, L. Teneva, V. J. Tulloch, A. T. White, and J. E. Watson. 2017. Opportunities and constraints for implementing integrated land–sea management on islands. Environmental Conservation:1-13.

Kaplan, K. A., G. N. Ahmadia, H. Fox, L. Glew, E. F. Pomeranz, and P. Sullivan. 2015. Linking ecological condition to enforcement of marine protected area regulations in the greater Caribbean region. Marine Policy **62**:186-195.

Karr, K. A., R. Fujita, B. S. Halpern, C. V. Kappel, L. Crowder, K. A. Selkoe, P. M. Alcolado, and D. Rader. 2015. Thresholds in Caribbean coral reefs: implications for ecosystem-based fishery management. Journal of Applied Ecology **52**:402-412.

Katikiro, R. E., E. D. Macusi, and K. A. Deepananda. 2015. Challenges facing local communities in Tanzania in realising locally-managed marine areas. Marine Policy **51**:220-229.

Kayal, M., J. Vercelloni, T. L. De Loma, P. Bosserelle, Y. Chancerelle, S. Geoffroy, C. Stievenart, F. Michonneau, L. Penin, and S. Planes. 2012. Predator crown-of-thorns starfish (Acanthaster planci) outbreak, mass mortality of corals, and cascading effects on reef fish and benthic communities. PLoS ONE **7**:e47363.

Kennedy, E. V., C. T. Perry, P. R. Halloran, R. Iglesias-Prieto, C. H. Schönberg, M. Wisshak, A. U. Form, J. P. Carricart-Ganivet, M. Fine, and C. M. Eakin. 2013. Avoiding coral reef functional collapse requires local and global action. Current Biology **23**:912-918.

Kroon, F. J., P. Thorburn, B. Schaffelke, and S. Whitten. 2016. Towards protecting the Great Barrier Reef from land-based pollution. Global Change Biology.

Krueck, N. C., G. N. Ahmadia, A. Green, G. P. Jones, H. P. Possingham, C. Riginos, E. A. Treml, and P. J. Mumby. 2017. Incorporating larval dispersal into MPA design for both conservation and fisheries. Ecological Applications:n/a-n/a.

Lamb, J. B., J. A. J. M. van de Water, D. G. Bourne, C. Altier, M. Y. Hein, E. A. Fiorenza, N. Abu, J.

Jompa, and C. D. Harvell. 2017. Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. Science **355**:731.

Lamb, J. B., A. S. Wenger, M. J. Devlin, D. M. Ceccarelli, D. H. Williamson, and B. L. Willis. 2016. Reserves as tools for alleviating impacts of marine disease. Philosophical Transactions of the Royal Society B **371**:20150210.

Lamb, J. B., D. H. Williamson, G. R. Russ, and B. L. Willis. 2015. Protected areas mitigate diseases of reef-building corals by reducing damage from fishing. Ecology **96**:2555-2567.

Landos, M. 2012. Investigation of the causes of aquatic animal health problems in the Gladstone Harbour and nearshore waters. Gladstone Fishing Research Fund.

Lapointe, B. E., and B. J. Bedford. 2010. Ecology and nutrition of invasive Caulerpa brachypus f. parvifolia blooms on coral reefs off southeast Florida, USA. Harmful Algae **9**:1-12.

Lauer, M., and S. Aswani. 2009. Indigenous ecological knowledge as situated practices: understanding fishers' knowledge in the western Solomon Islands. American Anthropologist **111**:317-329.

Le Grand, H. M., and K. Fabricius. 2011. Relationship of internal macrobioeroder densities in living massive Porites to turbidity and chlorophyll on the Australian Great Barrier Reef. Coral Reefs **30**:97-107.

Leisher, C., S. Mangubhai, S. Hess, H. Widodo, T. Soekirman, S. Tjoe, S. Wawiyai, S. N. Larsen, L. Rumetna, A. Halim, and M. Sanjayan. 2012. Measuring the benefits and costs of community education and outreach in marine protected areas. Marine Policy **36(5)**: 1005-1011.

Lohr, K. E., A. A. C. McNab, C. Manfrino, and J. T. Patterson. 2017. Assessment of wild and restored staghorn coral Acropora cervicornis across three reef zones in the Cayman Islands. Regional Studies in Marine Science **9**:1-8.

Lowry, K., A. White, and C. Courtney. 2005. National and local agency roles in integrated coastal management in the Philippines. Ocean and Coastal Management **48**: 314-335.

Lucas, E. Y., and R. Kirit. 2009. Fisheries–Marine Protected Area–Tourism Interactions in Moalboal, Cebu, Philippines. Coastal Management **37**:480-490.

Lyons, J. E., M. C. Runge, H. P. Laskowski, and W. L. Kendall. 2008. Monitoring in the context of structured decision-making and adaptive management. Journal of Wildlife Management **72**:1683-1692.

Macdonald, E. M., and R. D. Davidson. 1998. The occurrence of harmful algae in ballast discharges to Scottish ports and the effects of mid-water exchange in regional seas. Harmful Algae'. B. Reguera, J. Blanco, ML Fernandez, and T. Wyatt (Editors). Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO:220-223.

MacNeil, M. A., N. A. Graham, J. E. Cinner, S. K. Wilson, I. D. Williams, J. Maina, S. Newman, A. M. Friedlander, S. Jupiter, and N. V. Polunin. 2015. Recovery potential of the world's coral reef fishes. Nature **520**:341-344.

Manap, N., and N. Voulvoulis. 2015. Environmental management for dredging sediments – The requirement of developing nations. Journal of Environmental Management **147**:338-348.

Mangubhai, S., J. R. Wilson, L. Rumetna, and Y. Maturbongs. 2015. Explicitly incorporating socioeconomic criteria and data into marine protected area zoning. Ocean & Coastal Management **116**:523-529.

Mascia, M. B., H. E. Fox, L. Glew, G. N. Ahmadia, A. Agrawal, M. Barnes, X. Basurto, I. Craigie, E.

Darling, and J. Geldmann. 2017. A novel framework for analyzing conservation impacts: evaluation, theory, and marine protected areas. Annals of the New York Academy of Sciences **1399**:93-115.

Maynard, J. A., R. Van Hooidonk, C. M. Eakin, M. Puotinen, M. Garren, G. Williams, S. F. Heron, J. B. Lamb, E. Weil, and B. Willis. 2015. Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. Nature Climate Change **5**:688-694.

Mbaru, E. K., and T. R. McClanahan. 2013. Escape gaps in African basket traps reduce bycatch while increasing body sizes and incomes in a heavily fished reef lagoon. Fisheries Research **148**:90-99.

McClanahan, T. 2017. Changes in coral sensitivity to thermal anomalies. Marine ecology progress series **570**:71-85.

McClanahan, T., M. Ateweberhan, and A. Baker. 2011a. Preparing for Climate Change in the Western Indian Ocean: Identifying Climate Refugia, Biodiversity Responses, and Preferred Management. Western Indian Ocean Marine Science Association.

McClanahan, T., and J. Cinner. 2008. A framework for adaptive gear and ecosystem-based management in the artisanal coral reef fishery of Papua New Guinea. Aquatic Conservation: Marine and Freshwater Ecosystems **18**:493-507.

McClanahan, T. R., C. A. Abunge, and J. E. Cinner. 2012a. Heterogeneity in fishers' and managers' preferences towards management restrictions and benefits in Kenya. Environmental Conservation **39**:357-369.

McClanahan, T. R., M. Ateweberhan, C. A. Muhando, J. Maina, and M. S. Mohammed. 2007. Effects of climate and seawater temperature variation on coral bleaching and mortality. Ecological Monographs **77**:503-525.

McClanahan, T. R., S. D. Donner, J. A. Maynard, M. A. MacNeil, N. A. Graham, J. Maina, A. C. Baker, M. Beger, S. J. Campbell, and E. S. Darling. 2012b. Prioritizing key resilience indicators to support coral reef management in a changing climate. PLoS ONE **7**:e42884.

McClanahan, T. R., N. A. Graham, M. A. MacNeil, N. A. Muthiga, J. E. Cinner, J. H. Bruggemann, and S. K. Wilson. 2011b. Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. Proceedings of the National Academy of Sciences **108**:17230-17233.

McClanahan, T. R., M. J. Marnane, J. E. Cinner, and W. E. Kiene. 2006. A Comparison of Marine Protected Areas and Alternative Approaches to Coral-Reef Management. Current Biology **16**:1408-1413.

McClanahan, T. R., and N. A. Muthiga. 2017. Environmental variability indicates a climate-adaptive center under threat in northern Mozambique coral reefs. Ecosphere **8**:e01812-n/a.

McCook, L. J., T. Ayling, M. Cappo, J. H. Choat, R. D. Evans, D. M. De-Freitas, M. Heupel, T. P. Hughes, G. P. Jones, B. Mapstone, H. Marsh, M. Mills, F. J. Molloy, C. R. Pitcher, R. L. Pressey, G. R. Russ, S. Sutton, H. Sweatman, R. Tobin, D. R. Wachenfeld, and D. H. Williamson. 2010. Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. Proc Nat Acad Sci **107**:18278-18285.

McElwee, P. D. 2012. Payments for environmental services as neoliberal market-based forest conservation in Vietnam: Panacea or problem? Geoforum **43**:412-426.

Meals, D. W., S. A. Dressing, and T. E. Davenport. 2010. Lag time in water quality response to best management practices: a review. Journal of Environmental Quality **39**:85-96.

Miller, M. W., K. E. Lohr, C. M. Cameron, D. E. Williams, and E. C. Peters. 2014. Disease dynamics and potential mitigation among restored and wild staghorn coral, Acropora cervicornis. PeerJ **2**:e541.

Moberg, F., and C. Folke. 1999. Ecological goods and services of coral reef ecosystems. Ecological economics **29**:215-233.

Molnar, J. L., R. L. Gamboa, C. Revenga, and M. D. Spalding. 2008. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment **6**:485-492.

Mora, C., S. Andréfouët, M. J. Costello, C. Kranenburg, A. Rollo, J. Veron, K. J. Gaston, and R. A. Myers. 2006. Coral reefs and the global network of marine protected areas. SCIENCE-NEW YORK THEN WASHINGTON- **2006**:1750.

Moreno-Mateos, D., M. E. Power, F. A. Comín, and R. Yockteng. 2012. Structural and Functional Loss in Restored Wetland Ecosystems. Plos Biology **10**:e1001247.

Morris Jr, J. A., and P. E. Whitfield. 2009. Biology, ecology, control and management of the invasive Indo-Pacific lionfish: an updated integrated assessment.

Morrisey, D. J. 1993. Environmental impact assessment—A review of its aims and recent developments. Marine Pollution Bulletin **26**:540-545.

Mumby, P. J., A. J. Edwards, J. E. Arias-González, K. C. Lindeman, P. G. Blackwell, A. Gall, M. I. Gorczynska, A. R. Harborne, C. L. Pescod, and H. Renken. 2004a. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature **427**:533-536.

Mumby, P. J., A. J. Edwards, J. Ernesto Arias-Gonzalez, K. C. Lindeman, P. G. Blackwell, A. Gall, M. I. Gorczynska, A. R. Harborne, C. L. Pescod, H. Renken, C. C. C. Wabnitz, and G. Llewellyn. 2004b. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature **427**:533-536.

Mumby, P. J., I. A. Elliott, C. M. Eakin, W. Skirving, C. B. Paris, H. J. Edwards, S. Enríquez, R. Iglesias-Prieto, L. M. Cherubin, and J. R. Stevens. 2011. Reserve design for uncertain responses of coral reefs to climate change. Ecology letters **14**:132-140.

Mumby, P. J., A. R. Harborne, J. Williams, C. V. Kappel, D. R. Brumbaugh, F. Micheli, K. E. Holmes, C. P. Dahlgren, C. B. Paris, and P. G. Blackwell. 2007. Trophic cascade facilitates coral recruitment in a marine reserve. Proceedings of the National Academy of Sciences **104**:8362-8367.

Muradian, R., M. Arsel, L. Pellegrini, F. Adaman, B. Aguilar, B. Agarwal, E. Corbera, D. Ezzine de Blas, J. Farley, and G. Froger. 2013. Payments for ecosystem services and the fatal attraction of win-win solutions. Conservation Letters **6**:274-279.

Muradian, R., E. Corbera, U. Pascual, N. Kosoy, and P. H. May. 2010. Reconciling theory and practice: An alternative conceptual framework for understanding payments for environmental services. Ecological economics **69**:1202-1208.

Narloch, U., U. Pascual, and A. G. Drucker. 2012. Collective action dynamics under external rewards: experimental insights from Andean farming communities. World Development **40**:2096-2107.

Ng, C. S. L., S. C. Lim, J. Y. Ong, L. M. S. Teo, L. M. Chou, K. E. Chua, and K. S. Tan. 2015. Enhancing the biodiversity of coastal defence structures: transplantation of nursery-reared reef biota onto intertidal seawalls. Ecological Engineering **82**:480-486.

Norse, E. A. 2010. Ecosystem-based spatial planning and management of marine fisheries: why and how? Bulletin of Marine Science **86**:179-195.

Obura, D., S. Donner, S. Walsh, S. Mangubhai, and R. Rotjan. 2016. Phoenix Islands Protected Area Climate Change Vulnerability Assessment and Management.

Olds, A. D., R. M. Connolly, K. A. Pitt, and P. S. Maxwell. 2012. Habitat connectivity improves reserve performance. Conservation Letters **5**:56–63.

Oliver, D. P., J. S. Anderson, A. Davis, S. Lewis, J. Brodie, and R. Kookana. 2014. Banded applications are highly effective in minimising herbicide migration from furrow-irrigated sugar cane. Science of the Total Environment **466**:841-848.

Oliver, T., and S. Palumbi. 2011. Do fluctuating temperature environments elevate coral thermal tolerance? Coral Reefs **30**:429-440.

Oliver, T. A., K. L. Oleson, H. Ratsimbazafy, D. Raberinary, S. Benbow, and A. Harris. 2015. Positive Catch & Economic Benefits of Periodic Octopus Fishery Closures: Do Effective, Narrowly Targeted Actions ‘Catalyze’ Broader Management? PLoS ONE **10**:e0129075.

Oracion, E. G., M. L. Miller, and P. Christie. 2005. Marine protected areas for whom? Fisheries, tourism, and solidarity in a Philippine community. Ocean & Coastal Management **48**:393-410.

Ostrom, E. 1990. Governing the commons: The evolution of institutions for collective action. Cambridge University Press Cambridge:.

Palumbi, S. R., D. J. Barshis, N. Traylor-Knowles, and R. A. Bay. 2014. Mechanisms of reef coral resistance to future climate change. Science **344**:895.

Pascual, U., J. Phelps, E. Garmendia, K. Brown, E. Corbera, A. Martin, E. Gomez-Baggethun, and R. Muradian. 2014. Social equity matters in payments for ecosystem services. BioScience:biu146.

Peng, M., and K. L. Oleson. 2017. Beach Recreationalists' Willingness to Pay and Economic Implications of Coastal Water Quality Problems in Hawaii. Ecological economics **136**:41-52.

Pereira, N. N., and H. L. Brinati. 2012. Onshore ballast water treatment: A viable option for major ports. Marine Pollution Bulletin **64**:2296-2304.

Pérez-Ramírez, M., M. Castrejón, N. L. Gutiérrez, and O. Defeo. 2016. The Marine Stewardship Council certification in Latin America and the Caribbean: A review of experiences, potentials and pitfalls. Fisheries Research **182**:50-58.

Pietri, D., P. Christie, R. B. Pollnac, R. Diaz, and A. Sabonsolin. 2009. Information diffusion in two marine protected area networks in the Central Visayas Region, Philippines. Coastal Management **37**: 331-348.

Poiani, K. A., R. L. Goldman, J. Hobson, J. M. Hoekstra, and K. S. Nelson. 2011. Redesigning biodiversity conservation projects for climate change: examples from the field. Biodiversity and Conservation **20**:185-201.

Pollnac, R. B., B. R. Crawford, and M. L. Gorospe. 2001. Discovering factors that influence the success of community-based marine protected areas in the Visayas, Philippines. Ocean & Coastal Management **44**:683-710.

Pollnac, R. B. and R. S. Pomeroy. 2005. Factors influencing the sustainability of integrated coastal management projects in the Philippines and Indonesia. Ocean and Coastal Management **48**: 233-251.

Pollock, F. J., J. B. Lamb, S. N. Field, S. F. Heron, B. Schaffelke, G. Shedrawi, D. G. Bourne, and B. L. Willis. 2014. Sediment and turbidity associated with offshore dredging increase coral disease prevalence on nearby reefs. PLoS ONE **9**:e102498.

Pomeroy, R. S., E. G. Oracion, R. B. Pollnac, and D. A. Caballes. 2005. Perceived economic factors influencing the sustainability of integrated coastal management projects in the Philippines. Ocean & Coastal Management **48**:360-377.

Possingham, H. P., M. Bode, and C. J. Klein. 2015. Optimal conservation outcomes require both restoration and protection. PLoS Biol **13**:e1002052.

Pressey, R. L., P. Visconti, and P. J. Ferraro. 2015. Making parks make a difference: poor alignment of policy, planning and management with protected-area impact, and ways forward. Phil. Trans. R. Soc. B **370**:20140280.

Quiros, T. A. L., D. Croll, B. Tershy, M. D. Fortes, and P. Raimondi. 2017. Land use is a better predictor of tropical seagrass condition than marine protection. Biological Conservation **209**:454-463.

Ramos-Scharrón, C. 2012. Effectiveness of drainage improvements in reducing sediment production rates from an unpaved road. Journal of Soil and Water Conservation **67**:87-100.

Ramos-Scharrón, C. E., and M. C. LaFevor. 2016. The role of unpaved roads as active source areas of precipitation excess in small watersheds drained by ephemeral streams in the Northeastern Caribbean. Journal of Hydrology **533**:168-179.

Redding, J. E., R. L. Myers-Miller, D. M. Baker, M. Fogel, L. J. Raymundo, and K. Kim. 2013. Link between sewage-derived nitrogen pollution and coral disease severity in Guam. Marine Pollution Bulletin **73**:57-63.

Rhyne, A. L., M. F. Tlusty, and L. Kaufman. 2012. Long-term trends of coral imports into the United States indicate future opportunities for ecosystem and societal benefits. Conservation Letters **5**:478-485.

Richmond, R. H., T. Rongo, Y. Golbuu, S. Victor, N. Idechong, G. Davis, W. Kostka, L. Neth, M. Hamnett, and E. Wolanski. 2007. Watersheds and coral reefs: conservation science, policy, and implementation. BioScience **57**:598-607.

Rinkevich, B. 2008. Management of coral reefs: we have gone wrong when neglecting active reef restoration. Marine Pollution Bulletin **56**:1821-1824.

Rinkevich, B. 2014. Rebuilding coral reefs: Does active reef restoration lead to sustainable reefs? Current Opinion in Environmental Sustainability **7**:28-36.

Rodgers, K. S., M. H. Kido, P. L. Jokiel, T. Edmonds, and E. K. Brown. 2012. Use of integrated landscape indicators to evaluate the health of linked watersheds and coral reef environments in the Hawaiian Islands. Environ. Manage. **50**:21-30.

Rodrigues, J. G., and S. Villasante. 2016. Disentangling seafood value chains: Tourism and the local market driving small-scale fisheries. Marine Policy **74**:33-42.

Rose, J. M., S. B. Bricker, M. A. Tedesco, and G. H. Wikfors. 2014. A role for shellfish aquaculture in coastal nitrogen management. ACS Publications.

Russ, G. R., and A. C. Alcala. 1999. Management histories of Sumilon and Apo Marine Reserves, Philippines, and their influence on national marine resource policy. Coral Reefs **18**:307-319.

Russ, G. R., A. J. Cheal, A. M. Dolman, M. J. Emslie, R. D. Evans, I. Miller, H. Sweatman, and D. H. Williamson. 2008. Rapid increase in fish numbers follows creation of world's largest marine reserve network. Current Biology **18**:R514-R515.

Sandifer, P. A., A. E. Sutton-Grier, and B. P. Ward. 2015. Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. Ecosystem Services **12**:1-15.

Selig, E. R., K. S. Casey, and J. F. Bruno. 2012. Temperature-driven coral decline: the role of marine protected areas. Global Change Biology **18**:1561-1570.

Sievanen, L., B. Crawford, R. Pollnac, and C. Lowe. 2005. Weeding through assumptions of livelihood approaches in ICM: Seaweed farming in the Philippines and Indonesia. Ocean & Coastal Management **48**:297-313.

Smith, J. E., C. L. Hunter, and C. M. Smith. 2002. Distribution and reproductive characteristics of nonindigenous and invasive marine algae in the Hawaiian Islands. Pacific Science **56**:299-315.

Tarigan, S. D., Sunarti, K. Wiegand, C. Dislich, B. Slamet, J. Heinonen, and K. Meyer. 2016. Mitigation options for improving the ecosystem function of water flow regulation in a watershed with rapid expansion of oil palm plantations. Sustainability of Water Quality and Ecology **8**:4-13.

Terk, E., and N. Knowlton. 2010. The role of SCUBA diver user fees as a source of sustainable funding for coral reef marine Protected areas. Biodiversity **11**:78-84.

The WorldFish Center. 2008. Lessons learned and good practices in the management of coral reef marine protected areas. Available at: http://www.reefbase.org/gefll/pdf/lessonslearnedMPAbrief_English.pdf. Accessed 27 September 2017.

Thorburn, P., and S. Wilkinson. 2013. Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. Agriculture, Ecosystems & Environment **180**:192-209.

Thorburn, P. J., S. N. Wilkinson, and D. M. Silburn. 2013. Water quality in agricultural lands draining to the Great Barrier Reef: A review of causes, management and priorities. Agriculture, Ecosystems & Environment **180**:4-20.

Tsolaki, E., and E. Diamadopoulos. 2010. Technologies for ballast water treatment: a review. Journal of Chemical Technology and Biotechnology **85**:19-32.

UNTCAD. 2011. Trade and Development Report. United Nations Conference on Trade and Development, Geneva and New York.

van Oppen, M. J., R. D. Gates, L. L. Blackall, N. Cantin, L. J. Chakravarti, W. Y. Chan, C. Cormick, A. Crean, K. Damjanovic, and H. Epstein. 2017. Shifting paradigms in restoration of the world's coral reefs. Global Change Biology.

van Oppen, M. J., J. K. Oliver, H. M. Putnam, and R. D. Gates. 2015. Building coral reef resilience through assisted evolution. Proceedings of the National Academy of Sciences **112**:2307-2313.

Veron, J. E. N., L. M. Devantier, E. Turak, A. L. Green, S. Kinnmonth, M. Stafford-Smith, and N. Peterson. 2009. Delineating the Coral Triangle. Galaxea, Journal of Coral Reef Studies **11**: 91-100.

Waldie, P. A., G. R. Almany, T. H. Sinclair-Taylor, R. J. Hamilton, T. Potuku, M. A. Priest, K. L. Rhodes, J. Robinson, J. E. Cinner, and M. L. Berumen. 2016. Restricted grouper reproductive migrations support community-based management. Royal Society open science **3**:150694.

Wear, S. L. 2016. Missing the boat: Critical threats to coral reefs are neglected at global scale. Marine Policy **74**:153-157.

Wear, S. L., and R. V. Thurber. 2015. Sewage pollution: mitigation is key for coral reef stewardship. Annals of the New York Academy of Sciences **1355**:15-30.

Webster, M. S., M. A. Colton, E. S. Darling, J. Armstrong, M. L. Pinsky, N. Knowlton, and D. E. Schindler. 2017. Who Should Pick the Winners of Climate Change? Trends in Ecology & Evolution **32**:167-173.

Weeks, R., G. R. Russ, A. A. Bucol, and A. C. Alcala. 2010. Incorporating local tenure in the systematic design of marine protected area networks. Conservation Letters **3**:445-453.

Wenger, A. S., D. H. Williamson, E. T. da Silva, D. M. Ceccarelli, N. K. Browne, C. Petus, and M. J. Devlin. 2016. Effects of reduced water quality on coral reefs in and out of no-take marine reserves. Conservation Biology **30**:142-153.

White, A. T., R. Eisma-Osorio, and S. J. Green. 2005. Integrated coastal management and marine protected areas: Complementarity in the Philippines. Ocean and Coastal Management **48**: 948-971.

Wiedenmann, J., C. D/'Angelo, E. G. Smith, A. N. Hunt, F.-E. Legiret, A. D. Postle, and E. P. Achterberg. 2013. Nutrient enrichment can increase the susceptibility of reef corals to bleaching. Nature Clim. Change **3**:160-164.

Williams, D. E., M. W. Miller, A. J. Bright, and C. M. Cameron. 2014. Removal of corallivorous snails as a proactive tool for the conservation of acroporid corals. PeerJ **2**:e680.

Williams, I., W. Walsh, A. Miyasaka, and A. Friedlander. 2006. Effects of rotational closure on coral reef fishes in Waikiki-Diamond head fishery management area, Oahu, Hawaii. Marine ecology progress series **310**:139-149.

Williams, I. D., D. J. White, R. T. Sparks, K. C. Lino, J. P. Zamzow, E. L. Kelly, and H. L. Ramey. 2016. Responses of herbivorous fishes and benthos to 6 years of protection at the Kahekili Herbivore Fisheries Management Area, Maui. PLoS ONE **11**:e0159100.

Williams, S. L., and E. D. Grosholz. 2008. The Invasive Species Challenge in Estuarine and Coastal Environments: Marrying Management and Science. Estuaries and Coasts **31**:3-20.

Wooldridge, S. A., and J. E. Brodie. 2015. Environmental triggers for primary outbreaks of crown-of-thorns starfish on the Great Barrier Reef, Australia. Marine Pollution Bulletin **101**:805-815.

World Shipping Council. 2017. Top 50 World Container Ports. Available: http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports. Accessed 27 September 2017.

Wunder, S. 2005. Payments for environmental services: some nuts and bolts.

Yates, K. K., C. S. Rogers, J. J. Herlan, G. R. Brooks, N. A. Smiley, and R. A. Larson. 2014. Diverse coral communities in mangrove habitats suggest a novel refuge from climate change. Biogeosciences:4321.

Young, C., S. Schopmeyer, and D. Lirman. 2012. A review of reef restoration and coral propagation using the threatened genus Acropora in the Caribbean and Western Atlantic. Bulletin of

Marine Science **88**:1075-1098.

Zaneveld, J. R., D. E. Burkepile, A. A. Shantz, C. E. Pritchard, R. McMinds, J. P. Payet, R. Welsh, A. M. Correa, N. P. Lemoine, and S. Rosales. 2016. Overfishing and nutrient pollution interact with temperature to disrupt coral reefs down to microbial scales. Nature communications **7**.

Ziegler, M., F. O. Seneca, L. K. Yum, S. R. Palumbi, and C. R. Voolstra. 2017. Bacterial community dynamics are linked to patterns of coral heat tolerance. Nature communications **8**:14213.

Appendix

Appendix A. List of Practitioner Guidelines, Toolkits, Frameworks, and Other Resources

1) Climate Change Resources

Climate Change Adaptation for Coral Triangle Communities: **Guide for Vulnerability Assessment and Local Early Action Planning (LEAP Guide)**

- **Website:** http://www.uscti.org/
- **General Description:** The LEAP Guide is organized into four major steps to support the integration of planned adaptation within the context of existing development plans and ongoing projects. The guide is intended for national and local governments, marine and coastal managers, disaster managers, and community development practitioners who work with coastal communities on a wide range of development issues such as food security, health, biodiversity conservation, and economic development.

Reef Resilience (R2): Building Resilience into Coral Reef Conservation

- **Website:** http://www.reefresilience.org/
- **General Description:** The Nature Conservancy's (TNC) Reef Resilience (R2) Network links coral reef managers and practitioners. The network's website is a platform for their Reef Resilience (R2) Toolkit, which describes resilience; shares case studies, publications, and resources relating to reliance and coral reefs; and provides a platform for networking and learning through providing training, sharing newsletters, and hosting webinars.

National Oceanic and Atmospheric Administration's (NOAA) Sea Level Rise and Coastal Flooding Impacts Viewer

- **Website:** http://www.csc.noaa.gov/slr/viewer/#
- **General Description:** This online map-generation software from the NOAA Coastal Services Center overlays social and economic data onto potential sea level rise data for a view of impacts on communities and tidal marshes from inundation and tidal flooding. It provides simulations of sea level rise at local landmarks, uncertainties, models of potential marsh migration, and information about projected tidal flooding frequencies.

SLAMM—Sea Level Rise Affecting Marshes Model

- **Website:** http://www.warrenpinnacle.com/prof/SLAMM/
- **General Description:** SLAMM is a mathematical model that requires the use of Microsoft Excel and Esri ArcGIS and uses digital elevation data and other information to simulate potential impacts of long-term sea level rise on wetlands and shorelines. SLAMM has been used in several geographies and applications across the United States since its development in the mid-1980s.

Climate Adaptation Knowledge Exchange (CAKE)

- **Website:** http://www.cakex.org/

- **General Description:** CAKE is a rich exchange network that focuses on climate change adaptation. The website includes tabs to case studies, a library, directory, tools, and a networking tab called "community." The site highlights new and popular tools and documents and provides features. Some marine tools are highlighted there.

Data Basin Climate Center

- **Website:** http://climate.databasin.org/
- **General Description:** The Conservation Biology Institute Climate Center provides popular and recent climate change datasets through an online mapping and analysis environment. Its website and Data Basin Climate Center provides services in data processing and hosting, map creation and sharing, and training.

A Reef Manager's Guide to Coral Bleaching

- **Website:** http://www.iucn.org/about/work/programmes/marine/marine_resources/?524/A-reef-managers-guide-to-coral-bleaching
- **General Description:** This guide provides a synthesis of information, concepts, and practices designed to help reef managers better understand the phenomenon of coral bleaching and related climate change risks as they relate to coral reefs and their management. It points to detailed guidance about specific issues, including the Global Protocol for Assessment and Monitoring of Coral Bleaching as one of many resources to assist managers.

Caribbean Climate Online Risk and Adaptation TooL (CCORAL)

- **Website:** http://ccoral.caribbeanclimate.bz/
- **General Description:** The Caribbean Climate Online Risk and Adaptation tooL (CCORAL) is a web-based tool designed to help decision-makers in the Caribbean integrate climate resilience into their decision-making and planning processes.

Additional Resources

The Nature Conservancy. 2009. Conservation Action Planning Guidelines for Developing Strategies in the Face of Climate Change. 26 pp.

U.S. Agency for International Development (USAID). 2009. Adapting to Coastal Climate Change: A Guidebook for Development Planners. 163 pp.

2) Marine Spatial Planning

Decision Guide: Selecting Decision Support Tools (DSTs) for Marine Spatial Planning

- **Website:** http://www.ebmtools.org/decision-guide.html
- **General Description:** The Pacific Marine Analysis and Research Association and the Center for Ocean Solutions produced a Decision Guide to review and guide decision-makers' choice of DSTs for spatial planning in the marine environment (Coleman et al. 2011). The guide is intended to assist practitioners in selecting appropriate DSTs that can help them conduct marine spatial planning in their own jurisdictions.

Ecosystem-Based Management (EBM) Tools Network Database

- **Website:** www.ebmtoolsdatabase.org
- **General Description:** The EBM Tools Network Database describes itself as an “online hub for tools and projects for innovative interdisciplinary coastal-marine spatial planning and ecosystem-based management.” It provides an extensive list and links to software and web-based tools; projects which have used these types of tools; other resources such as publications, toolkits and databases; organizations that can provide assistance with interdisciplinary coastal-marine spatial planning and ecosystem-based management; and practitioners who offer tools or services relating to coastal-marine spatial planning.

Marine Planning Website (TNC)

- **Website:** http://www.marineplanning.org/Decision_Support/DecisionSupport.html
- **General Description:** The Marine Planning website provides support for multi-objective planning through EBM and marine spatial planning. The website’s section on decision support provides descriptions and links to a few DSTs in common use.

Locally Managed Marine Areas (LMMA) Toolkit

- **Website:** http://www.lmmanetwork.org/home
- **General Description:** The Locally Managed Marine Areas (LMMA) Network encompasses marine conservation practitioners working in Asia and the Pacific. The network shares useful information and resources for practitioners, as well as stories and lessons from communities that are using the LMMA approach in the management and conservation of their marine resources. Guides, reports, videos, survey protocols and other tools can be accessed online and the network provides training opportunities for project members.

Additional Resources

Belfiore, S., B. Cicin-Sain, and C. Ehler, editors. 2004. Incorporating Marine Protected Areas into Integrated Coastal and Ocean Management: Principles and Guidelines. IUCN, Gland, Switzerland and Cambridge, UK. 38 pp.

Coleman, H., M. Foley, E. Prahler, M. Armsby, and G. Shillinger. 2011. Decision Guide: Selecting Decision Support Tools for Marine Spatial Planning. The Woods Institute for the Environment, Stanford University, California. 45 pp.

IUCN World Commission on Protected Areas (IUCN). 2008. Establishing Marine Protected Area Networks—Making It Happen. IUCN-WCPA, National Oceanic and Atmospheric Administration and The Nature Conservancy, Washington, D.C. 118 pp.

Pomeroy, R., R. Brainard, M. Moews, A. Heenan, J. Shackeroff, and N. Armada. 2013. Coral Triangle Regional Ecosystem Approach to Fisheries Management (EAFM) Guidelines. The USAID Coral Triangle Support Partnership, Honolulu, Hawaii. 70 pp.

The Nature Conservancy. 2011. Best Practices for Marine Spatial Planning. 25 pp.

Van Lavieren, H. 2009. The Science of No-take Fishery Reserves. A Guide for Managers. CRTR Brochure, UNU-INWEH. 10 pp.

WCPA/IUCN. 2007. Establishing Networks of Marine Protected Areas: A Guide for Developing National and Regional Capacity for Building MPA networks. Non-technical Summary Report.

3) Reef Survey and Monitoring Protocols

Reef Check

- **Website:** http://www.reefcheck.org/
- **General Description:** The Reef Check Foundation is dedicated to the conservation of tropical coral reefs and California rocky reefs. Coral reef conservation is addressed through their Coral Reef Management Program, which focuses on establishing marine protected areas to conserve coral reefs while encouraging sustainable use of surrounding reefs by local residents. Of particular use to reef managers are their survey protocols.

Resilience Assessment of Coral Reefs: Rapid Assessment Protocol for Coral Reefs, Focusing on Coral Bleaching and Thermal Stress

- **Website:** www.iucn.org/about/work/programmes/marine/marine_resources/?3043/resilienceassessmentcoralreefs
- **General Description:** This publication provides an extensive protocol for assessing the resilience of coral reefs. The publication is one in a series on management tools to promote resilience in marine ecosystems including guides on managing mangroves and seagrasses for resilience to climate change.

A Global Protocol for Assessment and Monitoring of Coral Bleaching

- **Website:** http://www.reefbase.org/projects_partners/projects.aspx?projectid=8
- **General Description:** The WorldFish Center, the World Wildlife Fund, and the Great Barrier Reef Marine Park Authority developed this protocol for reporting and monitoring of bleaching events.

Rapid Ecological Assessment (REA)/Evaluación Ecológica Rápida (EER)/Rapid Reef Assessment (RRA)

- **General Description:** REA is a useful method for gathering data over small spatial scales. In the case of coral reefs, the approach provides a quick "snapshot" of major reef biota during a single dive or snorkel survey. It can be useful in assessing remote areas that are only rarely visited and where little time can be spent. Reef REAs typically include specialists in fish, coral, and possibly algae and invertebrates. Each specialist conducts survey protocols that are specific to their particular area of expertise typically along a set of transect lines that all the observers sample along.

4) Socioeconomic Survey Protocols

Global Socioeconomic Monitoring Initiative for Coastal Management (SocMon)

- **Website:** http://www.socmon.org/
- **General Description:** SocMon is an initiative aimed at helping coastal managers better understand and incorporate the socioeconomic context into coastal management programs. The initiative works through regional and local partners to facilitate community-based socioeconomic monitoring. SocMon provides guidelines for developing surveys and collecting

and analyzing household and community level data to inform dependence on coral reef resources, perceptions of resource conditions, threats to marine and coastal resources and support for marine management strategies.

SEM-Pasifika

- **Website:** http://www.socmon.org/
- **General Description:** SEM-Pasifika is a set of socioeconomic monitoring guidelines developed for sites in the Pacific by the Community Conservation Network. The guidelines synthesize already existing methods into a single, user-friendly document for Pacific communities. Methods and information used in creating SEM-Pasifika include SocMon, the Locally-Managed Marine Area Learning Framework, *Socioeconomic Fisheries Surveys in Pacific Islands: a Manual for the Collection of a Minimum Dataset* (Kronen et al. 2007), the Global Coral Reef Monitoring Network's *Socioeconomic Manual for Coral Reef Management* (Bunce et al. 2000), and International Union of Conservation of Nature's *How Is Your MPA Doing?* (Pomeroy et al. 2004).

Bunce, L., P. Townsley, R. Pomeroy, and R. Pollnac. 2000. Socioeconomic Manual for Coral Reef Management. Townsville, Australia: Australian Institute of Marine Science.

Kronen, M., Stacey, N., Holland, P., Magron, F., Power, M. 2007. Socioeconomic Fisheries Surveys in Pacific Islands: a Manual for the Collection of a Minimum Dataset. SPC, Noumea, New Caledonia.

Marshall, N.A., P.A. Marshall, J. Tamelander, D. Obura, D. Malleret-King, and J.E. Cinner. 2010. A Framework for Social Adaptation to Climate Change; Sustaining Tropical Coastal Communities and Industries. IUCN, Gland, Switzerland. 44 pp.

Pomeroy, R., J. Parks, and L. Watson. 2004. How Is Your MPA Doing? Gland, Switzerland and Cambridge, UK: IUCN.

5) Restoration Guidelines

Coral Restoration

Johnson, M.E., C. Lustic, E. Bartels, I.B. Baums, D.S. Gilliam, L. Larson, D. Lirman, M.W. Miller, K. Nedimyer, and S. Schopmeyer. 2011. Caribbean Acropora Restoration Guide: Best Practices for Propagation and Population Enhancement. The Nature Conservancy, Arlington, VA. 54 pp.

Mangrove Restoration

http://awsassets.panda.org/downloads/placencia_mangrove_reserves_case_study_final.pdf

http://seabelize.org/outreach-education-program/mangrove-reforestation/

http://mangroveactionproject.org/resources/

http://www.sprep.org/Publications/manual-for-mangrove-monitoring-in-the-pacific-islands-region

Seagrass Restoration

http://oceana.org/sites/default/files/reports/OCEANA_Restoration_of_seagrass_meadows.pdf

http://floridakeys.noaa.gov/review/documents/swhandbook.pdf

6) Data Resources

Atlantic and Gulf Rapid Reef Assessment (AGRRA)

- **Website:** http://www.agrra.org/
- **General Description:** The Atlantic and Gulf Rapid Reef Assessment (AGRRA) Program is a regional collaboration of scientists and managers who are determining the regional condition of reefs in the western Atlantic and Gulf of Mexico.

Coral Reef Ecosystem Division (CRED)

- **Website:** http://www.pifsc.noaa.gov/cred/index.php
- **General Description:** The Coral Reef Ecosystem Division (CRED) leads an integrated, interdisciplinary program of ecosystem assessment, monitoring, habitat mapping and applied research on coral reef systems of U.S.-affiliated Pacific islands. The work supports NOAA and other U.S. government agencies. In terms of DSTs, CRED uses standardized protocols for monitoring and basement within its programs.

Healthy Reefs for Healthy People Report Card

- **Website:** http://www.healthyreefs.org/cms/
- **General Description:** Healthy Reefs for Healthy People is a collaborative initiative that shares user-friendly tools to measure, track and report on the health of the Mesoamerican Reef Ecosystem. The initiative produces scientifically credible and respected biennial report cards on ecosystem health along with eco-audits that evaluate the implementation of recommended management actions.

National Park Service Inventory and Monitoring Program (NPS I&M)

- **Website:** http://science.nature.nps.gov/im/monitor/index.cfm
- **General Description:** The NPS I&M Program aims to provide park managers, planners, and other key audiences with scientifically credible data and information on the status and trends of park resources. This information can be used as a basis for making decisions for the long-term protection of park ecosystems.

7) Project Planning

Miradi

- **Website:** https://miradi.org/
- **General Description:** Miradi is a "user-friendly program that allows nature conservation practitioners to design, manage, monitor, and learn from their projects to more effectively meet their conservation goals. The program guides users through a series of step-by-step interview wizards, based on the Open Standards for the Practice of Conservation. As practitioners go through these steps, Miradi helps them to define their project scope, and design conceptual

models and spatial maps of their project site. The software helps teams to prioritize threats, develop objectives and actions, and select monitoring indicators to assess the effectiveness of their strategies."

Community-based Risk Screening Tool—Adaptation and Livelihoods (CRiSTAL)

- **Website:** http://www.iisd.org/cristaltool/
- **General Description:** CRiSTAL is a project-planning tool that helps users design activities to support climate adaptation at the community level.

Integrated Valuation of Environmental Services and Tradeoffs (InVEST)

- **Website**: http://www.naturalcapitalproject.org/InVEST
- **General Description:** InVEST is a family of modeling tools intended to help people map, measure and value nature's goods and services. InVEST enables decision-makers to assess the trade-offs associated with alternative policy options and to identify areas where investments in ecosystem services can enhance conservation of various ecosystems, including marine.

8) Spatial Data Visualizations and Planning

Marxan

- **Website**: http://www.uq.edu.au/marxan/
- **General Description:** Marxan is freely available conservation planning software that provides decision support to a range of conservation planning problems. The software can be applied to a wide range of problems such as reserve design and natural resource management in terrestrial, freshwater, and marine systems. It can provide multiple options to complex problems and encourages stakeholder participation. These features provide users with decision support to achieve an efficient allocation of resources across a range of different uses.

SeaSketch

- **Website**: http://www.seasketch.org/
- **General Description:** SeaSketch can be used to visualize and discuss spatial data layers as part of spatial planning processes such as developing zoning and management plans for a marine region.

Envision

- **Website:** http://envision.bioe.orst.edu/
- **General Description:** Envision is a geospatial information system (GIS)-based tool for scenario-based community and regional planning and environmental assessments. The tool combines a spatially explicit, polygon-based representation of a landscape, a set of application-define policies (decision rules) that are grouped into alternative scenarios, landscape change models and models of ecological, social and economic services to simulate land use change and provide decision-makers, planners, and the public with information about resulting effects on indices of valued products of the landscape.

Sites: An Analytical Toolbox for Ecoregional Conservation Planning

- **Website:** http://www.biogeog.ucsb.edu/projects/tnc/toolbox.html
- **General Description:** Sites 1.0 is a customized ArcView project that facilitates designing and analyzing alternative portfolios. The software in Sites 1.0 to select regionally representative systems of nature reserves for the conservation of biodiversity is called the Site Selection Module (SSM).

MarineMap

- **Website:** http://marinemap.org/marinemap
- **General Description:** MarineMap is a web-based application used for designing marine protected areas (MPAs). Users can view marine geospatial data layers, draw prospective MPAs, share these MPAs with other users and assemble MPAs into arrays. Users may generate reports on the resources captured within the MPAs relative to the amount of those resources represented in the entire study region and estimate economic impacts of prospective MPAs.

Coastal Resilience 2.0

- **Website:** http://coastalresilience.org/
- **General Description:** This approach was developed and supported by the “Coastal Resilience Network” and includes a theoretical approach for addressing coastal resilience issues. The main thrust is a visualization tool that includes “resilience apps” that have been developed for specific geographies. These apps are intended to simplify complex relationships or models, convey a specific ecological or social concept, or to be used to compare different future condition scenarios.

NatureServe Vista

- **Website:** http://www.natureserve.org/prodServices/vista/overview.jsp
- **General Description:** NatureServe Vista is a free decision-support system that helps users integrate conservation with land use and resource planning of all types. Planners, resource managers, scientists, and conservationists can use the tool to assess cumulative effects for any number of scenarios, including climate change, investigate site conflicts, and design on-site or off-site mitigation strategies. The tool also supports ongoing adaptive management by integrating monitoring data and new knowledge or models to understand how well an area is meeting a set of conservation objectives.

ARtificial Intelligence for Ecosystem Services (ARIES)

- **Website:** http://www.ariesonline.org/
- **General Description:** ARIES is a web-based technology to assist with rapid ecosystem service assessment and valuation. Its purpose is to make environmental decisions easier and more effective. ARIES helps users discover, understand, and quantify environmental assets and what factors influence their values, in a geographical area, according to needs and priorities set by its users.

CommunityViz

- **Website:** http://placeways.com/communityviz/index.php

- **General Description:** CommunityViz is advanced GIS software designed to help people visualize, analyze and communicate on important land-use decisions. The tool can be used to create 3D visual models and has interactive features for analyzing choices over time.

C-Plan Conservation Planning System

- **Website:** http://www.edg.org.au/free-tools/cplan.html
- **General Description:** C-Plan is conservation decision support software that links with GIS to map options for achieving explicit conservation targets. The system calculates the irreplaceability value of landscape elements in terms of characteristics such as species composition, vegetation types, etc. It acts as a graphical user interface for Marxan and can generate Marxan datasets from C-Plan datasets.

Ecosystem Management Decision Support (EMDS) System

- **Website:** http://www.spatial.redlands.edu/emds/
- **General Description:** The Ecosystem Management Decision Support (EMDS) system is a spatial decision support system (SDDS). SDDS are intended to help decision-makers rationally evaluate strategies or solutions for spatial or geographic problems. These are often complex problems with large datasets, a high degree of uncertainty, and multiple stakeholders with conflicting interests and viewpoints. EMDS is an application framework for knowledge-based decision support for environmental analysis at any geographical scale.

9) Additional Resources

INVEMAR-MADS-Alcaldía Mayor de Cartagena de Indias-CDKN. 2012. Lineamientos de Adaptación al Cambio Climático para Cartagena de Indias. Adaptacíon al Cambio Climático Cartagena de Indias, Navarrete. Cartagena. 40 pp.

Belize Integrated coastal zone management plan: https://www.coastalzonebelize.org/wp-content/uploads/2015/08/BELIZE-Integrated-Coastal-Zone-Management-Plan.pdf

Belize Lionfish management plan: http://pure.au.dk/portal/files/81508560/Belize_lionfish_report.pdf