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New Stresses, New Strategies: Managing Marine Protected Areas in an Age of Global Environmental Change

By Daniel Gleason

With the increasing threat and ongoing impacts of global change, *the concepts behind design and management of MPAs continue to evolve. No longer can MPAs be viewed and managed solely within the framework of local stressors. Rather, MPA managers must consider how global change phenomena may alter the ability of organisms to respond to local stressors and whether new management actions should be attempted.*

Federal marine protected areas (MPAs) in the United States are under the jurisdiction of several government agencies and are governed by no less than eight separate acts (Table 1). These MPAs are the best-known form of site-based management for conserving marine life and critical habitats. While used in the past primarily to safeguard marine biodiversity, the goals and expectations of MPA implementation have seen steady expansion. Depending on the MPA, these goals may include not only conservation of biodiversity and preservation of habitat, but fisheries management to improve or restore local fisheries stocks, and societal benefits such as economic vitality, environmental stewardship, and education (Hatziolos et al. 2006).

IMPACTS OF GLOBAL CHANGE ON MARINE ORGANISMS

While numerous stressors can affect marine ecosystems (e.g., Keller et al. 2009; McLeod et al. 2009), these generally fall into four broad groups: overfishing, land-based pollution, habitat destruction and degradation, and global change (Knowlton and Jackson 2008). The first three categories of stressors represent more traditional motives for implementing MPAs. These stressors often can be managed effectively on a local scale, even though their scope of impact may range well beyond MPA boundaries. The addition of global change stressors has complicated MPA management because of their widespread impact and the fact that the response of organisms to global change may affect their ability to respond to stressors that act on more local scales (Knowlton and Jackson 2008). This article uses the more general term, "global change," rather than "global climate change" or "climate change," because anthropogenic impacts from increased levels of carbon dioxide (CO_2) emissions in the atmosphere have far greater effects than solely increasing temperatures.

Two consequences of increased CO_2 emissions that are of immediate relevance to marine ecosystems worldwide are temperature increases and ocean acidification. Atmospheric temperatures have risen significantly over the last 50 years, with the oceans absorbing more than 80% of the excess heat added to the climate system. As a result, studies show that the 0 to 700 m depth layer of the ocean warmed by an average

Type of MPA/MMA	Number of Sites	Administration	Mandate
National Marine Sanctuary	13	NOAA/National Marine Sanctuary Program	National Marine Sanctuaries Act
Fishery Management Area	216	NOAA/National Marine Fisheries Service	Magnuson-Stevens Act, Endangered Species Act, Marine Mammal Protection Act
National Estuarine Research Reserve	27	NOAA/Office of Coastal and Resource Management	Coastal Zone Management Act
National Park	42	National Park Service	NPS Organic Act
National Monument	7	National Park Fish Wildlife Service	NPS Organic Act, Antiquities Act
National Wildlife Refuge	109	U.S. Fish and Wildlife Service	National Wildlife Refuge System Administration Act

Table 1. Types of marine protected areas, administration, and legislative mandates.

of 0.1°C worldwide between 1961 and 2003 (Bindoff et al. 2007). These increasing sea temperatures influence organismal processes such as foraging for food, growth, reproductive timing, and larval duration and dispersal, with ultimate impacts on the geographic ranges of species.

While a 0.1°C increase in ocean temperatures may not seem like much, shifts pole-ward in some zooplankton, intertidal invertebrate, and fish communities have already been observed (reviewed in Walther et al. 2002). For example, an analysis of the distributions of North Sea fish species between 1977 and 2001 found northward shifts of 48 to 403 km in 15 of 36 species (Perry et al. 2005). Shifts in distributions of this magnitude complicate efforts to manage commercially exploited fish stocks because species-specific differences in abilities to adjust ranges may alter historical overlaps between competing species, as well as between predators and prey. At the other end of the spectrum, species unable to expand their geographic ranges may be required to adapt to new temperature regimes, or compete with influxes of new residents that may be driven to extinction. As an example, many species of reef-building corals are living near the upper limit of their thermal tolerance (see discussion under "Ecosystem Resilience") and may possess no or limited ability to tolerate higher temperatures. A whole host of other environmental challenges are associated with temperature increases and may impact marine organisms. These include: melting polar ice, rising sea levels, increasing storm frequencies and intensities, unknown effects on surface currents, alterations in ocean circulation and stratification patterns, the spread and emergence of diseases, and increasing or decreasing freshwater input at the local scale.

Elevated CO_2 concentrations in the atmosphere also lower oceanic pH, making waters more acidic. This process occurs as CO_2 is absorbed by surface waters of the oceans and reacts with seawater to form carbonic acid (H_2CO_3). The acid then releases hydrogen ions that reduce the water's pH. The pH scale ranges from 0 (acidic) to 14 (basic) and is logarithmic, so a change of one pH unit is equal to a ten-fold difference in hydrogen ion concentration. The total inorganic carbon content of the world's oceans increased by 1.2×10^{11} tons from 1750 to 1994; and continues to rise because oceanic waters absorb about one-third of the excess CO_2 released into the atmosphere each year (Bindoff et al. 2007). Current estimates are that the pH of ocean surface waters has decreased by about 0.1 units (from 8.2 to 8.1 pH units) since the beginning of the industrial revolution (Feely et al. 2004). Furthermore, time series data for the last 20 years show a trend for decreasing pH of 0.02 pH units per decade (Bindoff et al. 2007).

By far the greatest threat of reducing pH is to organisms, including reef-building corals that build skeletal material from calcium carbonate ($CaCO_3$). Hydrogen ions (H^+) that are released from carbonic acid (H_2CO_3) combine with carbonate (CO_3^{2-}) to produce bicarbonate (HCO_3^-). The sum of these reactions is reduced availability of the carbonate needed for producing skeletal material and shells. Interestingly, because CO_2 has greater solubility in cooler waters, calcifying organisms (such as sea urchins, cold-water corals, coralline algae, and phyto-, zoo- and ichthyo-plankton) residing in temperate and Polar Regions appear to be the most threatened by ocean acidification (Feely et al. 2004). Appropriately, ocean acidification is a rapidly expanding area of study as scientists strive to identify the exact reductions in pH levels that will impact the broad array of organisms that can potentially be affected.

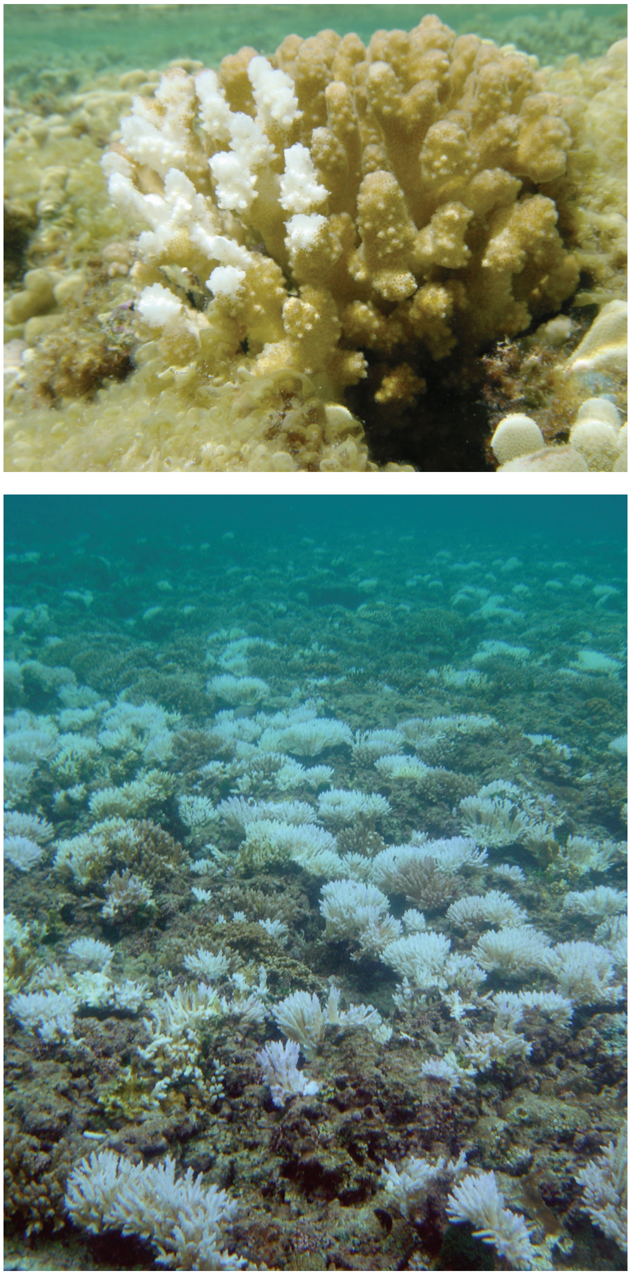

Figure 1. The white branches in the top photograph represent regions of the coral colony where symbiotic algae (known as zooxanthellae) have been lost. The bottom photograph shows a coral reef in Guam with fairly extensive coral bleaching.

ECOSYSTEM RESILIENCE

One of the key goals of MPAs is to maintain the integrity of ecosystems by fostering ecosystem resilience. According to McLeod et al. (2009), resilience refers to the ability of an ecosystem to maintain key functions and processes in the face of stresses or pressures, either by resisting or adapting to environmental change. Thus, resilience refers to the ability of an ecosystem to maintain a steady state in the face of a disturbance, or return to that same state after a disturbance. For example, in recent years there has been an upsurge in the severity and frequency of coral bleaching events worldwide (Donner et al. 2005). These episodes are most often caused by periods of abnormally high ocean temperatures (≥30 °C). During bleaching events, corals become ghostly white because the single-celled alga that normally resides in their tissues is lost (Figure 1). A reef where the majority of corals show little or no bleaching, or where the corals recover fully and quickly after a bleaching event, would be considered "resilient." Given the goal of maintaining resilient ecosystems, the pressing question for marine managers is: "In the face of local stressors and global change, how can MPAs be managed to maintain ecosystem resilience?" The short answer is to select new areas for protection that are predicted to have high resilience and to manage existing areas to maximize resilience.

Figure 2. Two coral reef sites at Turneffe Atoll, Belize in 2006. If scientific monitoring were initiated today, these two sites would start from radically different baselines. The reef in the top image looks "pristine," but is subject to human impacts such as overfishing and reduced water quality.

Identifying and maintaining ecosystem resilience is challenging. Among other necessary steps, identifying resilient sites for protection requires that ecosystem characteristics indicating resilience are well-defined, identified, and documented. The already onerous task of identifying resilient sites is made even more difficult by the shortage of pristine marine ecosystems to use as a baseline for determining which characteristics should be present (Knowlton and Jackson 2008). Relative to terrestrial systems, extensive exploration of most marine ecosystems began fairly recently and was initiated long after human impacts were already evident. Indeed, recent analyses indicate there is no marine ecosystem in the world that is free of human impacts (Halpern et al. 2008), bringing into question what constitutes a healthy and resilient ecosystem (Figure 2).

Efforts to identify indicators of resilience are not futile, however, and are needed for effective management of marine ecosystems. Traditionally, methods of quantifying ecosystem health involve tracking the abundance of the most conspicuous species over time (Hughes et al. 2005). For example, in coral reef systems the abundance of the major reef-building coral species is often monitored. An ecosystem showing a decline in the diversity and abundance of these corals would be considered to have reduced health and lower resilience. The problem with this approach is that the causes and consequences of changes in abundance of the species being monitored are usually not investigated.

A more recent approach to viewing ecosystem resilience is to focus on suites of species that carry out critical functions within the ecosystem, rather than concentrating on the most conspicuous species. Species groups with equivalent roles in terms of ecosystem function have been dubbed "functional groups" (Steneck 2001). For example, on tropical coral reefs herbivores are vital for allowing more slowly growing, reef-building corals to persist because they graze down rapidly growing algae. Herbivores on reefs are not created equal, however, and can be categorized into three functional groups as follows (Steneck 2001): deep grazing herbivores that remove all algae as well as pieces of the carbonate substrata (e.g., parrotfish, some urchins, Figure 3); denuding herbivores that remove most algae (e.g., surgeonfish, some snails); and non-denuding herbivores that have no or little ability to graze down algae (e.g., damselfish, amphipods). In this system, ecosystem function can be maintained if: 1) high-species diversity and high abundances are maintained for species in all three functional groups; or 2) low-species diversity occurs in one or more functional groups, but abundances for those species that persist are high. Both ecosystem function and resilience are possible in the second scenario because all three herbivore functional groups are present and the high abundance of individuals compensates for the low-species diversity that exists in one or more of the groups.

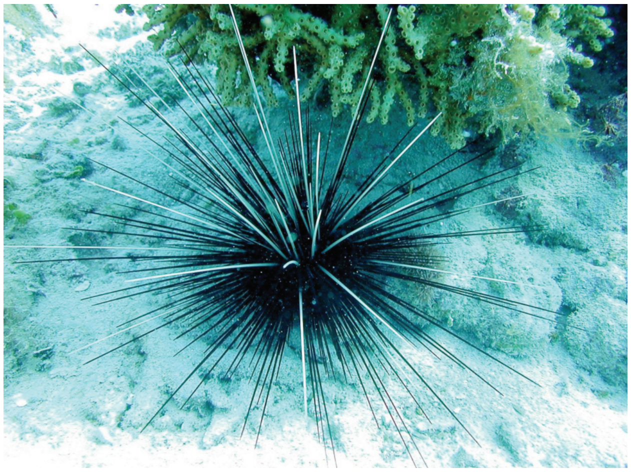

Figure 3. While princess parrotfish (*Scarus taeniopterus*) and long-spined urchins (*Diadema antillarum*) are clearly very different organisms, on coral reefs they belong to the same functional group—deep grazing herbivores that remove all algae as well as pieces of the carbonate substrata.

MANAGING FOR ECOSYSTEM RESILIENCE

The preceding discussion highlights how maintaining species diversity within functional groups incorporates redundancy within ecosystems and safeguards ecosystem function. Thus, managing for diversity is a vital component of sustaining ecosystem resilience, especially in light of the additional stresses imposed by global change. Ultimately, MPA managers can respond to global change challenges that threaten ecosystem resilience by taking actions at individual sites and regionally to ameliorate stressors such as overfishing and excessive input of nutrients; implementing MPA networks that preserve linkages and connectivity among sites; and integrating global change in MPA planning. Incorporating MPA networks and integrating global change in planning represent more recent concepts of management and merit further clarification.

MPA networks maintain ecosystem integrity by preserving the connections that occur naturally among habitat types. These linkages are usually viewed in terms of larval dispersal and movement of adults among habitats. Many marine organisms produce larvae that are carried by ocean currents, so maintenance of existing systems and reestablishment of those that have been damaged is often reliant on larval dispersal that originates from distant locations. The length of time spent dispersing on ocean currents differs from species to species, but can be anywhere from minutes to months. Thus, larval dispersal time must be taken into consideration when setting MPA size and constructing MPA networks. Current guidelines suggest that MPAs approximately 20 km in diameter and spaced 20-100 km apart will accommodate both short- and long-distance dispersers of a wide range of target species (reviewed by Keller et al. 2008). Further research is needed, however, to better define dispersal direction and distance for marine organisms. Doing so will allow refinement of these general MPA size guidelines.

In addition to the movement of larval and adult fishes and invertebrates, linkages among habitats often include functional connections that are vital for maintaining ecosystem integrity. For example, salt marshes export nutrients and biomass that are used by organisms occurring offshore; coral reefs provide mangroves and seagrasses with protection from wave erosion; and mangroves buffer coral reefs and seagrasses from siltation. Functional dependencies highlight the necessity of protecting entire ecological units (e.g., mangroves to seagrasses to coral reefs). Unfortunately, setting aside entire ecological units is often not possible due to competing priorities for ocean uses.

Recognition of the need to address global temperature increases in marine resource protection has been spurred by the observation that rising ocean temperatures are resulting, as noted earlier, in an uptick in the frequency and severity of coral bleaching events. In places such as the Maldives and Palau, bleaching has essentially destroyed 50% or more of the reefs. The Australian government has taken the lead in managing for climate change in reef systems by developing the Great Barrier Reef Climate Action Plan 2007-2012 (http://www.gbrmpa.gov.au/). This five-year plan is built around four objectives that will make the Great Barrier Reef (GBR) more resilient to climate change. First, targeted science will furnish knowledge for improving reef resilience and for helping reef-based industries and regional communities adapt to changes. Second, reef resilience will be maximized by managing locally to reduce the impact of regional-scale stressors (e.g., modifying water quality targets and fishing practices) on the ecosystem. Third, social and economic resilience will be enhanced by guiding local governments and other organizations dependent on the resources of the GBR through the process of adapting to global change. Finally, efforts will be implemented to enhance awareness of the effects of global change on the GBR and to encourage individuals, communities, organizations, and industries to reduce greenhouse emissions. This plan has been lauded as a model for managing MPAs in an era of global change (Keller et al. 2008).

With the more recent recognition of the harmful effects of ocean acidification on marine organisms, efforts to develop MPA management strategies around this issue are in their infancy. Within the past year the Sanctuary Advisory Councils of the Gulf of the Farallones, Monterey Bay, Olympic Coast, and Cordell Bank National Marine Sanctuaries passed resolutions recognizing ocean acidification as a significant threat to the long-term health of sanctuary resources. These Advisory Councils recommended that NOAA institute new research, monitoring, education, and outreach activities to mitigate the effects of ocean acidification within all west coast sanctuaries. The actions taken by these Sanctuary Advisory Councils have stimulated similar discussions and calls for action in other U.S. marine sanctuaries, most recently in the Florida Keys and Gray's Reef. In some instances, through collaborations with scientists from universities as well as other organizations, data gathering has already begun. For example, efforts to monitor CO_2 and pH have been initiated in the Olympic Coast, Gray's Reef, and Gulf of the Farallones, and tests of coral growth rates in relation to carbonate chemistry are being carried out in the Florida Keys National Marine Sanctuary. These recent actions and activities suggest that MPAs will play a prominent role in uncovering the impact of ocean acidification on marine ecosystems.

While the exact environmental conditions that will result from global change are uncertain, it is clear that MPAs make, and will continue to make, an important contribution to understanding the impacts of global change on marine ecosystems. One of the major advantages of MPAs is that they are at least partially buffered from the detrimental effects of local stressors. This feature makes them ideal for deciphering the effects of global change on ecosystems. In some instances the possibilities for detecting global change effects have yet to be fully realized (Figure 4). Furthermore, the infrastructure for monitoring physical factors—such as temperature and dissolved oxygen—that have been in place for many years in some MPAs elevates the role of MPAs to that of "sentinel" sites, where early changes in environmental conditions might be detected. In sum, MPAs are not only areas set aside to preserve biodiversity, but also dynamic sites where research and management are combining and adapting to inform future policy with regard to management of oceanic resources under the influence of environmental change, which is unprecedented in modern times.

Figure 4. Sponge landscape at Grays Reef National Marine Sanctuary off the Georgia coast. The two species on the left, *Ptilocaulis walpersi* (red) and *Smenospongia cerebriformis* (purple/black) are considered temperate and the one on the right, *Axinella waltonsmithi* (yellow) tropical. Grays Reef sits at the convergence of tropical and temperate water masses and may be a sentinel site for detecting northward progression of species under global climate change.

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