11

Marine Protected Area Planning in a Changing Climate

Rodney V. Salm, Terry Done, and Elizabeth McLeod

Abstract

The establishment of Marine Protected Areas (MPAs) has become an important part of society's approach to conserving coral reefs. Protected area managers now must attempt to take account of climate change in the design and implementation of MPAs. A network of MPAs provides a logical way to distribute their benefits to the wider reef system of which they are part, and to minimize the risk that spatially unpredictable and unmanageable insults of any type may decimate all protected areas. This chapter reviews the types of environmental factors and settings that might be considered in the network design process. We focus mainly on environmental factors that appear to confer ecological resilience to bleaching, and also briefly touch on physiological resistance conferred to corals by some strains of zooxanthellae. Finally, our chapter provides a model outlining these four actions that MPA managers may take to build resilience into coral reef conservation programs: 1) spread risk by protecting multiple examples of a full range of reef types; 2) identify and protect coral communities that demonstrate bleaching resistance and may thus increased contribute genetically based bleaching resistance to recovering areas; 3) incorporate connectivity into MPA and network design; and 4) increase effectiveness and flexibility of reef management strategies.

Introduction

The increased frequency and severity of mass coral bleaching due to sea temperature rise has increased stresses on coral reefs and raised concerns about appropriate response strategies [Hughes et al., 2003]. Marine Protected Areas (MPAs) have been identified as one of the most effective tools for conserving reefs and related marine systems [Kelleher, 1999; Lubchenco et al., 2003; Palumbi, 2003]. However, protected area managers must incorporate climate change as well as increasing human pressures into their conservation strategies, or MPAs may not be able to safeguard biodiversity effectively. Networks of MPAs, including no-take areas totaling 30-50% of available reef area [Hoegh-Guldberg and Hoegh-Guldberg, 2004], have been suggested as a critical way to protect coral reefs from human stresses. No-take areas increase fish biomass and variability both inside and outside the boundaries of those areas [Halpern, 2003] and permit critical functional groups to persist, thus contributing to local ecosystem resilience Bellwood et al. [2004].

Coral Reefs and Climate Change: Science and Management
Coastal and Estuarine Studies 61

10.1029/61CE12

The Challenge: MPA Manager's Perspective

MPA managers in the 21st Century are faced with a number of synergistic environmental changes that can adversely affect coral survival, and over which they have no control [Buddemeier et al., 2004]: increasing temperature [Hoegh-Guldberg, 1999]; sea level rise [Done, 1999]; increased exposure to UV light [Catala-Stucki, 1959; Gleason and Wellington, 1993, 1995; Hoegh-Guldberg, 1999; Siebeck, 1988] and reduced alkalinity [Gattuso et al., 1998; Kleypas et al., 1999; Langdon et al., 2000, 2003; Leclercq et al., 2000; Marubini et al., 2001]. The evidence is incontrovertible that the Earth has already warmed 0.6-0.8° C since 1880. The projections that it will warm 2-6° C by 2100 are credible (IPCC 2001).

MPA managers, accustomed only to addressing direct and usual threats related to fishing and tourism, for example, find it difficult enough to address the impacts of coastal development and inland activities, and may consider climatic sources of environmental stress totally beyond their sphere of influence. This perception is reinforced when even well managed reefs in the remotest MPAs (e.g., Ngeruangel atoll in Palau and Aldabra atoll in the Seychelles) succumb to a climate related bleaching event. However, there are some direct actions that MPA managers can take immediately, even as the scientific understanding improves. Salm et al. [2001] proposed that it might be possible to mitigate the negative impacts of bleaching on coral reef biodiversity in two broad ways:

1. Identify and protect from direct anthropogenic impacts, specific patches of reef where local conditions are highly favorable for survival generally, and that also may be at reduced risk of temperature-related bleaching and mortality (i.e., coral assemblages with a high level of "resistance");
2. Locate such protected sites in places that maximize their potential contribution to their own resilience, and, through larval dispersal, to that of reefs that are interconnected with it.

In this chapter, we explore these ideas further.

Exploring Possible Solutions

Locations to be avoided are those where exposures to both anomalous high sea surface temperatures and solar radiation are likely. These factors interact to cause severe coral bleaching and mortality, and are responsible (either alone or in combination) for the majority of climate related disturbances [Fitt et al., 2001; Glynn, 2000; Wellington et al., 2001], West and Salm [2003] group factors that may protect areas into four broad categories: physical factors that reduce temperature stress; physical factors that enhance water movement and flush toxins; physical factors that decrease light stress; and factors that confer stress tolerance in the corals. Sites where these factors reliably occur would make good candidates for MPA selection and the investment of conservation effort and funds.

Reduction of Temperature Stress

There is strong evidence that vertical mixing of deeper cool waters up through the water column effectively reduces temperature-related stress to shallow water corals [Skirving, this volume]. Tidal-driven or long-wave currents can thus prevent temperature stress anomalies occurring within coral zones, during times when regional heat stress is generally widespread. Following the 1998 El Niño Southern Oscillation (ENSO), areas of local upwelling protected central Indonesian reefs from severe bleaching [Goreau et al., 2000; Salm et al., 2001]. Additionally, some reefs had lowered mortality due to cooling effects of strong upwelling: the outer reefs of Alfonse, St. Francois, Bijoutier atolls, Western Zanzibar, and certain areas in the Maldives [Goreau et al., 2000]; some outer reefs in the Great Barrier Reef following a 2002 heat wave [Berkelmans et al., 2004; Wooldridge and Done, 2004].

Strong Currents and Flushing

Flushing by strong currents, even if the water remains warm, may also protect corals to some degree, apparently working by removing free radicals that are a toxic byproduct of bleaching in corals [Nakamura and van Woesik, 2001]. In laboratory experiments, these authors demonstrated that *Acropora digitata* suffered high bleaching mortality under low-flow conditions, and none under high-flow conditions. While field evidence for this effect is weak, there have been observations in Palau and Indonesia that clearly demonstrate synergisms at work. At several sites in Palau[4] where corals had died on reef slopes below 2-4m, reef flats and shallow reef crests with strong currents showed much higher coral survival. At Komodo National Park and Nusa Penida Island in Indonesia, there was a clear vertical mixing effect of strong cool currents. At these locations, there was little or no bleaching or temperature related mortality in corals following the 1998 event.

Reduction of Light Stress

Under ideal conditions, corals thrive at high light levels [Jokiel and Coles, 1990]. However, in combination with a second factor (i.e., increased temperature), high light levels can become a stress. High north-south orientated islands can sometimes provide shading for corals during one or other half of the day, and undercut karst islands or coastlines often provide intensely shaded shelves on which corals can grow. Trees growing on the slopes of these coasts can further extend the shading effect seawards. The Rock Islands in Palau demonstrate well this effect of shading in reducing bleaching and related mortality. At Nikko Bay, in particular, one of the most diverse permanent monitoring sites of the Palau International Coral Reef Research Center, corals in shaded areas survived well during the 1998 bleaching event that, elsewhere in the vicinity, caused major coral mortality.

Suspended particulate matter in the water column may also protect corals by screening them from destructive high light levels. On silty and often turbid fringing reefs on the inner Great Barrier Reef, coral cover can approach 100% over large areas [Stafford-Smith and Ormond, 1992]. In parts of the Rock Islands and sheltered bays off Babeldaob, Palau, *Porites rus* and *Porites cylindrica* succumbed to bleaching and died in clear water areas, but survived in cloudy water. Turbidity may also have contributed to lower mortality following the 1998 bleaching event in the Gulf of Kutch, Southwestern Sri Lanka, Mahé [Goreau, 1998a, 1998b], along the 18-foot break inside the barrier reef in the Florida Keys National Marine Sanctuary (Causey, pers. comm.), and inside the lagoon of Alfonse atoll [Goreau, 1998c; Goreau et al., 2000].

---

[4]Lighthouse Reef flats, patch reef east of Ebiil Channel off NW Babeldaob Island, Fantasy Island area reef flats (these later severely impacted by the crown-of-thorns starfish *Acanthaster planci*)

Stress Tolerance

The algal symbionts of reef corals are extraordinarily diverse [e.g., Rowan and Powers 1991], and it is possible that reef corals may mitigate the effects of climate change by hosting unusually heat-tolerant symbiont communities as a response to changing temperatures [Baker et al., 2004]. Some corals have adapted to higher temperatures by hosting more heat tolerant zooxanthellae better able to resist coral bleaching [Rowan, 2004; Baker et al., 2004]. Baker et al. [2004] found that corals containing thermally tolerant *Symbiodinium* in clade D are more abundant on reefs after episodes of severe bleaching and mortality. Rowan [2004] also found that corals have adapted to higher temperatures by hosting thermally tolerant *Symbiodinium*. Rowan [2004] observed that *Pocillopora* spp. with *Symbiodinium D* resisted warm-water bleaching whereas corals with *Symbiodinium C* did not. He also noted that *Pocillopora* spp. living in water over 31.5°C hosted only *Symbiodinium D*; whereas those living in cooler habitats hosted predominantly [Rowan, 2004]. Baker et al. [2004] propose that adaptive shifts to heat resistant algal symbionts will increase coral reef resilience to future bleaching events [Baker et al., 2004]. However while the prospect of heat-tolerant strains of symbionts protecting entire habitats and multi-species coral assemblages is appealing, its realization is less certain.

In selection of sites for conservation management, quantitative information about the current level of such genetically based resistance in candidate areas should be taken into consideration, should it exist [e.g., Van Oppen et al., 2005). In practice, protection afforded to any given site will depend on factors currently unknown, notably the rates of propagation of heat-tolerant strains across the candidate area, and rates of propagation across all coral species and functional groups. Should such habitat and community-wide propagation occur, there would likely be a decrease in zooxanthellae diversity across the community. This may have consequences in relation to other phenotypic traits of the corals. For example, corals hosting the more heat-vulnerable *Symbiodinium C* grow more quickly than those hosting the less vulnerable *Symbiodinium D* [Little et al., 2004].

Acclimatization is a second means of increasing local site resistance. A history of regular exposure to severe conditions [Brown et al., 2000; Coles and Brown, 2003; Dunne and Brown, 2001] appears to acclimatize corals to cope with anomalous excursions in light and temperature. This includes corals in habitats exposed to intense solar radiation [Brown et al., 2000] and/or high temperatures [Craig et al., 2001; Jokiel and Coles, 1990; Marshall and Baird, 2000]. Corals on reef flats that emerge at low tide are exposed to conditions of heating, desiccation and rainfall. Such prior exposures have been posited as explanations for lower bleaching susceptibility recorded for corals in some inner reefs and lagoons relative to conspecifics from deeper waters [Hoeksema, 1991; Salm et al., 2001; West and Salm, 2003]. The central Indian Ocean in 1998 provides another example. Here, there was localized survival of corals in reef flat and lagoon areas [Spalding et al., 2000], probably reflecting the wide ambient variability in light and heat in these habitats.

Reef flat and lagoonal coral communities should thus not be overlooked in management plans or reef conservation. Indeed, reef flats will be the coral habitat most affected by sea level: given a strong supply of coral larvae, a rise in sea level could allow for successful recruitment and growth of a greater variety of corals than are currently found on some reef flats [Done, 1999].

Coral Community Type

It is possible that the presence of some of these factors described above is correlated with specific coral community types. Coral species with rapid growth rates, thinner tissue, and branching forms, (e.g., *Acropora* spp., *Stylophora* spp., *Pocillopora* spp.) tend to bleach sooner and more severely than slow-growing, massive corals with thicker-tissues (e.g., *Porites, Goniopora* spp.) [Gates and Edmunds, 1999; Loya et al., 2001]. However, even in a specific location, there can be great intra-specific variability in susceptibility to heat stress responses to temperature fluctuations [Marshall and Baird, 2000; Smith and Buddemeier, 1992].

In one study of three hard coral genera, *Acropora* spp. showed the most severe bleaching, *Pocillopora* spp. showed intermediate bleaching, and *Porites* spp. showed the least bleaching [Hoegh-Guldberg and Salvat, 1995]. It was the corals that showed the fastest growth and metabolic rates (*Acropora* spp.) that were the most susceptible. All *Porites* spp. colonies recovered from bleaching, while *Acropora* spp. did not recover well. Here, mass bleaching quickly changed the dominance relationships by decimation of a major component. A similar change in community structure was observed in Okinawa [Loya et al., 2001]. Community shifts away from branching corals might have negative impacts on these ecosystems, as many fish and invertebrate populations are obligate associates of intact branching corals [Goreau et al., 2000].

Strong and diverse coral recruitment and growth signify a site's resilience in respect of its corals. Strong recruitment is measured by both the number per unit area and the cover of small coral colonies established since a prior disturbance. The chronology of recovery is often reflected in the presence of well-defined size classes of corals. It can be argued that such recruitment is also a proxy measure of local reef "health"; i.e., suitability of the substratum and of water quality. The 'sources' of larvae that recruited may be some kilometers upstream, and themselves need to be identified and protected in MPAs to ensure strong and rapid recovery of the downstream 'sink' reef. It is likely that these source coral communities have survived because of one or more of these factors reduce the risk of bleaching at the site. Full protection of these "resistant" or low risk coral communities in MPAs is essential, whatever the underlying reasons for survival.

What Can MPA Managers do?

While there is little that MPA managers can do to control large-scale stresses at their sources, there are direct actions they can take to help reefs survive catastrophic bleaching events. The "Resilience Model" developed by The Nature Conservancy, is a simple tool to assist conservation planners and managers build resilience into coral reef MPAs (Plate 1).

The components of the model and their application to MPA network design are described below. The most effective configuration would clearly be a network of highly protected areas nested within a broader management framework. Such a framework might include a vast multiple-use reserve managed for sustainable fisheries as well as protection of biodiversity. The ideal MPA system would be integrated with coastal management regimes to enable effective control of threats originating upstream, and to maintain high water quality [e.g., Done and Reichelt, 1998].

1) Representation and Replication

Protect multiple examples of a full range of reef types, seeking to represent the area's total reef biodiversity. Replication within each type reduces the chance of any one type being completely compromised by an unmanageable impact such as a major bleaching event.

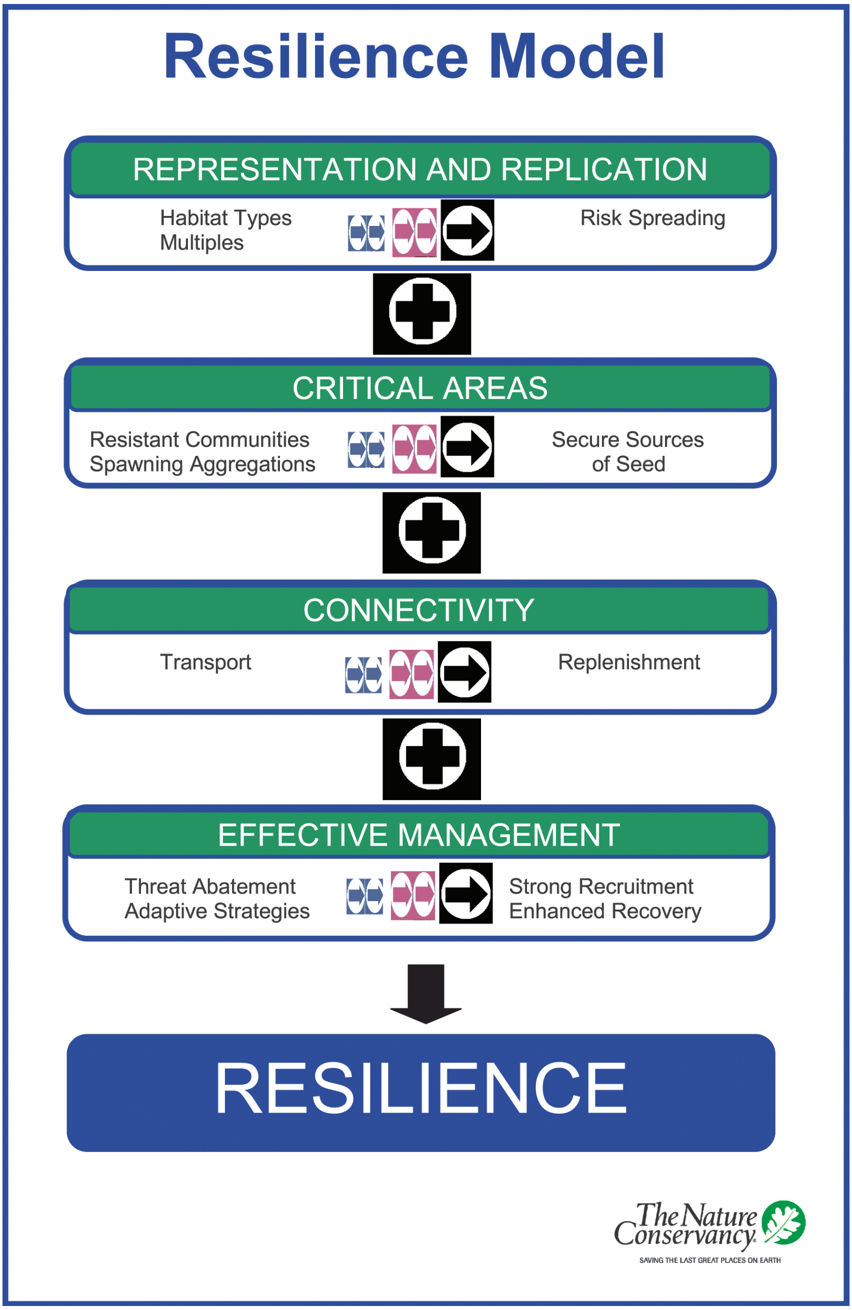

Plate 1. The Nature Conservancy's Resilience Model.

To fully represent regional biodiversity within fully protected areas, the range of reef types protected should include samples of offshore reefs (barriers, atolls) in areas with greater and lesser wave energy and exposure to trade wind, mid-shelf reefs (patch and fringing reefs) where these exist, and inshore fringing and patch reefs in sheltered locations. For long, linear coastlines, samples of all these reef types should be selected at regular intervals along the coast and reef tract. Wherever possible, multiple samples of each reef type should be included in MPA networks or larger management frameworks, such as multiple-use MPAs or areas under rigorous integrated management regimes. This overall approach has recently been put into practice with designation of around 30% of the Great Barrier Reef in 'no-take' areas in July 2004 [Day et al., 2002].

Selecting and securing multiple samples of reef types may also have the advantage of protecting essential habitat for a wide variety of commercially valuable fish and macroinvertebrates. Studies have confirmed that maintaining coral cover is important to maintaining fish biodiversity. According to an 8-year study in Papua New Guinea, a decline in coral cover caused by a combination of factors (e.g., coral bleaching, increase in sedimentation from terrestrial run-off, and outbreaks of crown-of-thorns) caused a parallel decline in fish biodiversity within marine reserves [Jones et al., 2004]. Therefore, it is essential to include replicates of representative habitats for two reasons: first, to spread the risk of losing any one of the representative habitat types through chronic or catastrophic events; and, second, to maintain a diverse range of habitat types and their associated communities.

2) Refugia

Identify and fully protect coral communities that can serve as refugia and thereby reseed other areas that are seriously damaged by bleaching.

Through analyzing local environmental factors that contribute to coral community resistance and resilience, managers can identify areas of cooling, shading, screening, stress tolerance, and strong currents, as described in the preceding section [West and Salm, 2003]. For example, in an area at the south end of Sulawesi, and along the Makassar Strait, a 17-year analysis (1985-2001) showed no thermal anomalies greater than 1°C in many parts of the region [WWF, 2003]. Kassem et al. [2002] suggests that this is due to a combination of oceanographic features including high current flow [WWF, 2003].

The Raja Ampat Islands in the heart of the Indo-West Pacific provide an example of a place that has escaped climate change impacts. This group of islands has over 75% of the world's known reef building corals, including 35 possible new species awaiting identification [Donnelly et al., 2003]. Raja Ampat is located in a major convergence of marine currents that circulate nutrients, transport larvae through the islands, and cool its waters, protecting the reefs from bleaching effects. The high biodiversity and apparent lack of coral bleaching, suggest that Raja Ampat is a key area, both as a major reservoir of biodiversity, and a secure source of propagules for reefs connected to it by currents. Historically, this region has been important in generating, maintaining and dispersing genetic diversity across large geographic areas of the Indo-West Pacific [Grigg, 1988; Veron, 1995] and is a strategically important area for the development of a MPA network with long term conservation objectives.

Finally, refugia must be large enough to support high species richness. Bellwood and Hughes [2001] suggest that high species richness in the Indo-Australian archipelago is maintained by large areas of suitable habitat. Large areas are more likely to support high genetic diversity because they may support larger populations which produce more offspring [Palumbi, 1997].

3) Connectivity

Identify patterns of connectivity among source and sink reefs, so that these can be used to inform reef selection in the design of MPA networks and provide rich stepping-stones for reefs, over longer time frames.

'Connectivity' describes the natural linkages among reefs that result from the dispersal and migration of organisms by ocean currents. The strength of connectivity depends on the abundance and fecundity of source populations, the longevity and pre-competency periods of their larvae, and the spawning sites and movement patterns of adults. Connectivity is thus a key driver of the strength and reliability of the replenishment of biodiversity on reefs damaged by natural or human-related agents. Ideally, to maximize a damaged site's chances of recovering from a bleaching event, it should have a bleaching resistant site upstream of it to supply its larvae.

Where protected areas are surrounded by intensively used lands and water, buffer zones are commonly established to provide a transition zone of partial protection. Such buffer zones will become increasingly important for coral reefs as sea level rises, potentially expanding the extent of some shallow water habitats for reefs and mangroves. As warm tropical waters extend more polewards, it may be timely to begin modeling future connectivity patterns. This would help guide planning of MPA configurations in light of possible expansions in latitudinal and longitudinal distributions of coral communities that presently are restricted by existing temperature ranges.

4) Effective Management

Manage reefs for both health and resilience, and monitor multiple indicators of the effectiveness of current actions as the basis for adaptive management.

Expanding the area of tropical seas managed for biodiversity conservation increases the impact on people's activities, access, and resource uses. Effective management must therefore address the socioeconomic impacts of both coral bleaching itself, and of the conservation measures introduced to counteract its ecological effects. Poverty reduction and sustainable development strategies become the cornerstones of effective MPA management. Partnerships are the key to both conservation and sustainable development.

For example, only through partnerships with local communities could managers hope to rehabilitate damaged sites by such actions as removal of crown-of-thorns starfishes or other coral predators, transplanting corals, restriction or reduction of fishing of herbivores, prevention of destructive practices, control of tourism impacts, improvement of water quality, and physical removal of macro-algal mats that are inhibiting coral settlement, survival, or growth. Only through the existence of influential partnerships among government agencies and the private sector could protection of coral reef resources be used as the leverage to bring about control of land-based sources of pollution. To engage communities in such ways, there is a clear need for managers to develop strategies that are attuned to local priorities and needs, with useful productivity and resilience of the reef resource system among those needs.

Socioeconomic Impacts of Bleaching

In many cases, MPA managers can best hope to engage local communities and mitigate any socioeconomic impacts of coral bleaching on them by managing MPAs as part of a sustainable fisheries program. Halpern [2003] reviewed 80 MPAs and discovered that on average reserves doubled abundance, tripled biomass, and increased both size and diversity of fish by a third. Additionally, the same data showed that increases usually became apparent within five years of protection [Halpern and Warner, 2002]. Importantly, fishing communities in some areas have noticed an increase in fish catch outside the protected area [Gell and Roberts, 2003; Russ, 2002]. Because it has yet to be conclusively demonstrated that increasing reef fish biomass will aid in reef resilience, it would be far better to emphasize the benefits that a resilient and productive coral reef system would provide for local communities.

Reef Restoration

Local population support for marine conservation has been gained by grass roots involvement of people in reef restoration projects. In Tanzania, for example, where dynamite fishing, wave action, and coral bleaching had seriously damaged the fringing coral reef around Mbudya Island [Wagner et al., 2001], local fishermen were key players in restoring damaged areas. They helped transplant hundreds of fragments of *Galaxea*, *Acropora*, *Porites*, and *Montipora* in seven dynamited sites, using cement filled, and disposable plastic plates. After three months, *Galaxea* showed 100% survival and *Porites* showed 55.7% complete survival and 13.9% partial survival. Over five months, *Galaxea* and *Porites* increased significantly in height, but not *Acropora*. Through such experiments, managers spread awareness of threats to the marine environment, determine the success of certain restorative options for degraded reefs, and gain an understanding of the ability of key coral species to reestablish on a damaged reef.

Predators, Herbivores and Nutrients

One of the greatest impediments to recovery of damaged coral areas is the pre-emption of the reef surface by carpets of algae: rates of algal production are too high relative to rates of export and consumption [e.g., Hughes, 1987; Littler and Littler, 1997; Williams et al., 2001]. This type of negative effect can be a result of sequential fishing down the fish food web, including herbivorous fish species [Bellwood et al., 2004; Dulvy et al., 2004; Pandolfi et al., 2003; Pauly et al., 1998]. For resilience in coral cover, there needs to be enough grazing by reef organisms to keep algal biomass on damaged reefs sufficiently low that corals can establish and flourish [Hatcher and Larkum, 1983; Sammarco, 1980; Steneck and Dethier, 1994]. In some circumstances, grazing rates can also be too high for corals to reestablish themselves. This can occur when top-level fish predators are fished out, causing populations of lower level grazers – notably sea urchins – to explode, eroding reef surfaces, and in the process, destroying small coral recruits [McClanahan, 1997]. Some intermediate level of grazing is therefore an important operational goal for coral reef management. Of equal importance to grazing, especially when coral reefs occur in enclosed waters, may be the reduction of runoff of nutrients that enhance the growth of seaweeds to the detriment of corals [Smith et al., 1981; McCook, 1999].

Monitoring and Adaptation

Coral reef management needs to be viewed as an adaptive, ‘learning by doing’ exercise; and baseline data and monitoring are essential bases for adaptive decision making. Not only is there a need to monitor the ecological well-being of the reef, but also to define and monitor indicators of the efficacy of reef-related governance measures and of reef-related socioeconomic trends [Pomeroy et al., 2004].

Retrospective surveys and follow-up studies of the spatial patterns of individual coral reef bleaching events in relation to the pattern of heat stress as recorded from satellites are a logical and informative means of assessing the vulnerability of particular reef systems at that time [Arceo et al., 2001; Berkelmans et al., 2004; Wooldridge and Done, 2004]. However, retrospective studies done long after the event are not always easy, as other factors (hurricane damage, disease, crown-of-thorns predation) may obscure the causes of mortality. There is no substitute for real-time tracking of an event with field work. This helps managers understand the vulnerabilities of particular species and communities in different locations and identify those places where corals merely bleach, as opposed to those where the corals die [Marshall and Baird, 2000].

In the long term, there is concern that the efficacy of MPAs and other management measures may also be compromised by several other manifestations of climate change [Pittock, 1999]: changes in ocean chemistry [brought about by increasing atmospheric CO_2 levels – Kleypas et al., 1999]; changes in salinity due to changed rainfall and runoff regimes [Pittock, 1999]; and changes in hydrography (sea level, currents, vertical mixing, storms and waves). Knowledge of their importance is building through both the accumulation of long-term monitoring data-sets of physico-chemical parameters at fixed sites (e.g., Hendee et al., 2001; Lough, 2000] and the understanding of processes based on intensive short term oceanographic studies. These studies may increasingly guide decisions about the configuration and management of MPAs in future, as we learn to anticipate changes better in the environment and reef communities. The results of such research and monitoring programs will provide an improved basis for recognizing truly bleaching-resistant sites for protection and for informing decisions relating to realization of the conservation goal.

Conclusion

The development of MPAs that can mitigate the impacts of global climate change needs a multidisciplinary approach based on the expertise of policy makers in government, MPA managers, a range of scientific disciplines, government agencies, conservation organizations, and local communities. One key message is that, with global changes affecting all countries irrespective of political boundaries, the design and management of MPAs will need to be adaptable, based on both improved scientific knowledge and the socio-political context at coral reef places around the world. The approach to MPAs is evolving away from a focus on individual sites to networks of mutually replenishing MPAs [Soto, 2002]. As iconic ecosystems, the plight of coral reefs should be one catalyst for increased efforts to mitigate the extent and effects of climate change worldwide. The only hope for coral reefs lies in both a slowing of the rate of global climate change, and actions that build survivability into reef systems. Strategically placed and well-managed MPAs seem to offer the most viable means of protecting and conserving key species and habitats in perpetuity.

References

Arceo, H. O., M. C. C. Quibilan, P. M. Aliño, W. Y. Licuanan, and G. Lim, Coral bleaching in the Philippines: Coincident Evidences of Mesoscale Thermal Anomalies. *Bulletin Marine Science,* 69(2): 579-594, 2001.

Baker, A. C., C. J. Starger, T. R. McClanahan, and P. W. Glynn, Corals' adaptive response to climate change. *Nature,* 430: 741, 2004.

Bellwood, D. R., T. P. Hughes, C. Folke, M. Nystrom, Confronting the coral reef crisis. *Nature* (London), 429: 827-833, 2004.

Bellwood, D. R. and T. P. Hughes, Regional-Scale Assembly Rules and Biodiversity of Coral Reefs. *Science,* 292: 1532-1534, 2001.

Bellwood, D. R., T. P. Hughes, S. R. Connolly, and J. Tanner, Environmental and geometric constraints on Indo-Pacific coral reef biodiversity. *Ecology Letters,* 8: 643-651, 2005.

Berkelmans, R., G. De'ath, S. Kininmonth, and W. J. Skirving, A comparison of the 1998 and 2002 bleaching events on the Great Barrier Reef: spatial correlation, patterns and predictions. *Coral Reefs,* 23: 74-83, 2004.

Brown, B. E., R. P. Dunne, M. S. Goodson, and A. E. Douglas, Bleaching patterns in reef corals. *Nature,* 404: 142-143, 2000.

Buddemeier, R. W., J. A. Kleypas, and R. B. Aronson, Coral Reefs and Global Climate Change: Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems. The Pew Center on Global Climate Change, Arlington, VA, USA, 2004.

Catala-Stucki, R, Fluorescence effects from corals irradiated with ultra-violet rays. *Nature,* 183: 949, 1959.

Coles, S. L. and B. E. Brown, Coral bleaching – capacity for acclimatization and adaptation. Advances in Marine Biology, 46: 183-223, 2003.

Craig, P., C. Birkeland, and S. Belliveau, High temperatures tolerated by a diverse assemblage of shallow-water corals in American Samoa. *Coral Reefs,* 20: 185-189, 2001.

Day, J., L. Fernandes, A. Lewis, G. De'ath, S. Slegers, B. Barnett, B. Kerrigan, D. Breen, J. Innes, J. Oliver, T. Ward and D. Lowe. The representative areas program for protecting the biodiversity of the Great Barrier Reef World Heritage Area. pp. 687-696. In M. K. Kasim Moosa, S. Soemodihardjo, A. Nontji, A. Soegiarto, K. Romimohtarto, Sukarno and Suharsono. 2002 (Editors) Proceedings of the Ninth International Coral Reef Symposium, Bali, Indonesia, October 23-27 2000. Published by the Ministry of Environment, the Indonesian Institute of Sciences and the International Society for Reef Studies. 1279 pp. ISBN 979-8105-97-4, 2002.

Done T. J. and R. E. Reichelt, Integrated coastal zone and fisheries ecosystem management: generic goals and performance indices. Ecological Applications 8 (Supplement): S110-118, 1998.

Done, T. J., Coral community adaptability to environmental changes at scales of regions, reefs and reef zones. *American Zoologist.* 39: 66-79, 1999.

Donnelly, R., D. Neville, and P. Mous, Report on the Rapid Ecological Assessment of the Raja Ampat Islands, Papua, Eastern Indonesia. Held on October 30-November 22, 2002. The Nature Conservancy, World Wildlife Fund, and Pemda Kabupaten Raja Ampat. 246 pp, 2003.

Dulvy, N. K., R. P. Freckleton, and N. V. C. Polunin, Coral reef cascades and the indirect effects of predator removal by exploitation. *Ecology Letters,* 7: 5, 410-416, 2004.

Dunne, R. and B. Brown, The influence of solar radiation on bleaching of shallow water reef corals in the Andaman Sea, 1993-1998. *Coral Reefs*, 20: 201-210, 2001.

Fitt, W., B. Brown, M. Warner, and R. Dunne, Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. *Coral Reefs*, 20: 51-65, 2001.

Gates, R. D., and P. J. Edmunds, The physiological mechanisms of acclimatization in tropical reef corals. *American Zoologist*, 39: 30-43, 1999.

Gattuso, J. P., M. Frankignoulle, I. Bourge, S. Romaine, and R. W. Buddemeier, Effect of calcium carbonate saturation of seawater on coral calcification. *Global and Planetary Change,* 18: 37-46, 1998.

Gell, F. R. and C. Roberts, The Fishery Effects of Marine Reserves and Fishery Closures. WWF U.S. and the University of York, Washington D.C. and York, 2003.

Gleason, D. F. and G. M. Wellington. Ultraviolet radiation and coral bleaching. *Nature*, 365: 836-838, 1993.

Gleason, D. F. and G. M. Wellington, Variation in UVB sensitivity of planula larvae of the coral *Agaricia agaricites* along a depth gradient. *Marine Biology* 123: 693-703, 1995.

Glynn, P. W. El Niño-Southern Oscillation mass mortalities of reef corals: a model of high temperature marine extinctions? pp. 117-133 in Insalaco, E., P. W. Skelton, and T. J. Palmer (eds.). Organism-Environment Feedbacks in Carbonate Platforms and Reefs. Geological Society, London, *Special Publications,* 178(151), 2000.

Goreau, T., T. McClanahan, R. Hayes, and A. Strong, Conservation of coral reefs after the 1998 global bleaching event. *Conservation Biology*, 14: 5-15, 2000.

Goreau, T. J., Coral Bleaching in Seychelles: impacts in the South Central Pacific during 1994. Report to the U.S. Department of State, Washington, D.C. Available through Global Coral Reef Alliance web site at http://www.fas.harvard.edu/~goreau, 1998a.

Goreau, T. J., Coral recovery from bleaching in Seychelles, December, 1998. Report to the Seychelles Marine Park Authority. Available through Global Coral Reef Alliance web site at http://www.fas.harvard.edu/~goreau, 1998b.

Goreau, T. J., Coral recovery from bleaching in Alphonse and Bijoutier. Report to the Seychelles Marine Park Authority. Available through Global Coral Reef Alliance web site at http://www.fas.harvard.edu/~goreau, 1998c.

Grigg, R. W., Paleoceanography of coral reefs in the Hawaiian-Emperor Chain. *Science,* 240(4860): 1737-1743, 1988.

Halpern, B. S, The impact of marine reserves: Do reserves work and does reserve size matter? *Ecological Applications*, 13: S117-S137, 2003.

Halpern, B. S. and R. R. Warner, Marine reserves have rapid and lasting effects. *Ecology Letters*, 5: 361-366, 2002.

Hatcher, B. G. and A. W. D. Larkum, An experimental analysis of factors controlling the standing crop of the epilithic algal community on a coral reef. *Journal of Experimental Marine Biology and Ecology*, 69: 61-84, 1983.

Hendee, J. C., E. Mueller, C. Humphrey, and T. Moore, A data-driven expert system for producing coral bleaching alerts at Sombrero Reef in the Florida Keys. *Bulletin of Marine Science,* 69(2): 673-684, 2001.

Hoegh-Guldberg, H. and O. Hoegh-Guldberg, The Implications of Climate Change for Australia's Great Barrier Reef: People and Industries at Risk. A joint report between WWF Australia and the Queensland Tourism Industry Association: 356 pp, 2004.

Hoegh-Guldberg, O., Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, 50: 839-866, 1999.

Hoegh-Guldberg, O. and B. Salvat, Periodic mass-bleaching and elevated sea temperatures: bleaching of outer reef slope communities in Moorea, French Polynesia. *Marine Ecology Progress Series*, 121: 181-190, 1995.

Hoeksema, B. W., Control of bleaching in mushroom coral populations (Scleractinia: Fungiidae) in the Java Sea: stress tolerance and interference by life history strategy. *Marine Ecology Progress Series*, 74: 225-37, 1991.

Hughes, T., A. H. Baird, D. R. Bellwood, M. Card, S. R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J. B. C. Jackson, J. Kleypas, J. M. Lough, P. Marshall, M. Nystrom, S. R. Palumbi, J. M. Pandolfi, B. Rosen, and J. Roughgarden, Climate Change, Human Impacts, and the Resilience of Coral Reefs. *Science*, 301: 929-933, 2003.

Hughes, T. P, Herbivory on coral reefs: community structure following mass mortalities of sea urchins. *Journal of Expt. Mar. Biol. Ecol.* 113: 39-59, 1987.

IPCC, Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change Houghton, J. T.,Y. Ding, D. J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: 881 pp., 2001.

Jokiel, P. L. and S. L Coles, Response of Hawaiian and other Indo-Pacific reef corals to elevated temperatures associated with global warming. *Coral Reefs*, 9: 155-162, 1990.

Jones, G. P, M. I. McCormick, M. Srinivasan, and J. V. Eagle, Coral decline threatens fish biodiversity in marine reserves. *PNAS*, 101(21): 8251-8253, 2004.

Kassem, K., M. Toscano, G. Llewellyn, and K. Casey. Where Do Coral Reefs Feel the Heat? A Global Analysis of HotSpot Frequencies and the Consequences for Tropical Marine Biodiversity Conservation Planning. American Geophysical Union/American Society of Limnology and Oceanography Ocean Sciences Meeting. Honolulu, Hawaii, 2002.

Kelleher, G., Guidelines for Marine Protected Areas. IUCN, Gland, Switzerland and Cambridge, UK: xxiv +107 pp, 1999.

Kleypas, J., R. Buddemeier, and J. Gattuso, The future of coral reefs in an age of global change. *Int. J. Earth Sci*., 90: 426-437, 2001.

Kleypas, J. A., R. Buddemeier, D. Archer, J. P. Gattuso, C. Langdon, and B. N. Opdyke, Geochemical consequences of increased atmospheric CO_2 on corals and coral reefs. *Science*, 284: 118-120, 1999.

Langdon, C., T. Takahashi, F. Marubini, M. Atkinson, C. Sweeney, H. Aceves, H. Barnett, D. Chipman, and J. Goddard, Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles*, 14: 639-654, 2000.

Langdon, C., W. S. Broecker, D. E. Hammond, E. Glenn, K. Fitzsimmons, S. G. Nelson, T. S. Peng, I. Hajdas, and G. Bonani, Effect of elevated CO_2 on the community metabolism of an experimental coral reef. *Global Biogeochemical Cycles,* 17: 10, 2003.

Leclercq, N., J. P. Gattuso, and J. Jaubert, CO_2 partial pressure controls the calcification rate of a coral community. *Global Change Biology*, 6: 329-334, 2000.

Little A. F., M. J. H. Van Oppen, and B. L. Willis, Flexibility in algal endosymbioses shapes growth in reef corals. *Science*, 304: 1492-1494 2004.

Littler, M. M. and D. S. Littler, Epizoic red alga allelopathic to a Caribbean coral. *Coral Reefs*, 16: 168, 1997.

Lough, J. M., Sea surface temperature variations on coral reefs: 1903-1998. AIMS Report No. 31. Australian Institute of Marine Science, Townsville, 109 pp, 2000.

Loya, Y., K. Sakai, K. Yamazoto, Y. Nakano, H. Sembali, and R. van Woesik., Coral bleaching: the winners and losers. *Ecology Letters*, 4: 122-131.2001.

Lubchenco, J., S. R. Palumbi, S. D. Gaines, and S. Andelman, Plugging a Hole in the Ocean: The Emerging Science of Marine Reserves. *Ecological Applications*, 13: S3-S7, 2003.

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

Marubini, F., H. Barnett, C. Langdon, and M. J. Atkinson, Dependence of calcification on light and carbonate ion concentration for the hermatypic coral *Porites compressa*. *Marine Ecology Progress Series*, 220: 153-162, 2001.

McClanahan, T., N. Polunin, and T. Done, Ecological states and the resilience of coral reefs. Conservation Ecology 6(2): 18. [online] URL: http://www.consecol.org/vol6/iss2/art18, 2002.

McClanahan, T. R., Primary succession of coral-reef algae: Differing patterns on fished versus unfished reefs. *Journal of Experimental Marine Biology and Ecology*, 218: 77-102, 1997.

McCook, L. J., Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. *Coral Reefs*, 18: 357-367, 1999.

Nakamura, T. and R. Van Woesik, Differential survival of corals during the 1998-bleaching event is partially explained by water-flow rates and passive diffusion. *Marine Ecology Progress Series*, 212: 301-304, 2001.

Palumbi, S. R., Molecular biogeography of the Pacific. *Coral Reefs*, 16: S47-S52, 1997.

Palumbi, S. R. Population Genetics, Demographic Connectivity, and the Design of Marine Reserves. *Ecological Applications.* 13: S146-S158, 2003.

Pandolfi, J. M., R. H. Bradbury, E. Sala, T. P. Hughes, K. A. Bjorndal, R. G. Cooke, D. McArdle, L. McClenachan, M. J. Newman, G. Paredes, R. R. Warner, and J. B. Jackson, Global trajectories of the long-term decline of coral reef ecosystems. *Science*, 301: 955-958, 2003.

Pauly D., V. Christensen, J. Dalsgaard, R. Froese and F. Torres, Fishing down marine food webs. *Science*, 279: 860-863, 1998.

Pittock, A. B., Coral reefs and environmental change: Adaptation to what? *Am. Zool*, 39(1): 10-29, 1999.

Pomeroy, R. S., J. E. Parks, and L. M. Watson, How is your MPA doing? A guidebook of natural ands social indicators for evaluating marine protected area management effectiveness. IUCN Gland. Switzerland and Cambridge, UK. xvi +216 pp, 2004.

Rowan, R., Thermal adaptation in reef coral symbionts. *Nature*, 430:742, 2004.

Rowan, R. and D. A. Powers, Molecular genetic identification of symbiotic dinoflagellates (zooxanthellae). *Marine Ecology Progress Series*, 71: 65-73 1991.

Rowan, R., N. Knowlton, A. C. Baker and J. Jara, Landscape ecology of algal symbiont communities explains variation in episodes of coral bleaching. *Nature,* 388: 265-269, 1997.

Russ, G., Yet another review of marine reserves as reef fishery management tools. pp. 421-443 in Sale, P. F. (ed.). Coral Reef Fishes. Dynamics and diversity in a complex ecosystem. *Academic Press*, *San Diego*, *20*02.

Salm, R.V., S. E. Smith and G. Llewellyn, Mitigating the impact of coral bleaching through marine protected area design. pp. 81-88 in Schuttenberg, H.Z. (ed.). Coral Bleaching: Causes, Consequences and Response. Selected papers presented at the 9th International Coral Reef Symposium on "Coral Bleaching: Assessing and Linking Ecological and Socioeconomic Impacts, Future Trends and Mitigation Planning." Coastal Management Report #2230, Coastal Resources Center, University of Rhode Island: 102 pp, 2001.

Sammarco, P. W., *Diadema* and its relationship to coral spat mortality: grazing, competition, and biological disturbance. *Journal of Experimental Marine Biology and Ecology*, 45: 245-272, 1980.

Siebek, O., Experimental investigation of UV tolerance in hermatypic corals (Scleractinia). *Marine Ecology Progress Series*, 43: 95-103, 1988.

Smith, S. V. and R. W. Buddemeier, Global change and coral reef ecosystems. *Annual Review of Ecological Systems*, 23: 89-118, 1992.

Smith, S. V., W. J. Kimmerer, E. A. Laws, R. E. Brock, and T. W. Walsh, Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. *Pacific Science*, 35: 279-402, 1981.

Soto, C., The potential impacts of global climate change on marine protected areas. *Reviews in Fish Biology and Fisheries*, 11: 181-195, 2002.

Spalding, M., K. Teleki, and T. Spencer. Biodiversity and Climate Change: Climate Change and Coral Bleaching Report. UNEP-World Conservation Monitoring Centre, 2000.

Stafford-Smith, M. G. and R. F. G. Ormond, Sediment rejection mechanisms of 42 species of Australian scleractinian corals. *Australian Journal of Marine and Freshwater Research*, 43: 683-705, 1992.

Steneck, R. S. and M. N. Dethier, A functional group approach to the structure of algal-dominated communities. *Oikos*, 69: 476-498, 1994.

Van Oppen, M. J. H., A. J. Mahiny and T.J. Done, Geographic distribution of zooxanthellae types in three coral species on the Great Barrier Reef sampled after the 2002 bleaching event. *Coral Reefs*, 24: 482.2005.

Veron, J. E. N., Corals in space and time: biogeography and evolution of the Scleractinia. Ithica, Comstock, *Cornell*, 321 pp, 1995.

Wagner, G. M., Y. D. Mgaya, F. D. Akwilapo, R. G. Ngowo, B. D. Sekadende, A. Allen, N. Price, E. A. Zollet, N. Mackentley, Restoration of coral reef and mangrove ecosystems at Kunduchi and Mbweni, Dar es Salaam, with community participation. Western Indian Ocean Marine Science Association, Zanzibar (Tanzania); Institute of Marine Sciences, Zanzibar (Tanzania) University of Dar es Salaam. Marine Science Development in Tanzania and Eastern Africa. 467-488, 2001.

Wellington, G. M., P. W. Glynn, A. E. Strong, S. A. Navarrete, E. Wieters, and D. Hubbard, Crisis on Coral Reefs Linked to Climate Change. EOS, Transactions, American Geophysical Union 82(1): 1-7, 2001.

West, J. M. and R. V. Salm, Resistance and resilience to coral bleaching: Implications for coral reef conservation and management. *Conservation Biology*, 17(4): 956-967, 2003.
Williams, I. D., N. V. C. Polunin, and V. J. Hendrick, Limits to grazing by herbivorous fishes and the impact of low coral cover on macroalgal abundance on a coral reef in Belize. *Marine Ecology Progress Series*, 222: 187-296, 2001.
Wooldridge, S. and T. J. Done, Learning to predict large-scale coral bleaching from past events: A Bayesian approach using remotely sensed data, in-situ data, and environmental proxies. *Coral Reefs*, 23: 96-108, 2004.
World Wide Fund for Nature (WWF). Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems. Hansen, L. J., J. L. Biringer, and J. R. Hoffmann (eds.). Published by Martin Hiller, 2003.