Conservation Biology

Essay

Expanding marine protected areas to include degraded coral reefs

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Abstract: *Marine protected areas (MPAs) are a commonly applied solution to coral reef degradation, yet coral reefs continue to decline worldwide. We argue that expanding the range of MPAs to include degraded reefs (DR-MPA) could help reverse this trend. This approach requires new ecological criteria for MPA design, siting, and management. Rather than focusing solely on preserving healthy reefs, our approach focuses on the potential for biodiversity recovery and renewal of ecosystem services. The new criteria would help identify sites with the highest potential for recovery and the greatest resistance to future threats (e.g., increased temperature and acidification) and sites that contribute to MPA connectivity. The DR-MPA approach is a compliment rather than a substitute for traditional MPA design approaches. We believe that the DR-MPA approach can enhance the natural, or restoration-assisted, recovery of DRs and their ecosystem services; increase total reef area available for protection; promote more resilient and better-connected MPA networks; and improve conditions for human communities dependent on MPA ecosystem services.*

Keywords: conservation, ecological rehabilitation, ecological restoration, ecosystem degradation, marine ecosystems, MPA

Expansión de las Áreas Marinas Protegidas para que Incluyan a los Arrecifes de Coral Degradados

Resumen: *Las áreas marinas protegidas (AMP) son una solución aplicada comúnmente a la degradación de los arrecifes de coral; sin embargo, los arrecifes siguen declinando a nivel mundial. Argumentamos que la expansión de la extensión de las AMP para que incluyan a los arrecifes degradados (AMP-AD) podría ayudar a revertir esta tendencia. Esta estrategia requiere de nuevos criterios ecológicos para el diseño, emplazamiento y manejo de las AMP. En lugar de enfocarse solamente en la preservación de los arrecifes sanos, nuestra estrategia se enfoca en el potencial de recuperación de la biodiversidad y la renovación de los servicios ambientales. Los nuevos criterios podrían ayudar a identificar sitios con el potencial más alto de recuperación y la mayor resistencia a futuras amenazas (por ejemplo, temperaturas y acidificación incrementadas) y sitios que contribuyen a la conectividad de las AMP. La estrategia de AMP-AD es un complemento en lugar de un*

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sustituto para la estrategia tradicional de diseño de AMP. Creemos que la estrategia de AMP-AD puede mejorar la recuperación natural, o asistida por restauración, de los arrecifes degradados y sus servicios ambientales; incrementar el área total del arrecife disponible para su protección; promover redes de AMP más resistentes y mejor conectadas; y mejorar las condiciones para las comunidades humanas dependientes de los servicios ambientales de las AMP.

Palabras Clave: AMP, conservación, degradación de los ecosistemas, ecosistemas marinos, rehabilitación ecológica, restauración ecológica

Background and Rationale

Coral-Reef MPAS Importance and Limitations

Natural and anthropogenic disturbances, including overfishing, habitat destruction, pollution, and climate change, threaten coral-reef biodiversity, ecological functioning, and ecosystem services (e.g., Bellwood et al. 2004; Wilkinson 2008; Burke et al. 2011). A management approach thought to counteract the decline of coral reefs is the designation of marine protected areas (MPAs) (Halpern & Warner 2002; Lester et al. 2009; Edgar et al. 2014).

Marine protected areas are designed to reduce human impacts by restricting certain activities. When well-designed, managed, and enforced, protected coral reefs and reefs otherwise isolated from human impact can enhance ecosystem recovery following wide-scale natural disturbances, such as coral bleaching (e.g., De'ath et al. 2012; Ateweberhan et al. 2013; Gilmour et al. 2013). Adjacent unprotected areas may also benefit from MPAs through spillover of adults or the export of larvae (e.g., Gaines et al. 2010; Russ & Alcala 2011). However, protection of functioning reefs alone may not reverse regional declines or maintain reef functioning (e.g., Knowlton 2012).

The continuing, large-scale degradation of coral reefs has reduced the availability of healthy reefs for MPA designation, and the most threatened reefs are often the most difficult to protect (Edgar et al. 2008). The minimum viable fraction of healthy reefs needed for future protection of reef biodiversity may not be available.

The Convention on Biological Diversity (CBD) recommends that at least 10% of each of the world's ecological regions be conserved by 2010 (UNEP-WCMC 2008). The impact of this protection, however, depends on the state of protected sites, and in many regions, it may be difficult to find 10% of reefs in good condition. For example, coral abundance has declined by >80% since 1980s on Chinese coastal fringing reefs and Hainan Island (Hughes et al. 2013). In the Philippines, where no-take MPAs encompass about 3% of coral reefs (Weeks et al. 2010), <10% of reefs are considered healthy (e.g., Nanola et al. 2004).

Even if a minimum viable fraction of sites can be protected, isolated reefs may substantially weaken connectivity among MPAs (Green et al. 2015), which may compromise ecosystem functions and neutralize the effectiveness of MPA networks (Gaines et al. 2010; Berglund et al. 2012; Green et al. 2015). Therefore, the continuing rapid degradation of reefs is expected to decrease the effectiveness of MPAs and MPA networks.

MPA Siting and Networks

Optimal siting of MPAs is traditionally based on environmental, ecological, and socioeconomic criteria (traditional criteria), generally with an emphasis on biodiversity conservation and fisheries management (e.g., Roberts & Hawkins 2000; Roberts et al. 2003; Gaines et al. 2010). Ecological criteria include levels of biodiversity, naturalness, dependency, representativeness, uniqueness, integrity, productivity, and vulnerability (e.g., Roberts et al. 2003; Gaines et al. 2010; Berglund et al. 2012). Within this set, biodiversity criteria include biogeographic and habitat representation, species richness, habitat heterogeneity, and presence of species of interest, and sustainability criteria include viable habitat size, exploitable species, vulnerable life stages, connectivity among reserves, links among ecosystems, and ecosystem services (Roberts et al. 2003).

These traditional criteria, notably the excluding criteria that identify excessive levels of threats from human or natural sources (Roberts et al. 2003), mean degraded reefs (DRs) are assigned low conservation priority. The inevitable question is whether this strategy inherently fails as the fraction of DRs grows.

DRs have been characterized based on, for example, amount of live coral cover, reef structural complexity, fish biomass, macroalgal cover, and disease rates (De'ath et al. 2012; MacNeil et al. 2015). However, designating a given reef as degraded or healthy is arbitrary and often based on the current state of the reef relative to its past state or the state of other reefs nearby. In our approach, DRs are defined during the siting process as reefs not selected for protection because of the low value of their current ecological attributes or selected as an inferior choice due to conflicting interests. Despite the widespread degradation of coral reefs, we have observed no significant attempts to consider DRs as explicit protection targets, with the exception of protecting reefs as a fishery management tool that promotes recovery of overfished stocks (e.g., Roberts et al. 2005). Current strategies for coral-reef conservation fail to consider protection of DRs based on their recovery and resilience potentials.

We argue that this oversight results in missed opportunities, especially with regard to MPA networks (i.e., a collection of individual MPAs operating cooperatively and synergistically to meet objectives that a single reserve cannot achieve [IUCN-WCPA 2008]). The traditional design of MPA networks (designated by location, size, and spacing of individual sites [e.g., IUCN-WCPA 2008; Gaines et al. 2010]) depends on habitat quality in individual MPA sites and on demographic and genetic connectivity of species of concern (e.g., Munday et al. 2009; Berglund et al. 2012).

The overarching goals of our proposed DR-MPA approach are to increase the fraction of protected reef sites in areas where healthy reefs are scarce; enhance the recovery of DRs, by either natural recovery following protection or successful restoration interventions; and improve connectivity where MPA network efficiency is compromised by large gaps between MPAs.

Encouraging the Recovery of Degraded Coral Reefs

The premises of the DR-MPA approach are that connectivity and thus MP-network function can be improved through the recovery of DRs and that active management, including stress relief (i.e., stress removal or alleviation) and restoration can accelerate recovery of DR-MPAs (Fig. 1). The recovery of spatially important DR sites (i.e., potentially key connectivity links within MPA networks) can improve MPA network function in areas with a high proportion of DRs. This may be especially important in areas where vital habitat types are scarce, degraded, or discontinuous. Although reefs protected from endogenous stressors (i.e., originating within the MPA), notably fishing and habitat destruction, can recover naturally, active management in the form of stress relief from exogenous stressors (i.e., originating outside the MPA), notably watershed-originated siltation, or ecological restoration (Fig. 1) (e.g., Edwards 2010; Bartley et al. 2014; Rogers et al. 2015) may accelerate the recovery of structure, function, and ecosystem services of reefs (Abelson et al. 2015).

Currently, protection and restoration are not integrated in comprehensive management programs. That is, protection from anthropogenic stressors is generally not a prerequisite for reef restoration, and restoration is not considered a tool in MPA management plans. We believe that ecosystem-based management that includes protection, stress relief, and restoration of low-quality DRs (Fig. 1) may be important to coral reef conservation and recovery.

Siting of DR-MPAs should prioritize natural recovery and resistance potential (Game et al. 2008) and potential future contribution to an MPA network and ecosystem services. However, effective siting and protection do not guarantee successful DR recovery and restoration of ecosystem services within a reasonable period (a few years). Thus, active management, including restoration to accelerate the recovery process, should be considered an integral part of DR-MPA endeavors.

Criticisms of coral-reef restoration are related to its scalability and failure to address the causes of degradation (e.g., Mumby & Steneck 2008) and may be attributable to persistent, major gaps in the science of reef restoration and the limitations of available methods. These gaps, however, are not likely to impede the effective implementation of DR-MPAs. Rather, we believe that the adoption of the DR-MPA and other adaptive-management approaches (e.g., Sale et al. 2005; Rogers et al. 2015) will stimulate the development of applicable restoration tools and further support the DR-MPA approach.

Ecological Criteria for Selection of DR-MPAs

The ecological criteria for selection of DR-MPAs include source or sink status, connectivity, larval supply, resilience capacity, past and present stressors, past reef communities, among-habitat and ecosystem links, and community resistance to environmental stressors.

The source or sink status of a reef may be evaluated based on its demographic potential (i.e., qualities that affect the survival and reproduction of individuals in the patch) and dispersal potential (i.e., measure of the patch connectivity) (Figueira 2009). Therefore, the selection of DR-MPA sites should focus on sink locations (those with high local recruitment) that could become (on recovery) effective source sites (as may be predicted by biophysical models of flow regime and larval transport) of ecologically and economically important species. Spillover potential (source of migrants for motile species), which can contribute to reef assemblages within the MPA network, should also be considered.

Spatial models that account for connectivity can improve reserve design, particularly when considering the population dynamics of certain species (Sala et al. 2002; White et al. 2014). Assessment of potential connectivity routes among sites within an area, based on physical models (e.g., Roberts 1997; Cowen et al. 2006), must account for both source and downstream sink reef sites. Some precedent exists for this approach. Using optimization algorithms and multiple levels of information, Sala et al. (2002) sought to maximize distance constraint to ensure strong larval connectivity for an MPA network design in Baja California. White et al. (2014) describe use of connectivity information to improve reserve design by applying an established optimization procedure. In their study, DRs protected from fishing serve as a source of larval recruits, juveniles, and subadults even before they are fully recovered, although newly settled fishes are assumed to rely on comparatively healthy reefs for their food and shelter.

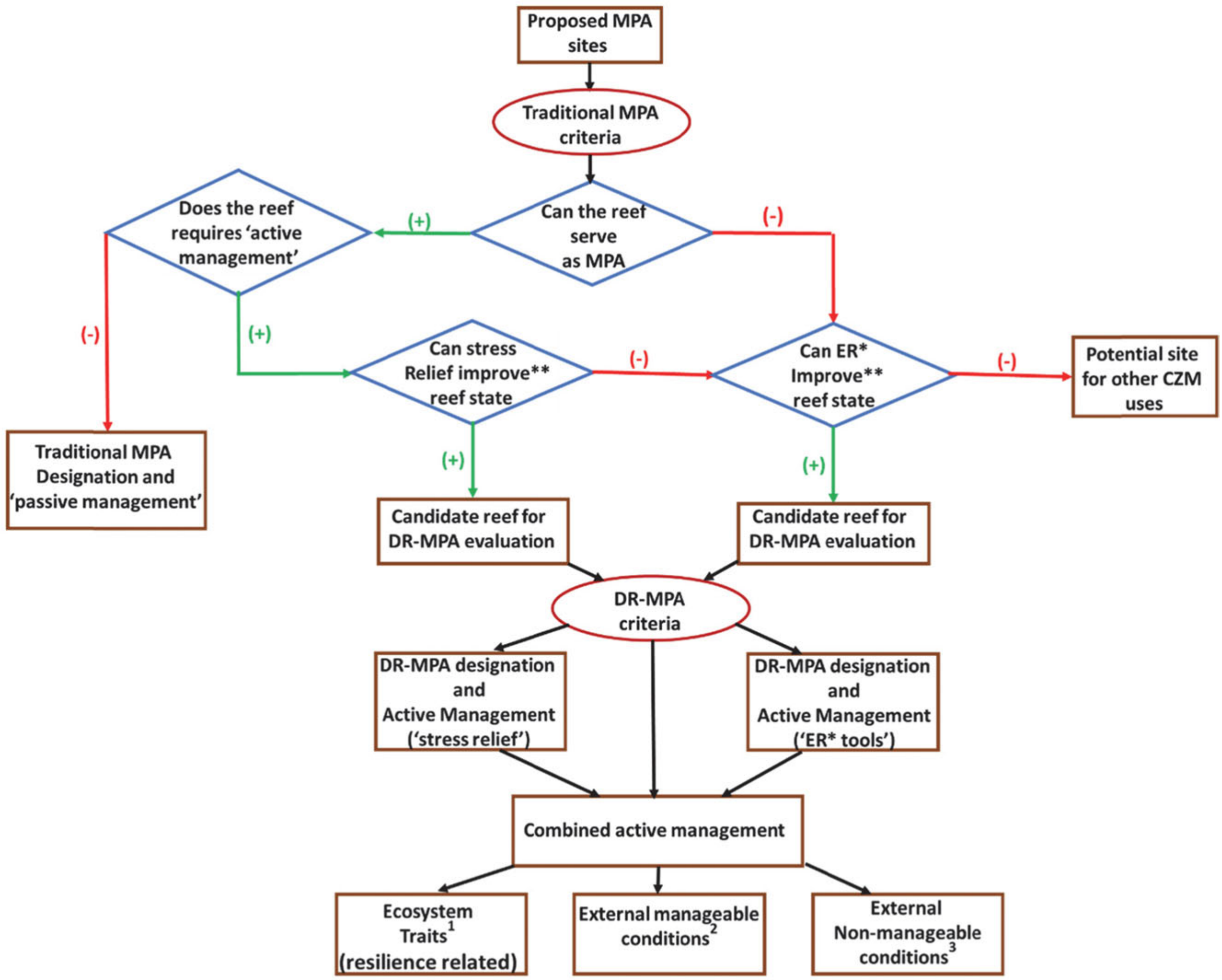

Figure 1. The decision-making process of the deteriorated-reef marine protected area (DR-MPA) framework (CZM, coastal zone management plans). The process separates healthy reefs (require regulations and enforcement of endogenous activities [i.e., passive management]) and deteriorated reefs (in addition to protection, require either or both stress relief [removal or alleviation] and ecological restoration interventions [i.e., active management]) into 2 distinct siting and management protocols to improve reef resilience, biodiversity, and ecosystem services. In active management, at least 1 of 3 traits or conditions is improved: (1) ecosystem traits (enhance reef resilience and resistance to perturbations), (2) exogenous manageable conditions (mainly stress removal or alleviation), and (3) nonmanageable environmental conditions (i.e., that cannot be changed or dictated by management intervention and therefore should be treated with risk-management tools or new methods that improve reef resistance to future, mainly climate-related, conditions [see text for details]). Improved reef state *is a relative phrase that may be related to the regional location and the needs of local stakeholders.* Ecological restoration *(ER) means diverse restoration interventions used to restore, mitigate, rehabilitate, or enhance a reef's ecological state or its ecosystem services.*

Ecological resilience is a key factor in the management of marine ecosystems, including coral reefs (e.g., Hughes et al. 2005; Mumby & Steneck 2008). The term refers to the capacity of an ecosystem to tolerate disturbance without abruptly shifting to an alternate regime and losing structure, function, or services (e.g., Hughes et al. 2005; Graham et al. 2013). Reef-resilience indicators have been used as a management tool (e.g., McClanahan et al. 2012; Maynard et al. 2015; Mumby & Anthony 2015). Resilience indicators include ecosystem-capacity features (e.g., recruitment and structural complexity), environmental conditions (e.g., temperature changes and storms), and anthropogenic stressors (e.g., eutrophication and fishing). We categorized these indicators based on their management implications as unmanageable (e.g., temperature); manageable (i.e., by stress relief [e.g., eutrophication]); or manageable by protection (to allow for natural recovery processes) and restoration (to induce or accelerate reef-community recovery and renewal of ecosystem services) (e.g., Edwards 2010; Abelson et al. 2015) (Fig. 1).

Broadly, the resilience concept has 2 separate processes: resistance, which is the disturbance magnitude required to cause a change in the system, and recovery, which is the ability of the system to return to its original structure (Côté & Darling 2010), where the speed of return is used as a common empirical metric of recovery (Selkoe et al. 2015). The ability of coral reefs to recover from perturbations (e.g., mass bleaching) or chronic stress is a major factor in the DR-MPA concept. Therefore, our concept includes resilience indicators of ecosystem capacity: recruitment and growth of corals (and other taxa of key functional groups), reef structural complexity, and algal grazing rates, which are key resilience traits governing the recovery of reefs following perturbations (e.g., Mumby & Anthony 2015). Thus, different degradation states (e.g., level of structural complexity and cover of coralline-, turf-, or macroalgae) (Fig. 2) are expected to be crucial to the recovery potential of the reef.

The ability of grazers to control the abrupt proliferation of benthic algae is key to coral-reef resilience (e.g., Bellwood et al. 2006; Green et al. 2009), and reef structural complexity (e.g., Alvarez-Filip et al. 2009; Spalding & Brown 2015) (Figs. 2b–2e) significantly affects grazing activities (e.g., Alvarez-Filip et al. 2009). Other factors, including the reciprocal connections between tropical coastal ecosystems (Gillis et al. 2014) and interhabitat links (among-habitat and ecosystem links criterion [Adam et al. 2011]), are also important to reef recovery and resilience, but habitat complexity and its role in affecting herbivory is one of the more easily assessed and manipulated factors in restoration.

Two major categories of stressors are associated with degraded but previously thriving coral reefs: discrete catastrophic events (mostly natural disturbances, such as typhoons or El-Niño-related mass bleaching events) and long-term chronic stressors (mostly local anthropogenic stressors, such as fishing. pollution, and siltation).

These local anthropogenic stressors (beyond endogenous fishing and habitat destruction) and the potential for halting, eliminating, or reducing them should also serve as key criteria. If the major degradation agent was a sharp acute disturbance, but the reef is not exposed to chronic stressors, unassisted natural recovery may occur (De'ath et al. 2012; Ateweberhan et al. 2013; Gilmour et al. 2013). If, however, the reef is exposed to minimal or manageable exogenous stressors (Fig. 1), its conservation priority should be relatively high. If the stressors that initially caused reef degradation are not removed or substantially reduced, then recovery of the reef system is not likely to occur within a reasonable period (few years). If the site is of disproportionate importance to the efficacy of the MPA network or some ecosystem service (e.g., coastal protection), restoration is an optional, although costly, solution (see "Management of DR-MPAs").

Another important parameter to consider for DR-MPA selection is the reef community state prior to the degradation. Existing data on reef condition (e.g., biodiversity, naturalness, dependency, and productivity) prior to substantial damage can help in the assessment of reef communities and their recovery potential. Alternatively, information about the causative agent category (discrete catastrophic, chronic, or both [past and present stressors criterion]) can help in the assessment of the value of the site and its potential for recovery. If data are not available, historical indicators of fishing values (e.g., information on abundant species and their sizes [McClenachan & Kittinger 2012]) can provide essential information.

Among-habitat and ecosystem links in tropical coastal ecosystems (i.e., coral reefs, mangrove forests, and seagrass meadows) can play an important role in the resilience potential and recovery of coral reefs (e.g., Mumby 2006). For instance, coral reefs in proximity to mangrove forests and seagrass meadows support higher levels of herbivore biomass than isolated reefs (Gillis et al. 2014). Among-habitat links offer another example. Studies in Moorea suggest that protecting lagoons, which serve as nursery habitats of herbivorous fishes, may play a critical role in maintaining reef resilience by preventing takeover by macroalgae following major perturbations (e.g., mass bleaching [Adam et al. 2011]). Higher connectivity therefore between a degraded reef and other habitats and ecosystems may indicate a higher quality site for DR-MPA.

Species assemblages of high potential resistance to environmental stressors (e.g., coral species, genotypes resistant to temperature fluctuations) can play a crucial role in reef survival in a human-dominated world (e.g., Palumbi et al. 2014; Shamberger et al. 2014). Although reefs are exposed to diverse disturbances and stressors, resistance may be a common character, where tolerance to a nonclimatic disturbance is correlated with its tolerance to climatic impacts (i.e., "positive cotolerance"; Côté & Darling 2010). Local selection for genotypes and species of corals with high resistance to disturbance has been described (e.g., Zvuloni et al. 2008; Palumbi et al. 2014). Relevant questions therefore when selecting DRs for protection include: (1) Does the site an assemblage of resistant species and (2) have local stressors-induced local selection of genotypes resistant to high levels of disturbance or to fluctuations of environmental conditions (e.g., turbidity, sedimentation, temperature, salinity, pH, and pollutants)? For example, sites with genotypes of high resistance should be given high priority as potential future refuges (e.g., Palumbi et al. 2014) under different scenarios of climate change (e.g., Makino et al. 2015).

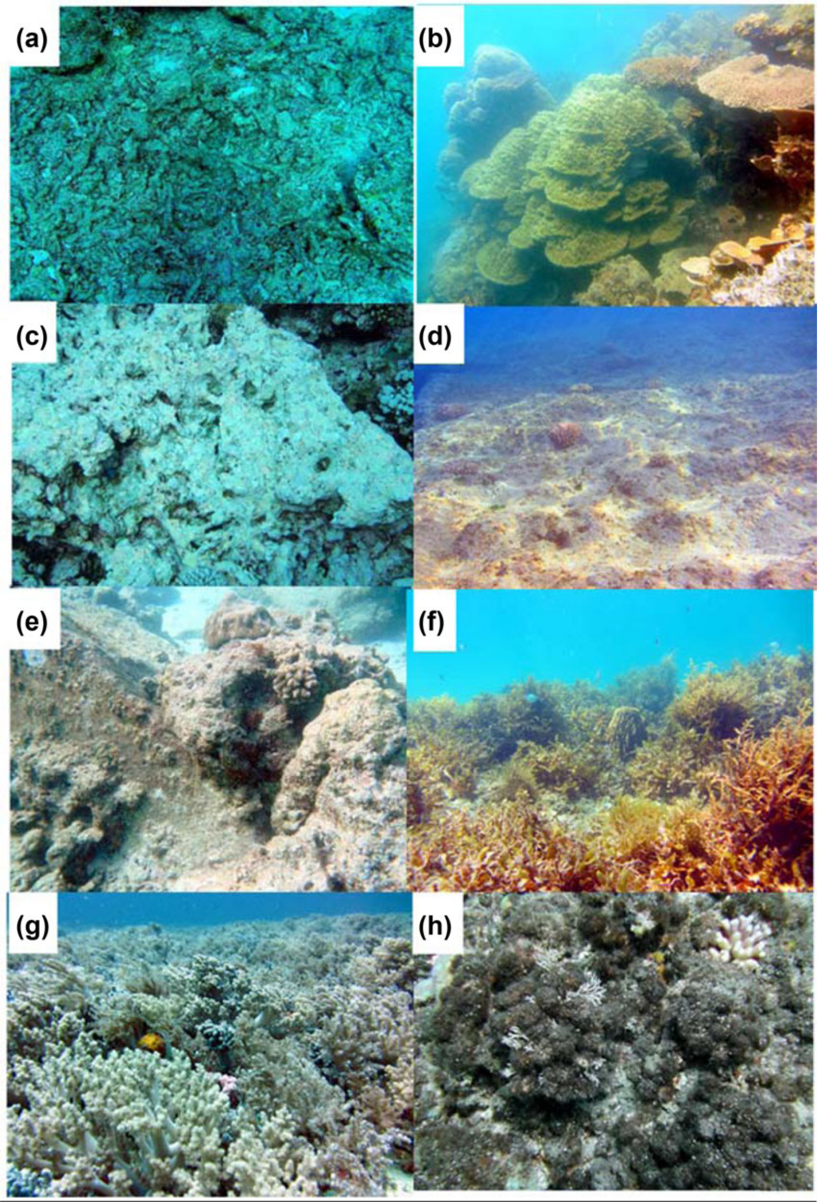

Figure 2. Degraded-reef states: (a) structurally destroyed reefs, (b) high stony coral cover with low fish densities, (c) exposed rocks and high coralline alga cover, (d) exposed rock with low structural complexity, (e) exposed rock with high structural complexity, (f) high macroalgal cover (e.g., Sargassum *sp.), (g) high cover of nonreef-building invertebrate taxa (e.g., soft corals, sponges, and tunicates), and (h) high turf-alga cover.*

Integrating Traditional and DR-MPA Criteria

The DR-MPA criteria should be integrated with traditional MPA criteria to assist with siting of regional MPAs and MPA networks (Fig. 1). A fundamental challenge in marine conservation is to balance the cost of maintaining an MPA network with regional conservation and management goals (e.g., Williams et al. 2004; Rassweiler et al. 2014). Optimization models (e.g., Marxan-algorithm-based models [Ball et al. 2009]) help delineate reserve configurations that minimize economic costs while protecting some minimum fraction of fish habitats and biodiversity (Sala et al. 2002; Williams et al. 2004; White et al. 2014). If such models are part of the DR-MPA framework, then data pertaining to DR-MPA criteria from the different candidate DR sites should be integrated with the MPA traditional criteria into an optimal-siting plan based on optimization models that include connectivity as a prerequisite. Where healthy reefs are rare and spatially limited, the inclusion of DRs in MPAs may evoke fewer objections from fishing communities. To the best of our knowledge, optimization models have not been designed for optimal siting of DRs, which may hinder the application of DR-MPAs as an effective management tool.

Management of DR-MPAs

DRs are often in a state from which recovery, even under no-take conditions, may take decades (e.g., Blackwood et al. 2011; MacNeil et al. 2015). Moreover, fishing is not the only stressor, and MPAs do not provide protection against other major threats, including climate-related changes, pollution, and terrigenous sedimentation (Hilborn 2015; Xu et al. 2015). Such threats, even if they do not seem to affect apparently healthy reefs, may slow or prevent the recovery of DRs due to existence of alternative attractors (Dudgeon et al. 2010). Therefore, an adaptive-management approach that includes an array of tools beyond protection may be required (Fig. 1) (e.g., Jaap 2000; Rogers et al. 2015; Obolski et al. 2016). When the reef requires active intervention (due to, for example, eutrophication or siltation from terrestrial runoff [Bartley et al. 2014]) or restoration (e.g., coral transplantation, enhancing structural complexity, and grazer reintroduction [Edwards 2010; Rogers et al. 2015; Obolski et al. 2016]), the siting criteria and management category should be defined based on the DR-MPA approach (Fig. 1). The DR-MPA management program is expected to address deficiencies in the quality of the sites, for example, by improving recruitment (Fig. 1).

The site-specific management program should emphasize protection from direct human impacts and includes relief from indirect impacts and restoration (Fig. 1). The program should be tuned to the particular reef state (Fig. 2), its resilience potential (Mumby & Anthony 2015), existence of local exogenous stressors (e.g., pollution, siltation [Fabricius 2005; Burke et al. 2011]), and management capabilities and funding limitations. Environmental risk assessment and management of the MPA that considers both exogenous and endogenous stressors (Xu et al. 2015) is an essential supporting tool in prioritizing management options.

Reef-Degraded States

We considered reefs that have been destroyed structurally (i.e., reduced to rubble [Fig. 2a]) and reefs with high stony-coral cover but poor fish abundance or community composition (Fig. 2b). These extreme states require significantly different restoration tools. Whereas the former may require intensive, costly restoration intervention (e.g., substrate stabilization, artificial marine structures, and coral transplantation; Jaap 2000; Abelson & Shlesinger 2002; Edwards 2010), the latter may recover through protection or fishing regulations (MacNeil et al. 2015) or relatively low-cost stock enhancement in cases of extreme herbivore depletion (Obolski et al. 2016). Along the spectrum of these degradation extremes, other degraded reef states (Figs. 2c–2h) may require different management plans, depending on their structural complexity (Figs. 2d and 2e) and the types and coverage of algae (Figs. 2c, 2f, and 2h) or other forms of undesirable benthic organisms (Fig. 2g).

Resilience Metrics

In addition to effects of reef state and environmental conditions, the expansion of live coral cover (i.e., recruitment and growth) is another metric of resilience and an important goal. The most common way to restore coral cover is to transplant corals (e.g., Edwards 2010). Other approaches, some of which have not been fully studied, may improve coral settlement and recruitment, such as fostering recruitment through beneficial communities of bacteria (Kelly et al. 2014), settlement inducers (e.g., Jaap 2000), and enhanced structural complexity (e.g., Abelson & Shlesinger 2002; Rogers et al. 2015).

Nonexploitative Stressors

Adverse exogenous stressors, often not covered by MPA regulations (Hilborn 2015), are manageable or practically unmanageable. Reefs exposed to chronic stressors are likely to develop unique assemblages of resistant species and genotypes that result from local selection (e.g., Palumbi et al. 2014). These reefs may provide an example of prioritized DR-MPA sites due to their future resistance potential (e.g., Palumbi et al. 2014). For instance, in many cases, adult reef-building corals can tolerate and even exploit moderate levels of chronic sedimentation (e.g., Fabricius 2005; Rosenfeld et al. 1999). However, the combination of chronic and acute stressors may make management difficult. A single catastrophic event (e.g., severe storms, mass bleaching [Russ et al. 2012; Gilmour et al. 2013]) that kills most of the live coral on a reef exposed to chronic siltation can create a barren reef due to low recruitment of corals (e.g., Fabricius 2005). In such cases, natural recovery is unlikely or may take decades. However, once the source of siltation is reduced (e.g., reforestation or retention ponds), the natural recovery of corals is expected, assuming appropriate larval supply.

The proliferation of benthic macroalgae (resilience-capacity criterion) is another management challenge. Identifying and fostering the conditions that enable efficient macroalgae grazing by native herbivores to reestablish coral dominance is a key goal of DR-MPA management (Graham et al. 2013). Reversing such degraded states may require reducing local chronic drivers (e.g., fishing pressure, land-sourced siltation, and eutrophication) and management of key ecological processes (e.g., controlling functional groups of herbivores; Green et al. 2009) to weaken the stability of the degraded state and strengthen the coral-dominated state. Slow reversal may require more intensive and costly interventions, such as stock enhancement of scarce local grazer populations (e.g., Cowx 1999; Obolski et al. 2016). If detrimental human impacts are reduced and key ecological processes are enhanced, pulse disturbances (e.g., extreme weather events) and ecological variability may provide opportunities for a return to a coral-dominated state. Achieving these outcomes necessitates alteration of human interactions with reef ecosystems (Graham et al. 2013).

Beyond reef protection and stress relief, a DR-MPA management program is expected to fill the gaps in habitat qualities and MPA networks through restoration of certain ecological attributes and acceleration of recovery processes. This aspect of the DR-MPA approach requires additional study.

Conclusions and Future Directions

Marine protected areas have limitations; they do not address all conservation goals, such as the socioeconomic needs of local users (e.g., McClanahan et al. 2006) and building ecological community resistance (Côté & Darling 2010) and are not a countermeasure to exogenous stressors (e.g., pollution and siltation [Hilborn 2015]). Moreover, the effects of rapid reef degradation (e.g., Burke et al. 2011) combined with conflicts of interest among and growing impacts on reefs by diverse stakeholders (notably overfishing [e.g., Teh et al. 2013]) and unpredictable climate-change effects (e.g., Makino et al. 2015) create new situations that require integration of traditional MPAs with new management tools (e.g., Graham et al. 2013; Rogers et al. 2015).

We attempted to address this need by developing a conceptual framework for active management (Fig. 1) and by identifying directions for future research. Our DR-MPA approach is not a substitute for the traditional MPA approach. Rather, it is a management-assisting framework directed at expanding the total area of MPAs by promoting the recovery of otherwise low-quality reefs and subsequently improving the connectivity of MPA networks and the reefs' ecosystem services. During selection of DR-MPA sites, it is crucial to develop a site-specific management program (Fig. 1). The management program should extend beyond simple protection to include stress relief (removal or alleviation) and implementation of restoration interventions if appropriate. Management plans should include greater regulation of areas beyond the MPA to better manage exogenous threats (e.g., effects of watershed activities on water quality). A DR-MPA program is expected to alleviate the deficiencies of selected sites by filling gaps in ecological attributes related to the sites' role in its MPA network or in ecosystem services.

Major gaps persist in reef conservation science, notably the cause and effect of stressors, databases for environmental risk assessment, and effective restoration tools. These gaps limit broad support for DR-MPA management objectives. However, we believe that implementation of the DR-MPA approach, if effective protection and stress relief interventions are applied, can promote reef recovery despite these gaps. Implementing the DR-MPA siting and management approach can help promote the recovery of coral reefs, notably where local endogenous and exogenous stressors (e.g., fishing and deforestation) are a key factor in reef degradation (e.g., Southeast Asia; Burke et al. 2011). The proposed approach is expected to promote 4 aims crucial to global reef conservation: increase total coverage of protected areas in regions of rapid reef degradation; enhance the probability of restoration success; improve the functionality and effectiveness of MPA networks (better linkage within the network MPAs and greater resilience of reefs within these MPAs); and restoration of crucial ecosystem services that support local human communities. We suggest that future marine spatial models include the DR-MPA concept and its related siting criteria and management-related improvement of ecosystem services in the MPA decision-making processes, especially in areas of dramatic reef decline, scarce healthy reefs, or strong conflict of interest.

The continued, rapid, deleterious changes to the oceans should serve as convincing evidence that the present natural world is immensely different from that which prevailed several decades ago, when the protected areas concept was first established. Given this reality, deteriorated and novel habitats must be considered along with comparatively healthy ecosystems in an effort to make the best of suboptimal circumstances. The DR-MPA concept is an example of this approach.

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