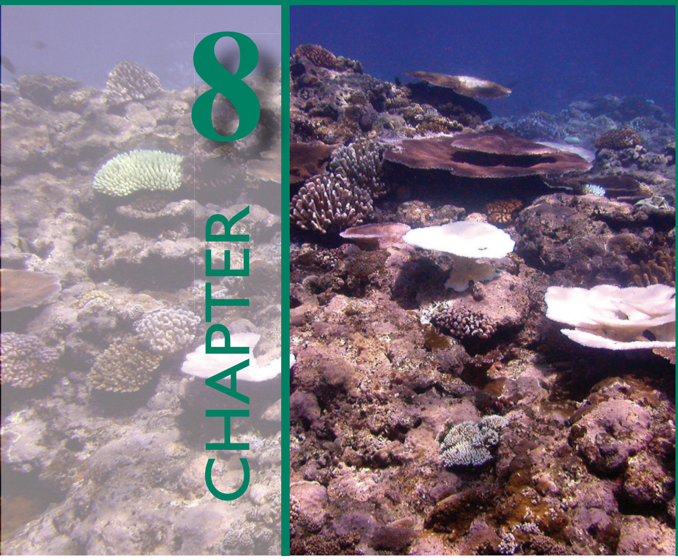


Marine Protected Areas

Lead Author: Brian D. Keller, National Oceanic and Atmospheric Administration

Contributing Authors: Satie Airamé, University of California, Santa Barbara; Billy Causey, National Oceanic and Atmospheric Administration; Alan Friedlander, National Oceanic and Atmospheric Administration; Daniel F. Gleason, Georgia Southern University; Rikki Grober-Dunsmore, National Oceanic and Atmospheric Administration; Johanna Johnson, Great Barrier Reef Marine Park Authority; Elizabeth McLeod, The Nature Conservancy; Steven L. Miller, University of North Carolina at Wilmington; Robert S. Steneck, University of Maine; Christa Woodley, University of California at Davis

8.1 SUMMARY

Marine protected areas (MPAs) such as national marine sanctuaries provide place-based management of marine ecosystems through various degrees and types of protective actions. A goal of national marine sanctuaries is to maintain natural biological communities by protecting habitats, populations, and ecological processes using community-based approaches. Biodiversity and habitat complexity are key ecosystem characteristics that must be protected to achieve sanctuary goals, and biologically structured habitats (such as coral reefs and kelp forests) are especially susceptible to degradation resulting from climate change. Marine ecosystems are susceptible to the effects of ocean acidification on carbonate chemistry, as well as to direct and indirect effects of increasing temperatures, changing circulation patterns, increasing severity of storms, and other factors.

KEY FINDINGS

Implementing networks of MPAs may help spread the risks posed by climate change by protecting multiple replicates of the full range of habitats and communities within an ecosystem. Recognizing that the science underlying our understanding of resilience is developing and that climate change will not affect marine habitats and species equally everywhere, an element of risk spreading is needed in MPA design. To help avoid the loss of a particular habitat type, managers can protect multiple examples of all habitats. In designing networks, managers can consider information on areas that may represent potential refugia from climate change impacts as well as information on connectivity (current patterns that support larval replenishment and recovery) among sites that vary in sensitivity to climate change. Larger MPAs may be necessary for networking to achieve goals such as protecting multiple refugia and addressing variability in connectivity.

Managers can increase resilience to climate change by managing other anthropogenic stressors that also degrade ecosystems and by protecting key functional groups. Examples of anthropogenic stressors that can be managed at the site level include overfishing and over-exploitation; excessive inputs of nutrients, sediments, and pollutants; and habitat damage and destruction. Reduction of these stressors may boost the ability of species, communities, and ecosystems to tolerate climate-related stresses or recover after impacts have occurred. Resilience is also affected by trophic linkages, which are key characteristics maintaining ecosystem integrity. Thus, a mechanism that has been identified to maintain resilience is the management of functional groups, specifically herbivores. In an experimental manipulation on the Great Barrier Reef, recovery from an algae-dominated to a coral-dominated state was driven by a single batfish species, not grazing by dominant parrotfishes or surgeonfishes that normally keep algae in check on Indo-Pacific reefs. This finding highlights the need to protect a diversity of species within functional groups, and the need for further research on key species and ecological processes that maintain resilience.

Overcoming the challenges of climate change will require creative collaboration among a variety of stakeholders. MPAs that reinforce social resilience can provide communities with opportunities to strengthen social relations and political stability, and diversify economic options. A variety of management actions that have been identified to reinforce social resilience include: (1) providing opportunities for shared leadership roles within government and management systems; (2) integrating MPAs and networks into broader coastal management initiatives to increase public awareness and support of management goals; (3) encouraging local economic diversification so communities are better able to deal with environmental, economic, and social changes; (4) encouraging stakeholder participation and incorporating stakeholders' ecological knowledge in a multi-governance system; and (5) making culturally appropriate conflict resolution mechanisms accessible to local communities.

A range of case studies highlight various ecological issues and management challenges found across MPAs. Three case studies are based on coral reef ecosystems, which have experienced coral bleaching events over the past two decades (see Case Study Summaries 8.1, 8.2, and 8.3). They span a range of levels of protection, from relatively low (Florida Keys) to moderate (Great Barrier Reef) to complete (Northwestern Hawaiian Islands). The Great Barrier Reef Marine Park is an example of an MPA with a relatively highly developed climate change program in place that can serve as an example to other MPAs. A Coral Bleaching Response Plan is part of its Climate Change Response Program, which is linked to a Representative Areas Program and a Water Quality Protection Plan in a comprehensive approach to enhance resilience of the coral reef ecosystem. In contrast, the Florida Keys National Marine Sanctuary is developing a bleaching response plan but does not have a climate change response program. The Florida Reef Resilience Program, led by The Nature Conservancy, is implementing a quantitative assessment of coral reefs before and after bleaching events. Finally, the recently established Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument is one of the largest MPAs in the world and provides a unique opportunity to examine the effects of climate change on a nearly intact large-scale marine ecosystem that will soon be a highly protected marine reserve.

A fourth case study (see Case Study Summary 8.4) examines the Channel Islands National Marine Sanctuary, located off the coast of southern California. The Sanctuary Management Plan for the Channel Islands National Marine Sanctuary mentions, but does not fully address, the issue of climate change. The plan describes a strategy to identify, assess, and respond to emerging issues through consultation with a stakeholder advisory committee and local, state, or federal agencies. Emerging issues that are not yet addressed by the management plan include ocean warming, sea level rise, shifts in ocean circulation, ocean acidification, spread of disease, and shifts in species ranges.

A number of opportunities exist for addressing barriers to implementation of adaptation options in MPAs. Barriers to implementation of adaptation options include lack of resources, varying degrees of interest in and concern about climate change impacts, and gaps in basic research on marine ecosystems and climate change effects. Opportunities include a growing public concern about the marine environment, recommendations of two ocean commissions, and an increasing dedication of marine scientists to conduct research that is relevant to MPA management. References to climate change as well as MPAs permeate both the Pew Oceans

Commission and U.S. Commission on Ocean Policy reports on the state of the oceans. Both commissions held extensive public meetings, and their findings reflect changing public attitudes about protecting marine resources and threats of climate change. The National Marine Sanctuary Program recently formed a Climate Change Working Group that is developing recommendations about adaptations to climate change to incorporate in site management plans. Concurrent with public and policy interests and needs, interests and involvement of the marine science community have evolved, with diminishing distinction between basic and applied research over recent decades. Although there is considerable research on physical impacts of climate change in marine systems, there are major opportunities for research on biological effects and ecological consequences of climate change. Attitudes of MPA managers have changed as well, with a growing recognition of the need to better understand ecological processes in order to implement science-based adaptive management in the ocean. Managers also perceive the increasing need to consider regional- and global-scale issues in addition to traditional local-scale approaches.

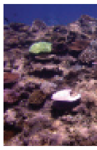
The most effective configuration of MPAs may be a network of highly protected areas nested within a broader management framework. As part of this configuration, areas that are ecologically and physically significant and connected by currents, larval dispersal, and adult movements could be identified and included as a way of enhancing resilience to climate change. Connectivity is fundamental to ensuring larval exchange and the replenishment of populations in areas damaged by natural or human-related agents, and thus can enhance recovery following disturbance events. Critical areas to consider include nursery grounds, spawning grounds, areas of high species diversity, areas that contain a variety of habitat types in close proximity, and potential climate refugia. A high level of protection for these types of areas should help protect key ecological processes that enhance resilience such as larval production and recruitment, ecological interactions among full complements of species, and ontogenetic changes in habitat utilization. Management of the areas surrounding MPAs helps increase the likelihood of success of MPAs by creating a buffer zone between areas with high levels of protective actions and those with none.

8.2 BACKGROUND AND HISTORY

8.2.1 Introduction

Coastal oceans and marine ecosystems are central to the lives and livelihoods of a large and growing proportion of the U.S. population. They provide extensive areas for recreation and tourism, and support productive fisheries. Some areas produce significant quantities of oil and gas, and commercial shipping crosses coastal waters. In addition, coral reefs and barrier islands provide coastal communities with some protection from storm-generated waves. In their global analysis of the value of ecosystem services, Costanza *et al.* (1997) estimated that coastal marine ecosystem services were worth more than one-third the value of all terrestrial and marine ecosystem services combined ($12.5 of $33 trillion). Despite their value, coastal ecosystems and the services they provide are becoming increasingly vulnerable to human pressures, and management of coastal resources and human impacts generally is insufficient or ineffective (Millennium Ecosystem Assessment, 2005).

As a result of human activities, marine ecosystems are exposed to a long list of threats and stressors, including overexploitation of living marine resources, pollution, redistribution of sediments, and habitat damage and destruction. There is an equally long list of regulatory responses, including managing fisheries for sustainability, restricting ocean dumping, reducing loads of nutrients and contaminants, controlling dredge-and-fill operations, managing vessel traffic to reduce large-vessel groundings, and so on. These regulations are managed by coastal states and the federal government, with state jurisdiction extending three nautical miles (nm) offshore (9 nm in the Gulf of Mexico) and federal jurisdiction on out to 200 nm or the edge of the continental shelf (the U.S. Exclusive Economic



Zone, or U.S. EEZ). The total area of the U.S. EEZ exceeds the total landmass of the conterminous United States by about one-half (Pew Oceans Commission, 2003).

Broad-scale protections in the U.S. EEZ cover a wide range of types of marine ecosystems, from low to high latitudes and across the Atlantic and Pacific Oceans. Shallow areas of these systems share basic features in the form of biologically generated habitats: temperate kelp forests and salt marshes, tropical coral reefs and mangroves, and temperate and tropical seagrass beds. These biogenic habitats are fundamental to ecosystem structure and function, and support a range of different community types (Bertness, Gaines, and Hay, 2001). In addition, there are significant deep-water coral formations about which we are just starting to increase our understanding (Rogers, 1999; Watling and Risk, 2002).

Embedded within the general protections of the U.S. EEZ are hundreds of federal marine protected areas (MPAs) that are designed to provide place-based management at "special" places (Barr, 2004) and other areas that have been identified as meriting particular regulations. The term "marine protected area" has been used in many ways (*e.g.,* Kelleher, Bleakley, and Wells, 1995; Agardy, 1997; Palumbi, 2001; National Research Council, 2001; Agardy *et al.*, 2003). We use the following definition: "Marine protected area" means any area of the marine environment that has been reserved by federal, state, territorial, tribal, or local laws or regulations to provide lasting protection for part or all of the natural and cultural resources therein.[1] It is important to emphasize at the onset that MPAs are managed across a wide range of approaches and degrees of protection (Wooninck and Bertrand, 2004). At the most protective end of the spectrum are highly protected (no-take) marine reserves (Sobel and Dahlgren, 2004). These reserves eliminate fishing and other forms of resource extraction, and enable some degree of recovery of exploited populations and restoration of ecosystem structure and function, generally within relatively small areas. It is also important to highlight at the onset that management of waters surrounding MPAs is critically important both to the effectiveness of the MPAs themselves as well as to the overall resilience of larger marine systems. By "resilience" we refer to the amount of change or disturbance that can be absorbed by a system before the system is redefined by a different set of processes and structures (*i.e.,* the ecosystem recovers from the disturbance without a major phase shift; see Glossary).

Federal MPAs have been established by the Department of the Interior (National Park Service and U.S. Fish and Wildlife Service) and the Department of Commerce, National Oceanic and Atmospheric Administration (National Marine Fisheries Service, National Estuarine Research Reserve System, and National Marine Sanctuary Program) (Table 8.1). A 2000 executive order established the National Center

Table 8.1. Types of federal marine protected and marine managed areas, administration, and legislative mandates. MPAs are intended primarily to protect or conserve marine life and habitat, and are a subset of marine managed areas (MMAs), which protect, conserve, or otherwise manage a variety of resources and uses including living marine resources, cultural and historical resources, and recreational opportunities.[2]

Type of MPA/MMA	Number of Sites	Administration	Mandate
National Marine Sanctuary	13	NOAA/National Marine Sanctuary Program	National Marine Sanctuaries Act
Fishery Management Areas	216	NOAA/National Marine Fisheries Service	Magnuson-Stevens Act, Endangered Species Act, Marine Mammal Protection Act
National Estuarine Research Reserve[3]	27	NOAA/Office of Ocean and Coastal Resource Management	Coastal Zone Management Act
National Park	42	National Park Service	NPS Organic Act
National Monument[4]	3	National Park Service	NPS Organic Act
National Wildlife Refuge	109	U.S. Fish and Wildlife Service	National Wildlife Refuge System Administration Act

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[1] Executive Order 13158 quoted in: **National Center for Marine Protected Areas**, 2006: *Draft Framework for Developing the National System of Marine Protected Areas*. National Center for Marine Protected Areas, Silver Spring, MD.

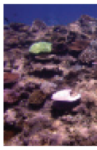
[2] **California Department of Fish and Game**, 2007: Marine life protection act initiatives. California Department of Fish and Game Website, http://www.dfg.ca.gov/mrd/mlpa/defs.html#mma, accessed on 7-27-2007.

[3] The National Estuarine Research Reserve System is a state partnership program.

[4] The Papahānaumokuākea Marine National Monument is included here. It is co-managed by NOAA/National Marine Sanctuary Program and National Marine Fisheries Service, the U.S. Fish and Wildlife Service, and the State of Hawaii and was established by Presidential Proclamation 8031.

Table 8.2. Type, number, area, and no-take area of federal marine managed areas (MMAs) and areas of Exclusive Economic Zones (EEZs) by region in U.S. waters.[5] *NP = National Parks, NWR = National Wildlife Refuges, NMS = National Marine Sanctuaries, FMA = Fishery Management Areas, NERR = National Estuarine Research Reserves, and NM = National Monuments.*

Region	Type of MMA	Number	Total Area (km^2)[6]	Total Area No Take (km^2)	% Area No Take	Area of EEZ in Region (km^2)
New England (Maine to Connecticut)						197,227
	NP	0	0	0	0%	
	NWR	1	30	0	0%	
	NMS	1	2,190	0	0%	
	FMA	30	212,930	0	0%	
	NERR[7]	1	27	0	0%	
Mid Atlantic (New York to Virginia)						218,151
	NP	3	36,472	0	0%	
	NWR	22	15	0	0%	
	NMS	0	0	0	0%	
	FMA	9	686,379	0	0%	
	NERR	1	27	0	0%	
South Atlantic (North Carolina to Florida)						525,627
	NP	8	1,421	119	8%	
	NWR	19	3,705	564	15%	
	NMS	3	9,853	591	6%	
	FMA	11	974,243	349	<0.1 %	
	NERR	5	928	0	0%	
Caribbean						212,371
	NP	2	27	1	2%	
	NWR	0	0	0	0%	
	NM[8]	2	128	76	59%	
	NMS	0	0	0	0%	
	FMA	6	168	55	33%	
	NERR	1	7	0	0%	
Gulf of Mexico						695,381
	NP	4	4,612	0	0%	
	NWR	24	2,375	2	<0.1%	
	NMS	1	146	0	0%	
	FMA	7	368,446	0	0%	
	NERR	5	2,195	0	0%	
West Coast						823,866
	NP	6	595	0	0%	
	NWR	15	226	16	7%	
	NMS	5	30,519	257	1%	
	FMA	56	386,869	0	0%	
	NERR	5	57	0	0%	
Alaska						3,710,774
	NP	3	29,795	0	0%	
	NWR	3	212,620	0	0%	
	NMS	0	0	0	0%	
	FMA	17	1,326,177	0	0%	
	NERR	1	931	0	0%	
Pacific Islands						3,869,806
	NP	4	21	< 1	<1%	
	NWR	10	281	158	56%	
	NM[8]	1	352,754	352,754	100%	
	NMS	3	3,556	1	<1%	
	FMA	6	1,467,614	0	0%	
	NERR	0	0	0	0%	
National Total						10,413,230
	NP	42	72,943	120	0.16%	
	NWR	109	219,252	740	0.34%	
	NM	3	352,882	352,882	100%	
	NMS	13	46,264	591	1.3%	
	FMA	216	5,422,826	488	0.01%	
	NERR	27	4,606	0	0.00%	
	TOTAL ALL FEDERAL MMAS[9]	410	6,118,773	354,820	5.8%	



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[5] **National Oceanic and Atmospheric Administration**, 2006: Marine Protected Areas of the United States: marine managed areas inventory. Marine Protected Areas Website, http://www3.mpa.gov/exploreinv/AlphaSearch.aspx, accessed on 2006.

[6] Total area includes only those sites for which data are available.

[7] NERRs are state/federal partnership sites.

[8] The Papahānaumokuākea Marine National Monument is scheduled to become a no-take area in five years when all fishing is phased out. This site has been included in the no-take category and will be the largest no-take MPA in the United States.

[9] This total is corrected for overlapping jurisdictions of Federal MMAs.

for Marine Protected Areas[10] to strengthen and expand a national system of MPAs. The total area of MMAs within the U.S. EEZ is considerable, but only a small area lies within highly protected marine reserves (Table 8.2). Only 3.4% of the U.S. EEZ lies within highly protected marine reserves, and most of this area is in the Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument; excluding the Monument reduces the percentage to 0.05%.

Manifestations of climate change are strengthening (IPCC, 2007c) against a background of long-standing alterations to ecological structure and function of marine ecosystems caused by fisheries exploitation, pollution, habitat degradation and destruction, and other factors (Pauly *et al.*, 1998; Jackson *et al.*, 2001; Pew Ocean Commission, 2003; U.S. Commission on Ocean Policy, 2004). Nowhere is the stress of elevated sea surface temperatures more dramatically expressed than in coral reefs, where local-scale coral bleaching has occurred in the Eastern Pacific and Florida for more than two decades (Glynn, 1991; Obura, Causey, and Church, 2006)[11] prior to the first global mass bleaching event in 1998. Impacts of climate variability and change in temperate ecosystems have not been as dramatic as coral bleaching. Interestingly, the combined effects of climate change, regime shifts, and El Niño-Southern Oscillation events (ENSOs) can strongly affect kelp forests (Paine, Tegner, and Johnson, 1998; Steneck *et al.*, 2002), but apparently not associated communities (Halpern and Cottenie, 2007).

The purpose of this chapter is to examine adaptation options for MPAs in the context of climate change. We will focus on the 14 MPAs that comprise the National Marine Sanctuary System (Table 8.3, Fig. 8.1) because they encompass a range of ecosystem types and are the only U.S. MPAs managed under specific enabling legislation. The National Marine Sanctuary Program has explicit approaches to and goals for MPA management, which simplify discussion of existing MPA management and how it may be adapted to climate change. Further, a goal of the program is to support ecosystem-based management (EBM) and, as will be discussed, EBM will become increasingly important in the context of climate change.

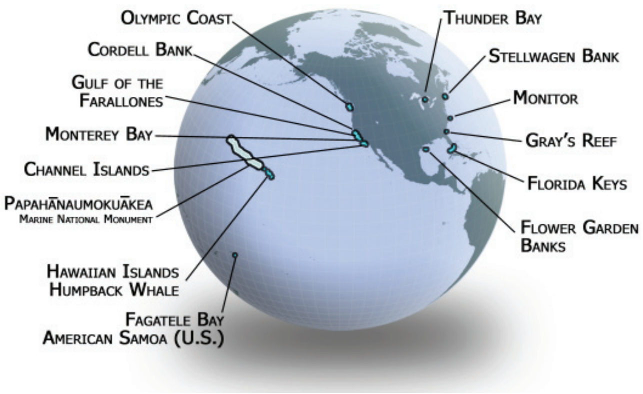

Figure 8.1. Locations of the 14 MPAs that comprise the National Marine Sanctuary System.[12]

The chapter provides background information about the historical context and origins of MPAs, with National Marine Sanctuaries highlighted as an example of effectively managed MPAs (Kelleher, Bleakley, and Wells, 1995; Agardy, 1997). MPAs are managed by several federal organizations other than the National Oceanic and Atmospheric Administration (NOAA) (Table 8.1), but it is beyond the scope of this chapter to cover all entities. National Marine Sanctuaries were selected to illustrate adaptation options for MPAs that apply broadly with respect to major anthropogenic and climate change stressors.

It is also beyond the scope of this chapter to cover issues concerning marine ecosystems from tropical to polar climates. This chapter highlights coral reef ecosystems, which have

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[10] http://mpa.gov/

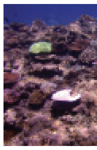
[11] See also **Causey**, B.D., 2001: Lessons learned from the intensification of coral bleaching from 1980-2000 in the Florida Keys, USA. In: *Coral Bleaching and Marine Protected Areas. Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Bishop Museum, Honolulu, HI, 29-31 May 2001* [Salm, R.V. and S.L. Coles (eds.)]. Asia Pacific Coastal Marine Program Report # 0102, The Nature Conservancy, Honolulu, HI, pp. 60-66.

[12] **National Marine Sanctuary Program**, 2006: National Marine Sanctuary system and field sites. National Marine Sanctuaries Program Webpage, http://www.sanctuaries.nos.noaa.gov/visit/welcome.html, accessed on 5-18-2007.

already shown widespread and dramatic responses to oceanic warming and additional global and local stressors. Mass coral reef bleaching events became worldwide in 1998, and have resulted in extensive mortality of reef-building corals (Wilkinson, 1998; 2000; 2002; Turgeon *et al*., 2002; Wilkinson, 2004; Wadell, 2005). There now exists a substantial and rapidly growing body of research on impacts of climate change on corals (such as bleaching) and coral reef ecosystems (*e.g.,* Smith and Buddemeier, 1992; Glynn, 1993; Hoegh-Guldberg, 1999; Wilkinson, 2004; Buddemeier, Kleypas, and Aronson, 2004; Donner *et al*., 2005; Phinney *et al*., 2006; Berkelmans and van Oppen, 2006). Climate change stressors, including effects of ocean acidification on carbonate chemistry (Kleypas *et al*., 1999; Soto, 2001; The Royal Society, 2005; Caldeira and Wickett, 2005), will be reviewed later in this chapter. Management approaches to coral reef ecosystems in response to mass bleaching and/or climate change have also received some attention (Hughes *et al*., 2003; Hansen, Biringer, and Hoffman, 2003; West and Salm, 2003; Bellwood *et al*., 2004; Wooldridge *et al*., 2005; Marshall and Schuttenberg, 2006).[13]

Table 8.3. Sites in the National Marine Sanctuary System.[12]
Regions: PC = Pacific Coast, PI = Pacific Islands, SE = Southeast, Gulf of Mexico, and Caribbean, NE = Northeast.

Site	Location	Region	Year Designated	Size (km^2)	Yr of First Mgt Plan	Status of Mgt Plan Revision
Channel Islands	CA	PC	1980	4,263	1983	2008 planned publication
Cordell Bank	CA	PC	1989	1,362	1989	Central CA Joint Mgt Plan Review[14]
Fagatele Bay	Amer. Samoa	PI	1986	0.66	1984	Ongoing
Florida Keys	FL	SE	1990	9,844	1996	Published 2007
Flower Garden Banks	TX	SE	1992	2.0	In preparation	
Gray's Reef	GA	SE	1981	58	1983	Published 2006
Gulf of the Farallones	CA	PC	1981	3,252	1983	Central CA Joint Mgt Plan Review
Hawaiian Islands HW[15]	HI	PI	1992	3,548	1997	Published 2002
Monitor[16]	NC	NE	1975	4.1	1997[17]	
Monterey Bay	CA	PC	1992	13,784	1992	Central CA Joint Mgt Plan Review
Olympic Coast	WA	PC	1994	8,573	1994	Ongoing
Papahānaumokuākea MNM[18]	HI	PI	2006	~360,000	In preparation	
Stellwagen Bank	MA	NE	1992	2,188	1993	2009 planned publication
Thunder Bay[16]	MI	NE	2000	1,160	1999	Ongoing
Key Largo[19]	FL		1975	353		
Looe Key[19]	FL		1981	18		



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[13] See also **Salm**, R.V. and S.L. Coles (eds.), 2001: *Coral Bleaching and Marine Protected Areas. Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Bishop Museum, Honolulu, HI, 29-31 May 2001.* Asia Pacific Coastal Marine Program Report # 0102, The Nature Conservancy, Honolulu, HI, 118 pp.
Marshall, P. and H. Schuttenberg, 2006: A Reef Manager's Guide to Coral Bleaching. Great Barrier Reef Marine Park Authority, http://www.coris.noaa.gov/activities/reef_managers_guide/, pp.1-178.

[14] The Central California Joint Management Plan Review is a coordinated process to obtain public comments on draft management plans, proposed rules, and draft environmental impact statements for the three Central California Sanctuaries.

[15] HW = humpback whale.

[16] The Monitor (http://monitor.noaa.gov/) and Thunder Bay (http://thunderbay.noaa.gov/) NMSs were designated for protection of maritime heritage resources.

[17] This plan is a comprehensive, long-range preservation plan for the Civil War ironclad U.S.S. *Monitor.*

[18] The Papahānaumokuākea Marine National Monument is co-managed by NOAA/National Marine Sanctuary Program and National Marine Fisheries Service, U.S. Fish and Wildlife Service, and the State of Hawaii.

[19] The Key Largo and Looe Key NMSs were subsumed within the Florida Keys NMS as Existing Management Areas.

Climate-change stressors in and ecological responses of colder-water marine ecosystems only partially overlap those of warmer-water and tropical marine ecosystems (IPCC, 2001; Kennedy *et al.*, 2002). The Channel Islands National Marine Sanctuary is included as a temperate-zone case study (see Case Study Summary 8.4) to contrast with case studies of tropical coral reef ecosystems from the Florida Keys to Hawaii to Australia (Case Study Summaries 8.1–8.3), which differ in extent of no-take protection.

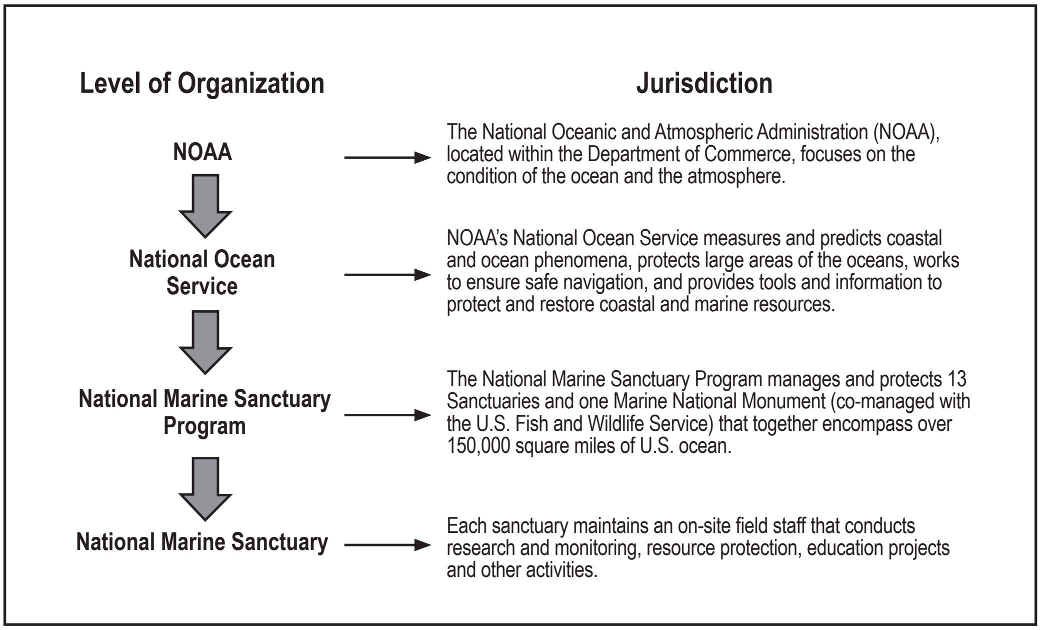
8.2.2 Historical Context and Origins of National Marine Sanctuaries and Other Types of Marine Protected Areas

8.2.2.1 Mounting Environmental Concerns and Congressional Actions

In 1972 the United States acknowledged the dangers and threats of uncontrolled industrial and urban growth and their impacts on coastal and marine habitats through the passage of a number of Congressional acts that focused on conservation of threatened coastal and ocean resources. The Water Pollution Control Act addressed the nation's threatened water supply and coastal pollution. The Marine Mammal Protection Act imposed a five-year ban on killing whales, seals, sea otters, manatees, and other marine mammals. The Coastal Zone Management Act provided a framework for federal funding of state coastal zone management plans that created a nationwide system of estuarine research reserves. A final environmental bill that focused on ocean health, the Marine Protection, Research and Sanctuaries Act of 1972, established a system of marine protected areas—national marine sanctuaries (NMS)—administered by NOAA (Fig. 8.2).

8.2.2.2. Types of Federal MPAs and Focus on National Marine Sanctuaries

In addition to the 13 national marine sanctuaries and one marine national monument, there are hundreds of marine managed areas (MMAs) under other, sometimes overlapping jurisdictions (Table 8.2) (National Research



The National Oceanic and Atmospheric Administration (NOAA), located within the Department of Commerce, focuses on the condition of the ocean and the atmosphere.

NOAA's National Ocean Service measures and predicts coastal and ocean phenomena, protects large areas of the oceans, works to ensure safe navigation, and provides tools and information to protect and restore coastal and marine resources.

The National Marine Sanctuary Program manages and protects 13 Sanctuaries and one Marine National Monument (co-managed with the U.S. Fish and Wildlife Service) that together encompass over 150,000 square miles of U.S. ocean.

Each sanctuary maintains an on-site field staff that conducts research and monitoring, resource protection, education projects and other activities.

Figure 8.2. Organizational chart of the National Marine Sanctuary Program.[20]

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[20] **NOAA National Ocean Service**, 2006: NOAA's National Ocean Service: program offices. NOAA Website, http://www.oceanservice.noaa.gov/programs/, accessed on 7-29-2007.

CASE STUDY SUMMARY 8.1

Florida Keys National Marine Sanctuary
Southeast United States

Why this case study was chosen

The Florida Keys National Marine Sanctuary:

- Surrounds the Florida Reef Tract, the only system of bank-barrier coral reefs in the conterminous United States and one of the most biodiverse areas in North America;
- Draws millions of visitors each year due to its ready access to a unique environment, a burgeoning population in southern Florida, and its status as a destination for cruise ships at Key West;
- Is a relatively data-rich environment, with an existing baseline of information for detecting presumptive climate change effects;
- Is an example of a marine protected area with a relatively low level of protection using no-take marine reserves (6% of total area).

Management context

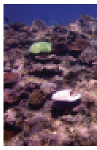
The Florida Keys National Marine Sanctuary encompasses multiple areas with different degrees of protection and management histories, some going back to 1960. It was designated as a national marine sanctuary in 1990, but management regulations did not go into effect until 1997, once the final management plan was approved. There are five types of management zones, with varying degrees of restrictions, including "no-take," limits on specific types of fishing or vessel access, and research-only access. In addition, a water quality protection program is administered through the U.S. Environmental Protection Agency, working with the State of Florida and the National Oceanic and Atmospheric Administration. Enforcement efforts complement education and outreach programs; mooring buoys and waterway markers help minimize physical impacts from anchoring and vessel groundings.

Key climate change impacts

- Projected increase in water temperatures by several degrees in the next 100 years;
- Projected reduction in rates of calcification associated with increased ocean acidification;
- Projected increase in intensity of storms;
- Expected exacerbation of coral bleaching events;
- Potential increased prevalence of diseases;
- Potential changes in ocean circulation patterns;
- Potential geographic range shifts of individual species, and changes in reef community composition, in response to temperature increases.

Opportunities for adaptation

- Bleaching-resistant sites could be targeted for priority protection as refugia and as larval sources for recovery; the National Oceanic and Atmospheric Administration's Coral Reef Watch program to predict mass bleaching events presents an opportunity for designing before-during-after sampling around bleaching events, which will be crucial for site identification.
- The Florida Reef Resilience Program, led by The Nature Conservancy, is conducting surveys to identify resilient areas and is promoting public awareness and education.
- In the short time since their establishment, no-take zones have been shown to enhance heavily fished populations, which in turn may support resilience through re-establishment of key predators. (Much additional research is needed on the effects of community structure on resilience.)
- Protecting habitats similar to those that thrived during the middle Holocene, when coral reefs flourished north of their current distribution, could allow for northward range migration. (This would be contingent on mitigation of existing stressors that may otherwise limit the ability of corals to migrate.)
- Mangrove restoration not only provides habitat and shoreline protection, but is also a source of dissolved organic compounds that have been shown to provide protection from photo-oxidative stress in corals.



Conclusions

Environmental problems that spurred the creation of the Florida Keys National Marine Sanctuary are already being exacerbated by climate change, in particular coral bleaching and disease. Some of the management protections to reduce other anthropogenic stressors may also increase coral reef resilience and allow range expansion northward in response to climate change. Monitoring and research can identify bleaching resistant and resilient sites, so that protection efforts can be adjusted for future climate conditions.

CASE STUDY SUMMARY 8.2

Great Barrier Reef Marine Park
Northeastern Australia

Why this case study was chosen

The Great Barrier Reef Marine Park:

- Is at the forefront of climate change adaptation planning for marine protected areas (MPAs) and is thus an excellent model for U.S. MPAs;
- Has exhibited signs of climate change effects, with increases in coral bleaching events and seabird nesting failures correlated with increases in sea and air temperatures;
- Has a high conservation value as a World Heritage Area and as the largest coral reef ecosystem in the world;
- Is an example of an MPA with a moderate level of no-take protection.

Management context

The Great Barrier Reef (GBR) Marine Park has been under a management regime since 1975. Marine park zoning was revised in 2003 to increase no-take zones to 33% of the total area, with at least 20% protected in each habitat bioregion. Also in 2003, the Reef Water Quality Protection Plan was implemented to manage diffuse sources of pollution entering the GBR from the adjacent large catchment area. Tourism and fishing industries are highly regulated through the GBR Marine Park Authority and the Queensland Government, respectively. The GBR coast is one of the fastest growing regions in Australia, with different aspects of coastal development regulated at the local, state, and federal levels. The GBR Climate Change Response Program developed a Climate Change Action Plan in 2007 to facilitate: 1) targeted science; 2) a resilient GBR ecosystem; 3) adaptation of GBR industries and communities; and 4) reduced climate footprints.

Key climate change impacts

- Observed increase in regional sea surface temperatures (0.4°C since 1850) and projected further increase of 1–3°C by 2100, which will increase coral bleaching and disease, and will have implications for primary productivity;
- Projected decrease in ocean pH of 0.4–0.5 units by 2100, which will limit calcification rates of corals, forams, some plankton and molluscs;
- Projected rise in sea level of 30–60 cm by 2100, which will affect seabird and turtle nesting, island and coastal habitats, light penetration, and connectivity;
- Projected increase in tropical cyclone intensities, with potentially greater damage to coastal and shallow habitats including coral reefs;
- Projected changes in rainfall, river flow, and El Niño Southern Oscillation regimes;
- Expected losses of coral reef habitat, with associated decreases in ecosystem diversity and changes in community composition.

Opportunities for adaptation

- Areas with high resilience factors (water quality, coral cover, community composition, larval supply, recruitment success, herbivory, disease, and effective management) are being identified as priority areas to protect from other stresses; areas with low resilience are also being identified as candidates for more active management to improve their condition.
- Landward areas could be conserved through land acquisition and removal of barrier structures to allow migration of mangroves and wetlands as sea level rises.
- Sites of specific importance could be protected from coral bleaching through artificial shading or water mixing in summer months;
- Through partnerships with stakeholders to identify impacts on tourism, options for how the industry can respond, and strategies for becoming climate ready, the GBR has developed a Marine Tourism and Climate Change Action Strategy.
- By having a variety of management tools ready as new information becomes available, it may be possible to manage flexibly and respond rapidly to ongoing climatic changes.

Conclusions

The GBR Climate Change Response Program has already documented observed climate change effects, identified likely vulnerabilities, and developed a Climate Change Action Plan. The combination of dramatic potential ecosystem effects and a strong national and international constituency for protection has made the GBR Marine Park an international leader in addressing climate change impacts on coral reefs. Management examples for other MPAs include initiatives that support local industries and communities in adapting to climate change, management plans that are flexible in the face of uncertainty, and resilience-based management strategies.

CASE STUDY SUMMARY 8.3

Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument Pacific United States

Why this case study was chosen

The Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument:

- Provides an opportunity to assess how a nearly intact, large-scale coral reef ecosystem responds to climate change;
- Has a high conservation value due to high levels of endemism, a unique apex-predator-dominated ecosystem, and the occurrence of a number of protected and endangered species;
- Is an example of a large Marine Protected Area with a high level of no-take protection.

Management context

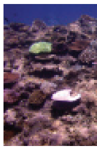
The Northwestern Hawaiian Islands (NWHI) are an isolated, low lying, primarily uninhabited archipelago that is relatively free from human impacts due to its remoteness. Eight of the 10 NWHI have been protected since 1909 as part of what is now the Hawaiian Islands National Wildlife Refuge. The Papahānaumokuākea Marine National Monument was designated in 2006 as the largest marine protected area in the world, managed jointly by the State of Hawaii, the U.S. Fish and Wildlife Service, and the National Oceanic and Atmospheric Administration. The new protections will phase out commercial fishing over five years, and already ban other types of resource extraction and waste dumping. The dominant stressors are natural ones, including large inter- and intra-annual water temperature variations, seasonally high wave energy, and inter-annual and inter-decadal variability in ocean productivity. Marine debris is the largest anthropogenic stressor; a debris removal program between 1999 and 2003 resulted in a removal of historical debris accumulation, but the current level of effort is not sufficient to keep up with the annual rate of accumulation. The draft Monument Management Plan does not address climate and ocean change management actions specifically, but many of the research, monitoring, and education plans focus on climate, which will provide managers with tools for addressing climate change.

Key climate change impacts

- Projected increase in the intensity of storm events, which will in turn intensify wave impacts on habitat;
- Projected decreases in important habitat for sea turtles, endangered monk seals, and seabirds as sea level rise inundates low-lying emergent areas;
- Expected increase in temperature-related coral bleaching events like those observed in 2002 and 2004;
- Projected increases in ocean temperature that could lead to shifts in the distribution of corals and other organisms; shallow-water species that are adapted to cooler water may see habitat loss, while those adapted to warmer water might extend their range.

Opportunities for adaptation

- Monitoring and research provide an opportunity to evaluate the hypothesis that large, intact predator-dominated ecosystems are more resistant and resilient to stressors, including climate change, and expanded efforts will help better understand how climate change affects an ecosystem in the absence of localized human stressors.
- The Coral Reef Ecosystem Integrated Observing System (CREIOS) serves to alert resouce managers and researchers to environmental events considered significant to the health of the surrounding coral reef ecosystem, allowing managers to implement response measures in a timely manner and allowing researchers to increase spatial or temporal sampling resolution, if warranted; with supplementary sensors, CREIOS can help to capture climate change impacts at finer spatial and temporal scales than currently exist.
- The draft monument science plan includes several specific climate change research activities, including determining habitat changes due to sea level rise; mapping areas that will be most affected by extreme wave events; and determining how specific habitat, communities, and populations will be affected by climate change effects.
- Beach nourishment could counter the effects of sea level rise on the habitats of critical endemic and protected species.



Conclusions

The high level of protection, the healthy intact predator-dominated ecosystem, the limited human impact, and the current ocean observing system present a unique research opportunity for studying adaptation to climate change in the Papahānaumokuākea Marine National Monument (PMNM). An increased understanding of natural resistance and resilience in this system will inform management planning in other marine protected areas. To date, management goals for adapting the PMNM to climate change have not looked beyond efforts to understand the system, but as endangered species habitat becomes affected, more active management efforts will be necessary.

CASE STUDY SUMMARY 8.4

Channel Islands National Marine Sanctuary
Western United States

Why this case study was chosen

The Channel Islands National Marine Sanctuary:

- Supports a diverse community based around the dominant, habitat-forming, giant kelp forests;
- Is sensitive to natural variability and has exhibited large responses to El Niño Southern Oscillation events, in particular;
- Encompasses a biogeographic boundary between the warm waters of the Davidson Current and the cool, nutrient-rich waters of the California Current.

Management context

The Channel Islands National Marine Sanctuary was designated in 1980 and was managed through overlapping state and federal jurisdictions. In 2003, 10 new fully protected marine reserves and two conservation areas that allow limited take were established to protect marine habitats and species of interest. The network of marine protected areas, which was designed with input from a broad array of stakeholders, offers additional protection to 10% of sanctuary waters. In 2007, the sanctuary implemented a second phase of the network of marine protected areas, by extending seven reserves and one conservation area into federal waters and adding a reserve to form a network of marine protected areas that includes 21% of sanctuary waters. The Sanctuary Management Plan includes a mechanism for addressing emerging issues; climate change has not yet been, but could be, explicitly identified as an emerging issue.

Key climate change impacts

- Projected increases in storm intensity that may increase damage to kelp stocks and rip kelp holdfasts from rocky substrata;
- Projected increase in frequency of El Niño-like conditions, which may suppress kelp growth by lowering nutrient levels due to associated relaxation of coastal winds;
- Projected increase in water temperature, which will affect metabolism, growth, reproduction, rates of larval development, spread of non-native species, and outbreaks of marine disease;
- Projected changes in currents and upwelling that may affect the location of biogeographic boundaries, and change primary productivity and species assemblages.

Opportunities for adaptation

- Marine reserves can be used as a management tool to increase resilience of kelp forest communities; in a marine reserve where fishing has been prohibited since 1978, kelp forests were less vulnerable to storms, ocean warming, overgrazing, lower nutrient concentrations, and disease compared with other areas of the sanctuary.
- With a slight adjustment, monitoring and research can be refocused to capture important information about climate and ocean change; observed changes associated with climate could be used to trigger more intensive observations.
- Outreach mechanisms such as the Sanctuary Naturalist Corps, Ocean Etiquette program, and sanctuary publications are well positioned to communicate information to the public on climate change impacts, mitigation, and adaptation options.
- Protection in reserves and more hands-on techniques, such as removal of non-indigenous species, could preserve the integrity of marine communities in the sanctuary.

Conclusions

The high degree of natural environmental variability in the Channel Islands National Marine Sanctuary supports remarkable biological diversity. Climate change, in concert with anthropogenic stressors, will likely intensify the range of variability of the system. A marine reserve within the sanctuary has allowed kelp forests to flourish and increased their resilience to environmental shifts, such as those associated with El Niño events. Similarly, marine reserves are likely to be effective tools for minimizing the negative ecological impacts of climate change. The Sanctuary Management Plan is an appropriate mechanism for identifying climate change as an emerging issue and developing a strategic plan for management of climate change impacts, and for research, education, and outreach about climate change.

Council, 2001).[21] The National Park System, administered by the National Park Service of the Department of the Interior, includes more than 70 ocean sites (Davis, 2004). Certain national parks such as Everglades (founded in 1947), Biscayne (founded in 1968 as Biscayne National Monument), and Dry Tortugas National Parks (founded in 1935 as Fort Jefferson National Monument) have much longer histories of functioning as MPAs than the 35-year history of National Marine Sanctuaries. The National Marine Sanctuary Program and National Park Service have collaborated on ocean stewardship for a number of years (Barr, 2004). The U.S. Fish and Wildlife Service, also under the Department of the Interior, manages more than 100 national wildlife refuges that include marine ecosystems (Table 8.2). In some cases, jurisdictions overlap. For example, there are four national wildlife refuges within the Florida Keys National Marine Sanctuary (Keller and Causey, 2005), three of which cover large areas of nearshore waters (Fig. 8.3).

NOAA's National Marine Fisheries Service (NMFS) has jurisdiction over a large number of fishery management areas (Table 8.2). Collectively, these areas are more than an order of magnitude greater in size than all the other MMAs combined, but with a very small area under no-take protection (Table 8.2). NOAA also administers the National Estuarine Research Reserve System, which is a partnership program with coastal states that includes 27 sites.

This chapter is focused on NOAA's National Marine Sanctuary Program (NMSP), because it is dedicated to place-based protection and management of marine resources at nationally significant locations and has gained international

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[21] See also **National Center for Marine Protected Areas**, 2006: *Draft Framework for Developing the National System of Marine Protected Areas*. National Center for Marine Protected Areas, Silver Spring, MD.

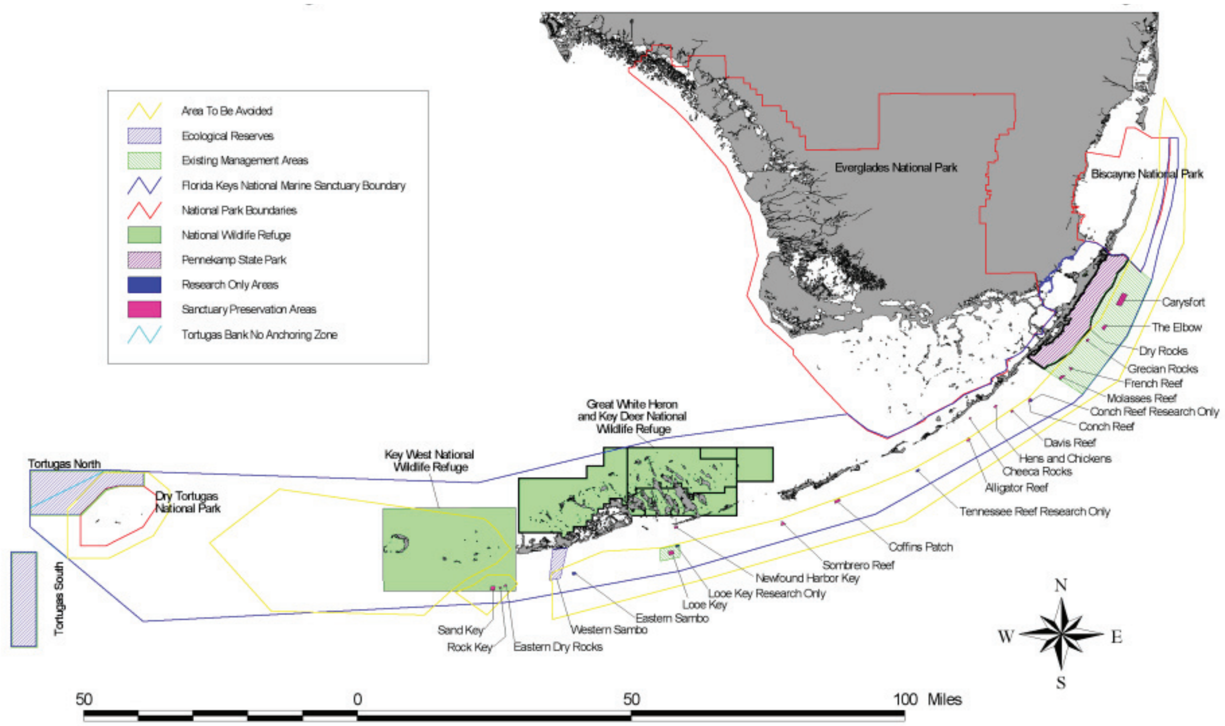
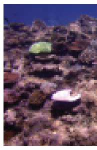


Figure 8.3. Map of the Florida Keys National Marine Sanctuary. The 1990 designation did not include the Tortugas Ecological Reserve, located at the western end of the sanctuary, which was implemented in 2001. The Key Largo NMS corresponded to the Existing Management Area (EMA) just offshore of the John Pennekamp Coral Reef State Park; the Looe Key NMS corresponded to the EMA surrounding the Looe Key Sanctuary Preservation Area and Research Only Area.[8]



recognition over the years (Barr, 2004). The principles of adaptation of MPA management to climate change (*i.e.,* institutional responses) that are identified will be broadly applicable to MPAs under other jurisdictions and forms of management, such as national parks, national wildlife refuges, and MMAs established by the NMFS, although institutional responses to adaptation likely will differ among the agencies responsible for resource management (Holling, 1995; McClanahan, Polunin, and Done, 2002). As the only federal program specifically mandated to manage MPAs, the NMSP is in a unique position to respond to challenges and recommendations in reports by the U.S. Commission on Ocean Policy (U.S. Commission on Ocean Policy, 2004) and Pew Oceans Commission (Pew Ocean Commission, 2003). Both reports encourage the use of ecosystem-based management, which is one of the hallmarks of the NMSP.

8.2.2.3 The National Marine Sanctuary Program

The NMSP was established to identify, designate, and manage ocean, coastal, and Great Lakes resources of special national significance to protect their ecological and cultural integrity for the use and enjoyment of current and future generations. In addition to natural resources within national marine sanctuaries, NOAA's Maritime Heritage Program is committed to preserving historical, cultural, and archaeological resources.[22]

The inclusion of consumptive human activities as a major part of the management programs in national marine sanctuaries distinguishes them from other federal or state resource protection programs. Sanctuaries are established for the long-term public benefit, use, and enjoyment, both recreationally and commercially. However, it is critical that sanctuary management policies, practices, and initiatives ensure that human activities in sanctuaries are compatible with long-term protection of sanctuary resources.

Thirteen national marine sanctuaries and one marine national monument, representing a wide variety of ocean environments as well as one cultural heritage site in the Great Lakes, have been established since 1975 (Table 8.3; Fig. 8.1; Fig 8.4). The national marine sanctuaries encompass a wide range of temperate and tropical environments: moderately deep banks, coral reef-seagrass-mangrove systems, whale migration corridors, deep sea canyons, and underwater archaeological sites. The sites range in size from 0.66 km^2 in Fagatele Bay,

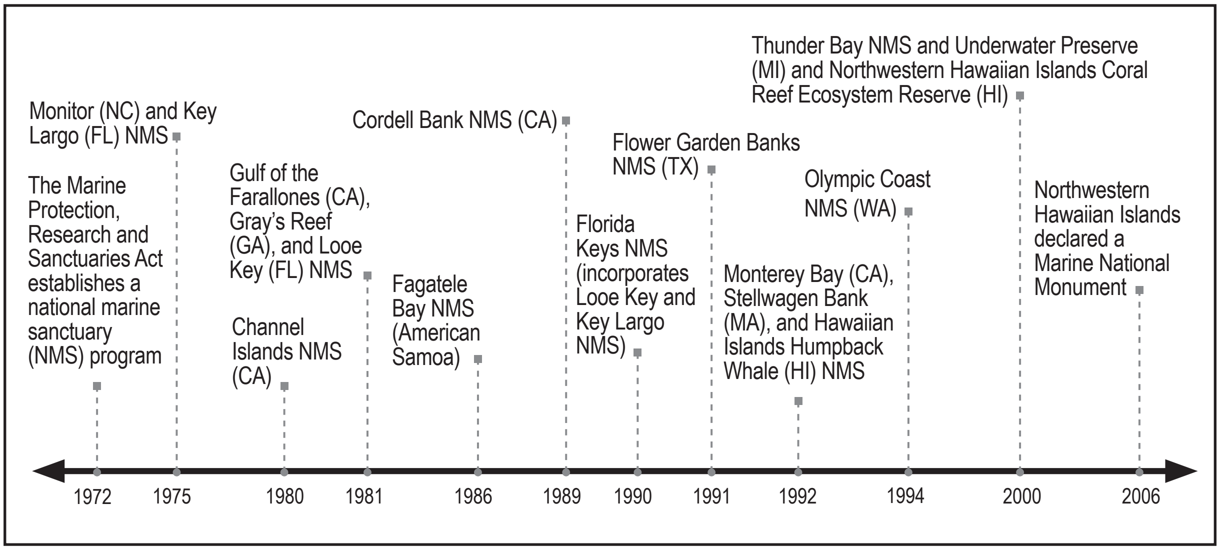


Figure 8.4. Timeline of the designation of the national marine sanctuaries in the National Marine Sanctuary Program.[23]

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[22] **National Marine Sanctuary Program**, 2006: Maritime heritage program. National Marine Sanctuaries Program Webpage, http://www.sanctuaries.nos.noaa.gov/maritime/welcome.html, accessed on 5-18-2007.

[23] **National Marine Sanctuary Program**, 2006: History of the national marine sanctuaries. NOAA's National Marine Sanctuaries Website, http://sanctuaries.noaa.gov/about/history, accessed on 7-29-2007.

American Samoa, to more than 360,000 km^2 in the Northwestern Hawaiian Islands (Table 8.3), the largest marine protected area in the world.

The NMSP has implemented a regional approach to managing the system of sanctuaries[12] (Table 8.3). Four regions have been established to improve support for the sites and to enhance an integrated ecosystem-based approach to management of sanctuaries. An important function of the regions is to provide value-added services to the sites, while taking a broader integrated approach to management. The four regions are the Pacific Islands; West Coast; Northeast-Great Lakes; and the Southeast, Gulf of Mexico, and Caribbean. Boundaries for these regions are focused on physical and biological connectivity among sites, rather than political boundaries.

8.2.3 Enabling Legislation

8.2.3.1 Enabling Legislation for Different Types of MPAs

The U.S. National Park System Organic Act established the National Parks System in 1916. Several parks and national monuments have marine waters within their boundaries or are primarily marine; they were the earliest federal MPAs. Similarly, a large number of national wildlife refuges function as MPAs (Table 8.1) under the authority of the U.S. Fish and Wildlife Service. The 1966 National Wildlife Refuge System Administration Act was the first comprehensive legislation after decades of designations of federal wildlife reservations and refuges.[24]

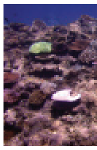
NOAA's National Marine Fisheries Service implements and manages more than 200 fishery management areas (Table 8.1) under several different statutory authorities, with four major categories: Federal Fisheries Management Zones, Federal Fisheries Habitat Conservation Zones, Federal Threatened and Endangered Species Protected Areas, and Federal Marine Mammal Protected Areas. The purposes of these fishery management areas include rebuilding and maintaining sustainable fisheries, conserving and restoring marine habitats, and promoting the recovery of protected species. NOAA's National Estuarine Research Reserve System was established by the Coastal Zone Management Act of 1972.[25] This system consists of partnerships between NOAA and coastal states to protect habitat, offer educational opportunities, and provide areas for research. This same year, Congress also established a system of national marine sanctuaries.

8.2.3.2 The Marine Protection, Research, and Sanctuaries Act

The Marine Protection, Research, and Sanctuaries Act[26] established both the NMSP and a regulatory framework for ocean dumping, which was a major issue at the time. In Title III of the Act, later to be known as the National Marine Sanctuaries Act (NMSA),[27] the Secretary of Commerce received the authority to designate national marine sanctuaries for the purpose of preserving or restoring nationally significant areas for their conservation, recreational, ecological, or esthetic values. The NMSA is reauthorized every four to five years, allowing for updating and adaptation as necessary.

8.2.3.3 Legislation Designating Particular National Marine Sanctuaries

On November 16, 1990, the Florida Keys National Marine Sanctuary and Protection Act (FKNMS Act), P.L. 101-605, set out as a note to 16 U.S.C. 1433, became law. The FKNMS Act designated an area of waters and submerged lands, including the living and nonliving resources within those waters, surrounding most of the Florida Keys (Fig. 8.3). This was the first national marine sanctuary to be designated by an act of Congress.



The FKNMS Act immediately addressed two major concerns of the residents of the Florida Keys. First, it placed an instant prohibition on oil drilling, including mineral and hydrocarbon leasing, exploration, development, or production, within the sanctuary. Second, the Act created an internationally recognized area to be avoided (ATBA) for ships greater than 50 m in length, with special designated access corridors into ports (Fig. 8.3). The ATBA provides a buffer

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[24] **U.S. Fish and Wildlife Service**, 2007: Origins of the U.S. Fish and Wildlife Service. U.S. Fish and Wildlife Service Website, http://training.fws.gov/history/origins.html, accessed on 5-18-2007.

[25] 16 U.S.C. 1451-1456 P.L. 92-583

[26] 33 U.S.C. 1401-1445, 16 U.S.C. 1431-1445 P. L. 92-532

[27] 16 U.S.C. 1431-1445 P.L. 106-513

zone along the coral reef tract to protect it from oil spills and groundings by large vessels.

The FKNMS Act also called for a comprehensive, long-term strategy to protect and preserve the Florida Keys marine environment. The sanctuary seeks to protect marine resources by educating and interpreting for the public the Florida Keys marine environment, and by managing those uses that result in resource degradation. At the time it was thought that the greatest challenge to protecting the natural resources of the Keys and the economy they support was to improve water quality. To address this challenge, the FKNMS Act brought together various agencies to develop a comprehensive Water Quality Protection Program (WQPP). The U.S. Environmental Protection Agency (EPA) is the lead agency in developing and implementing the WQPP, the purpose of which is to "recommend priority corrective actions and compliance schedules addressing point and nonpoint sources of pollution to restore and maintain the chemical, physical, and biological integrity of the sanctuary, including restoration and maintenance of a balanced, indigenous population of corals, shellfish, fish, and wildlife, and recreational activities in and on the water" (U.S. Department of Commerce, 1996).

The FKNMS Act called for an Interagency Core Group to be established to compile management issues confronting the sanctuary as identified by the public at scoping meetings, from written comments, and from surveys distributed by NOAA. The Core Group consisted of representatives from several divisions of NOAA, National Park Service, U.S. Fish and Wildlife Service, EPA, U.S Coast Guard, Florida Governor's Office, Florida Department of Environmental Protection, Florida Department of Community Affairs, South Florida Water Management District, and Monroe County.

The FKNMS Act also called for the public to be a part of the planning process using a Sanctuary Advisory Council (SAC) to aid in the development of a comprehensive management plan. A 22-member SAC was selected by the Governor of Florida and the Secretary of Commerce. The council consisted of members of various user groups; local, state, and federal agencies; scientists; educators; environmental groups; and private citizens.

It quickly became evident that the Congressional option to designate national marine sanctuaries would expedite the designation process. In 1992, four other national marine sanctuaries were designated by Congress, including the Flower Garden Banks, Monterey Bay, Hawaiian Islands Humpback Whale, and Stellwagen Bank (Table 8.3; Fig. 8.1). These designations were very similar to the FKNMS Act in that they laid out a process by which sanctuary management should proceed.

8.2.3.4 Recent Proclamation of the Papahãnaumokuãkea (Northwestern Hawaiian Islands) Marine National Monument

In 2000 President William J. Clinton signed Executive Orders that created the Northwestern Hawaiian Islands (NWHI) Coral Reef Ecosystem Reserve. The orders also initiated a process to designate the waters of the NWHI as a national marine sanctuary. Scoping meetings for the proposed sanctuary were held in 2002. In 2005 Hawaii Governor Linda Lingle signed regulations establishing a state marine refuge in the nearshore waters of the NWHI (out to 3 nautical miles, except Midway Atoll) that excluded all extractive uses of the region, except those permitted for research or other purposes that benefited management. In 2006, after substantial public comment in support of strong protections for the area, President George W. Bush issued Presidential Proclamation 8031, creating the Northwestern Hawaiian Islands Marine National Monument. The President's actions followed Governor Lingle's lead and immediately afforded the NWHI the highest form of marine environmental protection as the world's largest MPA (360,000 km^2). Administrative jurisdiction over the islands and marine waters is shared by NOAA/NMSP and NMFS, U.S. Fish and Wildlife Service, and the State of Hawaii.

8.2.4 Interpretation of Goals

The mission of the NMSP is to identify, protect, conserve, and enhance natural and cultural resources, values, and qualities. The NMSP has developed a draft strategic plan with a set of goals (Box 8.1) to provide a bridge between the broad mandates of the NMSA and daily operations at the site level.

At the site level, management and annual operating plans for each national marine sanctuary and the marine national monument identify specific plans and tasks for day-to-day management of the 14 sites. Sanctuaries work closely with their stakeholder Sanctuary Advisory Councils in the processes of developing and revising management plans. Sanctuary staff support SAC members in forming working groups to analyze each of the action plans that comprise a management plan. There are public scoping meetings to ensure the opportunity for participation by the public. The NMSA stipulates that plans should be reviewed and revised on a five-year time frame, and various sanctuaries are at different phases of this process (Table 8.3). Three Central California sanctuaries are undergoing a joint management plan review, some revisions have been completed, and some are nearing completion. Sanctuary management plans are available via the internet (http://sanctuaries.noaa.gov).

8.3 CURRENT STATUS OF MANAGEMENT SYSTEM

8.3.1 Key Ecosystem Characteristics on Which Goals Depend

In keeping with the goals of the National Marine Sanctuary Program (Box 8.1), sanctuaries within U.S. waters generally are set aside for the preservation of natural or maritime heritage resources. Sites such as the Florida Keys and Channel Islands NMS are of the former, while the Monitor NMS is of the latter. Sites designated to protect marine biological resources have their primary focus on maintaining biodiversity or preserving key species, and are therefore directly related to NMSP Goals 1 and 4. These sites are in particular need of management in response to climate change, yet have management plans that were designed to address local stressors, not to protect flora and fauna from climate change. Management options in the context of climate change will be discussed below (section 8.4).

8.3.1.1 Biodiversity

The extraordinary biodiversity of tropical and subtropical coral reef sites is well recognized (see Case Study Summaries 8.1–8.3), but recent findings underscore the fact that high biodiversity is also characteristic of many temperate sanctuaries. For example, the recent discovery of deep, temperate corals in the Olympic Coast NMS raises the possibility that benthic invertebrate and associated fish diversity is significantly higher than previously thought. Though receiving substantially less attention from the scientific community than their tropical counterparts, subtidal temperate reefs may be no less important in promoting species diversity and enhancing production (Jonsson *et al.*, 2004; Roberts and Hirshfield, 2004). In the past, these reefs have been overlooked and under-studied primarily because of limited accessibility; they often occur in deeper or lower-visibility waters than those of tropical reefs. Recently, and primarily because of greater accessibility to deep-water ecosystems, the importance of temperate reefs as critical habitat has begun to be fully

BOX 8.1. Draft Goals of the National Marine Sanctuary Program, 2005–2015.

Goal 1. Identify, designate, and manage sanctuaries to maintain the natural biological communities in sanctuaries and to protect and, where appropriate, restore and enhance natural habitats, populations, and ecological processes, through innovative, coordinated and community-based measures and techniques.

Goal 2. Build and strengthen the nation-wide system of marine sanctuaries, maintain and enhance the role of the NMSP's system in larger MPA networks and help provide both national and international leadership for MPA management and marine resource stewardship.

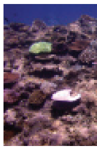
Goal 3. Enhance nation-wide public awareness, understanding, and appreciation of marine and Great Lakes ecosystems and maritime heritage resources through outreach, education, and interpretation efforts.

Goal 4. Investigate and enhance the understanding of ecosystem processes through continued scientific research, monitoring, and characterization to support ecosystem-based management in sanctuaries and throughout U.S. waters.

Goal 5. Facilitate human use in sanctuaries to the extent such uses are compatible with the primary mandate of resource protection, through innovative public participation and interagency cooperative arrangements.

Goal 6. Work with the international community to strengthen global protection of marine resources, investigate and employ appropriate new management approaches, and disseminate NMSP experience and techniques.

Goal 7. Build, maintain, and enhance an operational capability and infrastructure that efficiently and effectively support the attainment of the NMSP's mission and goals.



recognized (*e.g.,* Reed, 2002; Jonsson *et al.*, 2004; Roberts and Hirshfield, 2004; Roberts, Wheeler, and Freiwald, 2006). These reefs may host an array of undescribed species, including endemic gorgonians, corals, hydroids, and sponges (Koslow *et al.*, 2001; Jonsson *et al.*, 2004). Furthermore, the value of these offshore reefs to fisheries has long been recognized by commercial and recreational fishers. Fish tend to aggregate on deep-sea reefs (Husebø *et al.*, 2002), and scientific evidence supports the contention by commercial fishers that damage to temperate reefs affects both the abundance and distribution of fish (Fosså, Mortensen, and Furevik, 2002; Krieger and Wing, 2002).

8.3.1.2 Key Species

Key species within sanctuary boundaries may be resident as well as migratory, and may or may not represent species that are extracted by fishing (*i.e.,* NMSP Goal 5; Box 8.1). For example, three adjacent sanctuaries off the California coast—Cordell Bank, Gulf of the Farallones, and Monterey Bay—are frequented by protected species of blue (*Balaenoptera musculus*) and humpback (*Megaptera novaeangliae*) whales. In contrast, during the spring of each year king mackerel (*Scomberomorus cavalla*) migrate through Gray's Reef NMS off the coast of Georgia, representing a vibrant and sought-after recreational fishery. Under various climate change scenarios, management strategies employed to protect these key species may differ. For example, marine zones with dynamic boundaries reflecting shifting areas for feeding or reproduction may need to be considered by MPA managers.

Key species within sanctuaries may not be limited to subtidal marine organisms but, depending on the sanctuary, may also include intertidal species (*e.g., Mytilus californianus* in Monterey Bay NMS) or sea- and shorebirds. It has been suggested that intertidal species are more likely to be stressed by climate change and may serve as a bellwether for change in other ecosystems (Helmuth, 2002).

8.3.1.3 Habitat Complexity

National marine sanctuary sites, especially subtidally, are characterized by habitat complexity that is either biologically or geologically structured; this complexity is an invaluable resource supporting biodiversity. Subtidal habitats in sanctuaries that are biologically structured are represented most notably by temperate kelp forests and tropical coral reefs, whereas geologically structured habitats are centered around sea mounts and rocky outcrops. The topographic complexity of geologically structured habitats, especially in temperate systems, is often enhanced by settlement and growth of sessile benthic invertebrates such as sponges, arborescent bryozoans, and ascidians (*e.g.,* Gray's Reef NMS).

Habitat complexity is a key ecosystem characteristic that must be protected in order to achieve NMSP Goals 1 and 4 (Box 8.1). Biologically structured habitats are more susceptible to degradation resulting from climate change than geologically structured habitats. When habitat-building organisms such as corals are killed by climate change and other sources of mortality, skeletal material increases in susceptibility to bioerosion that may lead to reduced habitat complexity. As indicated in section 8.3.2 (Stressors of Concern), excess CO_2 absorbed by sea water lowers pH and results in reduced calcification rates in organisms that provide complex structure, such as arborescent bryozoans, bivalves, coralline algae, and temperate and tropical corals (Hoegh-Guldberg, 1999; Kleypas *et al.*, 1999; Kleypas and Langdon, 2006). Non-calcifying biological structures, such as kelp, as well as all shallow-water structures, are also at risk primarily from changes in storm intensity, ocean warming, and reduced upwelling associated with climate change (see Case Study Summary 8.4: Channel Islands National Marine Sanctuary).

8.3.1.4 Trophic Cascades

In addition to biodiversity and habitat complexity, trophic links between the benthos and water column help maintain ecosystem integrity within sanctuaries. In keeping with NMSP Goal 5 (Box 8.1) regarding human use, the strength of these benthic-pelagic linkages must be considered when designating fishing restrictions (Grober-Dunsmore, Wooninck, and Wahle, forthcoming).[28] Fishing regulations often involve removal of top predators and

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[28] See also **Wahle**, C., R. Grober-Dunsmore, and L. Wooninck, 2006: Managing recreational fishing in MPAs through vertical zoning: the importance of understanding benthic-pelagic linkages. *MPA News*, **7(8)**, 5.

have direct impacts on trophic cascades that are defined as: (1) having top-down control of community structure, and (2) having conspicuous indirect effects on two or more links distant from the primary one (Frank *et al.*, 2005). The consequences of ignoring past experiences regarding these trophic cascades could be deleterious to sanctuary goals (Hughes *et al.*, 2005). As highlighted in a recent workshop sponsored by the MPA Science Institute, however, knowledge in this critical area is lacking.[28] Facilitating a better understanding of trophic cascades by supporting scientific inquiry into this topic would do much to enhance understanding of ecosystem processes in marine sanctuaries (NMSP Goal 4, Box 8.1). Further research may also provide insight into how these processes might be affected by climate change.

8.3.1.5 Connectivity

The open nature of marine ecosystems means that they do not function, and likewise should not be managed, in isolation (Palumbi, 2003). Connectivity among marine ecosystems and across biological communities contributes to maintaining the biological integrity of all marine environments (Kaufman *et al.*, 2004). While NMS boundaries are well defined, the separation between ecosystems and communities is blurred because of export and import of resources. At the broadest scale these linkages are manifested as sources and sinks of nutrients and recruits (*e.g.,* Crowder *et al.*, 2000).

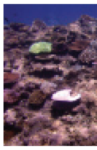
8.3.1.6 Nutrient Fluxes

While excess nutrients can lead to degradation of offshore ecosystems (Rabalais, Turner, and Wiseman Jr, 2002), it is also hypothesized that the function of offshore ecosystems is dependent on nutrients that have their origins in upland productivity. Estuaries are thought to represent the conduit through which dissolved and particulate material from the continent passes to offshore areas through rivers (Gattuso, Frankignoulle, and Wollast, 1998). This "outwelling" characteristic was first proposed by Odum[29] and has since been applied to mangroves and seagrasses (Lee, 1995). The direct and indirect trophic links that exist between these ecosystems are thought to be critical to ecosystem function, and highlight the importance of assessing the downstream effects that upland and nearshore activities have on increasing and decreasing nutrient availability offshore. In areas where climate change alters historical rainfall patterns, concomitant alteration of the supply of nutrients to offshore ecosystems might also occur.

8.3.1.7 Larval Dispersal and Recruitment

One of the strengths of the NMSP is protection of entire ecosystems rather than management of single species. As such, a key characteristic of these ecosystems rests in their ability to serve as sources of recruits for both fish and invertebrate species and as foci for fish aggregations. Most benthic marine invertebrates and fish species have a planktonic larval stage that results from spawned gametes (Pechenik, 1999). Successful recruitment of planktonic larvae to the benthos depends on processes that function at multiple spatial scales in contrast to non-planktonic larvae, which generally recruit at a small spatial scale. At the broadest scale, hydrodynamic forces may disperse passive larvae long distances, potentially delivering them to suitable settlement sites far from the source population (Williams, Wolanski, and Andrews, 1984; Lee *et al.*, 1992). Alternatively, complex, three-dimensional secondary flows resulting from barriers, such as headlands, islands, and reefs, as well as cyclonic motion can retain passive larvae within estuaries, around islands, or within ocean basins, resulting in more settlement to natal populations (Black, Moran, and Hammond, 1991; Lee *et al.*, 1992; Black *et al.*, 1995; Lugo-Fernandez *et al.*, 2001).

Because of their small size and limited swimming ability, invertebrate larvae may be passively dispersed at a broad spatial scale (Denny, 1988; Mullineaux and Butman, 1991). Yet larvae of many marine invertebrates, including coral planulae, use swimming behavior, stimulated by chemical or physical cues, to control their position within the water column—thereby increasing the probability that they will be transported to suitable settlement substrata (Scheltema, 1986; Raimondi and Morse, 2000; Gleason, Edmunds, and Gates, 2006; Levin, 2006). In contrast, researchers



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[29] **Odum**, E.P., 1969: A research challenge: evaluating the productivity of coastal and estuarine water. In: *Proceedings of the Second Sea Grant Conference*. University of Rhode Island, Kingston, Rhode Island, pp. 63-64.

continue to be surprised by the swimming and sensory capabilities of fish larvae (Stobutzki and Bellwood, 1997; Tolimieri, Jeffs, and Montgomery, 2000; Leis and McCormick, 2002; Leis, Carson-Ewart, and Webley, 2002; Lecchini *et al.*, 2005; Lecchini, Planes, and Galzin, 2005). That these larvae orient in the water column and swim directionally either at hatching or soon thereafter may explain recent evidence for localized recruitment (Jones *et al.*, 1999; Swearer *et al.*, 1999; Taylor and Hellberg, 2003; Cowen, Paris, and Srinivasan, 2006).

While connectivity among ecosystems and among biological communities in terms of both nutrients and recruits is an important feature of marine sanctuaries, boundaries of protected areas rarely encompass the continuum of habitats (*e.g.,* rivers to estuaries to mangroves to seagrasses to reefs) or the maximum dispersal distances of critical species. Recent information obtained for dispersal of fish and invertebrates suggests that sanctuaries must be managed for both self-recruitment and larval subsidies from upstream (Roberts, 1997b; Hughes *et al.*, 2005; Cowen, Paris, and Srinivasan, 2006; Steneck, 2006). Effective exchange of offspring is facilitated by MPA networks that are in close proximity [10–50 km apart according to Roberts *et al.* (2001)]. This would allow larval exchange among populations and also buffer these populations from climate-driven changes in current regimes. The NMSP should be a critical player in the development of such an MPA network. NMSP Goal 2 (Box 8.1) provides for the expansion of the nationwide system of MPAs and encourages cooperation among MPAs administered under a range of programs.

8.3.2 Stressors of Concern

Population growth and coastal development increasingly affect U.S. MPAs; an estimated 153 million people (53% of the U.S. population) lived in coastal counties in 2003, and that number continues to rise (World Resources Institute, 1996; National Safety Council, 1998; U.S. Census Bureau, 2001; Crossett *et al.*, 2004).[30] Growing human impacts are compounded by the fact that, in contrast to most terrestrial conservation areas, MPAs lack fences or other barricades and are subjected to anthropogenic stressors (*e.g.,* coastal development, pollution, unsustainable fishing and aquaculture practices, habitat degradation) that originate externally. MPA management has focused on minimizing impacts of these existing anthropogenic stressors. The addition of climate change may exacerbate effects of existing stressors and require new or modified management approaches, which are discussed in section 8.4.

The purpose of this section is: (1) to outline major stressors on marine organisms and communities resulting from climate change and (2) to introduce ways in which major "traditional" stressors may interact with climate change stressors.

There are excellent, extensive reviews of impacts of climate change on marine organisms and communities (*e.g.,* Scavia *et al.*, 2002; Walther *et al.*, 2002; Goldberg and Wilkinson, 2004; Harley *et al.*, 2006). By contrast, the scientific knowledge required to reach general conclusions related to the impact of multiple stressors at community and ecosystem levels is for the most part absent for marine systems. Thus, information concerning interactions among stressors is limited and MPA managers are faced with even higher levels of uncertainty about likely outcomes of management actions as climate change impacts have increasingly strong interactions with existing stressors.

8.3.2.1 Direct Climate Change Stressors

Ocean Warming

According to Bindoff *et al.* (2007), there is high confidence that an average warming of 0.1°C has occurred in the 0–700 m depth layer of the ocean between 1961 and 2003. Increasing ocean temperatures, especially near the surface, affect physiological processes in organisms ranging from enzyme reactions to reproductive timing (Fields *et al.*, 1993;

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[30] See also **National Ocean Service**, 2000: Spatial patterns of socioeconomic data from 1970 to 2000: a national research dataset aggregated by watershed and political boundaries. http://cads.nos.noaa.gov/.
Hinrichsen, D., B. Robey, and U.D. Upadhyay, 1998: *Solutions for a Water-Short World*. Population Report, Series M, No. 14, Population Information Program, Center for Communication Programs, the Johns Hopkins University School of Public Health, Baltimore, MD, pp.1-60.
World Resources Institute, 2000: *Gridded Population of the World*. Version 2, Center for International Earth Science Information Network, Columbia University, Palisades, NY.

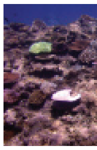
Roessig *et al*., 2004; Harley *et al*., 2006). The historical stability of ocean temperatures makes many marine species sensitive to thermal perturbations just a few degrees higher than those experienced over evolutionary time (Wainwright, 1994). However, it is not always intuitive which species might be most intolerant of temperature increases. For example, studies on porcelain crabs (*Petrolisthes*) and intertidal snails (*Tegula*) show that individuals in the mid-intertidal are closer to upper temperature limits and have less capacity to acclimate to temperature perturbations than subtidal congeners in temperature-stable conditions (Tomanek and Somero, 1999; Stillman, 2003; Harley *et al*., 2006).

What is clear is that increasing sea temperatures will continue to influence processes such as foraging, growth, and larval duration and dispersal, with ultimate impacts on the geographic ranges of species. In fact, poleward latitudinal shifts in some zooplankton, fish, and intertidal invertebrate communities have already been observed along the California coast and in the North Atlantic (reviewed in Walther *et al*., 2002). Within marine communities, these temperature changes and range shifts may result in new species assemblages and biological interactions that affect ecological processes such as larval dispersal, competitive interactions, and trophic interactions and webs (Barry *et al*., 1995; Roessig *et al*., 2004; Precht and Aronson, 2004; O'Connor *et al*., 2007). Species that are unable to shift geographic ranges (perhaps due to physical barriers) or compete with other species for resources may face local—and potentially global—extinction. Conversely, some species may find open niches and dominate regions because of release from competition or predation.

Impacts at the ecosystem or community level are even more difficult to predict. For example, warmer waters stimulate increases in population sizes of the mid-intertidal sea star, *Pisaster ochraceus,* and its per capita consumption rates of mussels (Sanford, 1999). Continued warming may enable *P. ochraceus* to clear large sections of mussel beds, indirectly affecting hundreds of species associated with these formations (Harley *et al*., 2006). How such an outcome affects trophic links and other biological processes within this community is not clear.

The latest reports from the IPCC (2007b; 2007c) state that temperature increases over the last 50 years are nearly twice those for the last 100 years, with projections that temperature will rise 2–4.5ºC, largely caused by a doubling of atmospheric carbon dioxide emissions. Increases in seawater surface temperature of about 1–3ºC are likely to cause more frequent coral bleaching events that cause widespread mortality, unless thermal adaptation or acclimatization by corals occurs (IPCC, 2007c). However, the ability of corals to adapt or acclimatize to increasing seawater temperature is largely unknown (Berkelmans and van Oppen, 2006) and remains a research topic of paramount importance.

Consequences of coral bleaching, during which corals lose their symbiotic algae, depend on the severity and duration of the bleaching event. They range from minimal affects on growth and reproduction to widespread mortality. Coral bleaching at the ecosystem level is a relatively recent phenomenon, first receiving widespread attention in 1987 when abnormally high summer seawater surface temperatures throughout the Caribbean resulted in a mass bleaching event (Williams, Goenaga, and Vicente, 1987; Ogden and Wicklund, 1988; Williams and Bunkley-Williams, 1990). Soon after, coral reef scientists identified climate change as a major long-term threat to coral reefs (Glynn, 1991; Smith and Buddemeier, 1992) and determined that irradiance interacts with temperature to cause bleaching (Gleason and Wellington, 1993; see also Hoegh-Guldberg, 1999; and Hoegh-Guldberg *et al*., 2007). Reciprocity between these two parameters may provide MPA managers with options to alleviate stress during bleaching events (see section 8.4.2).



In 1997–1998, a mass bleaching event in association with an ENSO event caused worldwide bleaching and coral mortality (Wilkinson, 1998; 2000), and in 2005 the most devastating Caribbean-wide coral bleaching event to date occurred that, based on modeling, is highly unlikely to have occurred without anthropogenic forcing (Donner, Knutson, and Oppenheimer, 2007). Over the last 20 years, an extensive body of literature has conclusively identified anomalously high summer surface seawater temperatures as the major cause of coral bleaching (Wilkinson, 1998; 2000; Fitt *et* *al.*, 2001; Wilkinson, 2002; U.S. Climate Change Science Program and Subcommittee on Global Change Research, 2003; Donner *et al.*, 2005; Donner, Knutson, and Oppenheimer, 2007), with widespread agreement that continued warming—as little as 1ºC warmer than the average summer maxima is sufficient—will increase the severity and frequency of mass bleaching events (Smith and Buddemeier, 1992; Hoegh-Guldberg, 1999; Hughes *et al.*, 2003; Douglas, 2003; Done and Jones, 2006).

Effects of coral reef bleaching are both biological, including lost biodiversity and other ecosystem services, and economic, resulting in the decline of fisheries and tourism (Buddemeier, Kleypas, and Aronson, 2004). Coral reefs affected by mass bleaching typically take decades or longer to recover and sometimes may not recover at all. In general, coral reef decline throughout the Caribbean region has been caused by a combination of bleaching, disease, die-off of the sea urchin *Diadema antillarum*, overfishing, pollution, hurricanes, and other factors (Gardner *et al.*, 2003; Gardner *et al.*, 2005).

Ocean Acidification

Increased CO_2 concentrations lower oceanic pH, making it more acidic. According to the most recent IPCC report, the total inorganic carbon content of the ocean increased by 118 (±19) billion metric tons of carbon from 1750–1994, and continues to increase through absorption of excess CO_2 (Bindoff *et al.*, 2007). Furthermore, time series data for the last 20 years show a trend of decreasing pH of 0.02 pH units per decade (Bindoff *et al.*, 2007). Long-term exposures to low pH (-0.7 unit) have been shown to reduce metabolic rates, growth, and survivorship of both invertebrates and fishes (Michaelidis *et al.*, 2005; Shirayama and Thornton, 2005; Pane and Barry, 2007), but by far the greatest threat of reducing pH is to organisms that build their external skeletal material out of calcium carbonate ($CaCO_3$). Calcifying organisms such as sea urchins, cold-water corals, coralline algae, and various plankton that reside in cooler temperate waters appear to be the most threatened by acidification, because CO_2 has greater solubility in cooler waters (Hoegh-Guldberg, 1999; Kleypas *et al.*, 1999; Hughes *et al.*, 2003; Feely *et al.*, 2004; Kleypas and Langdon, 2006).

The response of corals and coral reefs to ocean acidification has received substantial attention, and results show that lowering pH results in significant reductions in calcification rates in both reef-building corals and coralline algae (Kleypas *et al.*, 1999; Feely *et al.*, 2004; Orr *et al.*, 2005; Kleypas and Langdon, 2006). Declines in calcification rates of 17–35% by the year 2100 have been estimated based on projected changes in the partial pressure of CO_2 (Hoegh-Guldberg, 1999; Kleypas *et al.*, 1999; Hughes *et al.*, 2003; Orr *et al.*, 2005). On the other hand, McNeil, Matear, and Barnes (2004) suggest that net coral reef calcification rates will increase with future ocean warming and exceed pre-industrial rates by the year 2100. Additional research is needed to resolve this issue. Because of the greater solubility of CO_2 in cooler waters, reefs at the latitudinal margins of coral reef development (*e.g.,* Florida Keys and Hawaiian Islands) may show the most rapid and dramatic response to changing pH.

Rising Sea Level

During the last 100 years, global average sea level has risen an estimated 1–2 mm per year and is expected to accelerate due to thermal expansion of the oceans and melting ice-sheets and glaciers (Cabanes, Cazenave, and Le Provost, 2001; Albritton and Filho, 2001; Rignot and Kanagaratnam, 2006; Chen, Wilson, and Tapley, 2006; Shepherd and Wingham, 2007; Bell *et al.*, 2007; IPCC, 2007c). Rates of sea level rise at a local scale vary from -2 to 10 mm per year along U.S. coastlines (Nicholls and Leatherman, 1996; Zervas, 2001; Scavia *et al.*, 2002). Low-lying areas, especially intertidal zones, along the eastern and Gulf coasts are at the greatest risk of damage from rising sea level (Scavia *et al.*, 2002). The consequences of sea level rise include inundation of coastal areas, erosion of vulnerable shorelines, and landward shifts in species distributions.

On undeveloped coasts with relatively gentle slopes, it is thought that plant communities such as mangroves and *Spartina* salt marshes will move inland as sea level rises (Scavia *et al.*, 2002; Harley *et al.*, 2006). In contrast, coastline development will interfere with these plant migrations (see the National Estuaries chapter, section 7.3.2, for further discussion). As a result, wetlands may become submerged and soils may become waterlogged, resulting in plant physiological stress due to chronic and intolerable elevated salinity. Marshes, mangroves and dune plants are critical to coastal environments because they produce and add nutrients to coastal systems, stabilize substrata, and serve as refuges and nurseries for many species. Their depletion or loss would therefore affect nutrient flux, energy flow, and essential habitat for a multitude of species, with ultimate long-term impacts on biodiversity (Scavia *et al.*, 2002; Galbraith *et al.*, 2002; Harley *et al.*, 2006). The projected 35–70% loss of barrier islands and intertidal and sandy beach habitat over the next 100 years could also drastically reduce nesting grounds for key species such as sea turtles and birds as these critical habitats disappear (Scavia *et al.*, 2002).

Climatic Variability and Ocean Circulation

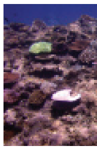
Natural climatic variability resulting from ocean-atmosphere interactions such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation/Northern Hemisphere Annular Mode result in changes in open ocean productivity, shifts in the distribution of organisms, and modifications in food webs that foreshadow potential consequences of accelerated climate change (*e.g.,* Mantua *et al.*, 1997; McGowan *et al.*, 1998). These recurring patterns of ocean-atmosphere variability have very different behaviors in time. For example, whereas ENSO events persist for 6–18 months and have their major impact in the tropics, the PDO occurs over a much longer time frame of 20–30 years and has primary effects in the northern Pacific (Mantua *et al.*, 1997). Regardless of the temporal scale and region of impact, however, these natural modes of climate variability have existed historically, independent of anthropogenically driven climate change. These climate phenomena may act in tandem with (or in opposition to) human-induced alterations, with consequences that are difficult to predict (Philip and Van Oldenborgh, 2006).

Ocean-atmosphere interactions on a warming planet may also result in long-term alterations in the prevailing current and upwelling patterns (Bakun, 1990; McPhaden and Zhang, 2002; Snyder *et al.*, 2003; McGregor *et al.*, 2007). While at present there is no clear indication that ocean circulation patterns have changed (Bindoff *et al.*, 2007), modifications could have large effects within and among ecosystems through impacts on ecosystem and community connectivity in terms of both nutrients and recruits (see section 8.3.1., Key Ecosystem Characteristics on Which Goals Depend). Considering that there is evidence for warming of Southern Ocean mode waters and Upper Circumpolar Deep Waters from 1960–2000, changes in oceanic current and upwelling patterns are likely in the future (Bindoff *et al.*, 2007). The direction that these changes will take, however, is not evident. For example, it has been hypothesized that the greater temperature differential between the land mass and ocean that will occur with climate warming will increase upwelling because of stronger alongshore winds (Bakun, 1990). In contrast, Gucinski, Lackey, and Spence (1990) proposed that warming at higher latitudes will reduce latitudinal temperature gradients, resulting in decreased wind strength and less upwelling; some models show potential for Atlantic thermohaline circulation to end abruptly if high-latitude waters are no longer able to sink (Stocker and Marchal, 2000).

Storm Intensity

Whether or not storm frequency has changed over time is not clear, due to large natural variability resulting from such climate drivers as ENSO (IPCC, 2007c). However, since the mid 1970s there has been a trend toward longer storm duration and greater storm intensity (IPCC, 2007c). An increase in storm intensity generally has impacts on two fronts. First, it may increase pulses of fresh water to coastal and nearshore habitats (see below). Second, increasing storm intensity may cause physical damage to coastal ecosystems, especially those in shallow water (IPCC, 2007c).

Recent hurricanes in the southern United States have caused extensive destruction to homes and businesses; altered nearshore water quality; scoured the ocean bottom; over-washed beaches; produced immense amounts of marine debris (wood, metals, plastics) and pollution (household hazardous wastes, pesticides, metals, oils and other toxic chemicals) from floodwaters; and damaged many mangrove, marsh, and coral reef areas (Davis *et al.*, 1994; Tilmant *et al.*, 1994; McCoy *et al.*, 1996; Lovelace and MacPherson, 1998; Baldwin *et al.*, 2001).[31] Even 30–60 days after



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[31] See also **U.S. Fish and Wildlife Service**, 2005: U.S. Fish and Wildlife Service conducting initial damage assessments to wildlife and National Wildlife Refuges. http://www.fws.gov/southeast/news/2005/r05-088.html.

storms, some areas still experienced increased turbidity, breakdown of mangrove peat soils, and elevated concentrations of ammonia, dissolved phosphate, and dissolved organic carbon (Davis *et al*., 1994; Tilmant *et al*., 1994; Lovelace and MacPherson, 1998). In some instances, algal blooms from high nutrients further increased turbidity while driving down dissolved-oxygen concentrations (*i.e.,* caused eutrophication), resulting in mortalities in fish and invertebrate populations (Tilmant *et al*., 1994; Lovelace and MacPherson, 1998). Given that most climate change models project increasing storm intensity as well as higher sea levels in many areas, it is evident that low-lying and shallow marine ecosystems such as mangroves, salt marshes, seagrasses, and coral reefs are at greatest risk of long-term damage.

Freshwater Influx

Observations indicate that changes in the amount, intensity, frequency, and type of precipitation are occurring worldwide (IPCC, 2007c). Consistent with observed changes in precipitation and water transport in the atmosphere, large-scale trends in oceanic salinity have become evident for the period 1955–1998 (Bindoff *et al*., 2007). These trends are manifested as lowered salinities at subpolar latitudes and increased salinities in shallower parts of the tropical and subtropical oceans.

In addition to altering salinity in major oceanic water masses, changes in precipitation patterns can have significant impacts in estuarine and other nearshore environments (see the National Estuaries chapter, section 7.3.4.2.9). For instance, in regions where climate change results in elevated rainfall, increased runoff may cause greater stratification of water layers within estuaries as fresh water floats out on top of higher salinity layers (Scavia *et al.*, 2002). One consequence of this stratification may be less water column mixing and thus lower rates of nutrient exchange among water layers. Combining this stratification effect with shorter water residence times stemming from higher inflow (Moore *et al*., 1997) may result in significantly reduced productivity because phytoplankton populations may be flushed from the system at a rate faster than they can grow and reproduce. On the other hand, estuaries that are located in regions with lower rainfall may also show decreased productivity due to lower nutrient influx. Thus, the relationship between precipitation and marine ecosystem health is complex and difficult to predict.

Another source of fresh water is melting of polar ice (IPCC, 2007c). In the Atlantic Ocean, accelerated melting of Arctic ice and the Greenland ice sheet are predicted to continue producing more freshwater inputs that may alter oceanic circulation patterns (Dickson *et al*., 2002; Curry, Dickson, and Yashayaev, 2003; Curry and Mauritzen, 2005; Peterson *et al*., 2006; Greene and Pershing, 2007; Boessenkool *et al*., 2007).

8.3.2.2 Climate Change Interactions with "Traditional" Stressors of Concern

Pollution

Marine water quality degradation and pollution stem primarily from land-based sources, with major contributions to coastal watershed and water quality deterioration falling into two broad categories: point-source pollution and non-point-source pollution. Point-source pollution from factories, sewage treatment plants, and farms often flows into nearby waters. In contrast, marine non-point-source pollution originates from coastal urban runoff where the bulk of the land is paved or covered with buildings. These impervious surfaces prevent soils from capturing runoff, resulting in the input of untreated pollutants (*e.g.,* fuels, oils, plastics, metals, insecticides, antibiotics) to coastal waters. Increased terrestrial runoff due to more intense storm events associated with climate change may increase land-based water pollution from both of these sources. In some areas, increased groundwater outflows may also contribute to coastal pollution.

Deterioration and pollution of coastal watersheds can have far-reaching effects on marine ecosystems. As an example, the Gulf of Mexico "dead zone" that occurs each summer and extends from the Mississippi River bird-foot delta across the Louisiana shelf and onto the upper Texas coast can range from 1–125 km offshore (Rabalais, Turner, and Wiseman Jr, 2002). This mass of hypoxic (low-oxygen) water has its origins in the increased nitrate flux coincident with the exponential growth of fertilizer use that has occurred since the 1950s in the Mississippi River basin. This hypoxia results in changes in species diversity and community structure of the benthos and has impacts on trophic links that include higher-order consumers in the pelagic zone (Rabalais, Turner, and Wiseman Jr, 2002).

Until recently, pollution has been the major driver of decreases in the health of marine ecosystems such as coral reefs, seagrass beds, and kelp forests (Jackson *et al.*, 2001; Hughes *et al.*, 2003; Pandolfi *et al.*, 2003). Because pollution is usually more local in scope, it historically could be managed within individual MPAs; however, the addition of climate change stressors such as increased oceanic temperature, decreased pH, and greater fluctuations in salinity present greater challenges with regard to potentially deleterious effects of pollution (Coe and Rogers, 1997; Carpenter *et al.*, 1998; Khamer, Bouya, and Ronneau, 2000; Burton, Jr. and Pitt, 2001; Sobel and Dahlgren, 2004; Orr *et al.*, 2005; Breitburg and Riedel, 2005; O'Connor *et al.*, 2007; IPCC, 2007c). Also, in regions where climate change causes precipitation and freshwater influxes to increase, MPA managers may need to expand the scale at which they attempt to address issues of water quality, for example by forging stronger partnerships with organizations involved in watershed management both nearby and at more-distant locations.

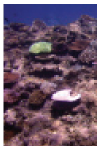
For example, coral bleaching from the combined stresses of climate change and local pollution (*e.g.,* high temperature and sedimentation) have already been observed (Jackson *et al.*, 2001; Hughes *et al.*, 2003; Pandolfi *et al.*, 2003). Identifying those stressors with the greatest effect is not trivial. Research in coral genomics may provide diagnostic tools for identifying stressors in coral reefs and other marine communities (*e.g.,* Edge *et al.*, 2005).

Commercial Fishing and Aquaculture

Commercial fishing has ecosystem effects on three fronts: through physical impacts of fishing gear on habitat, overfishing of commercial stocks, and incidental take of non-targeted species. The use of trawls, seines, mollusk dredges, and other fishing gear can cause damage to living seafloor structures and alterations to geologic structures, reducing habitat complexity (Engel and Kvitek, 1998; Thrush and Dayton, 2002; Dayton, Thrush, and Coleman, 2002; Hixon and Tissot, 2007). Overfishing is also common in the United States, with a conservative estimate of 26% of fisheries overexploited (Pauly *et al.*, 1998; National Research Council, 1999; Jackson *et al.*, 2001; Pew Oceans Commission, 2003; National Marine Fisheries Service, 2005; Lotze *et al.*, 2006). Meanwhile, non-specific fishing gear (*e.g.,* trawls, seines, dredges) causes considerable mortality of by-catch that includes invertebrates, fishes, sea turtles, marine mammals, birds, and early life stages of commercially targeted species (Condrey and Fuller, 1992; Norse, 1993; Sobel and Dahlgren, 2004; Hiddink, Jennings, and Kaiser, 2006).

Aquaculture has sometimes been introduced to augment fisheries production. Unfortunately, experiences in countries such as Southeast Asia show that aquaculture can have negative environmental impacts, including extensive mangrove and coastal wetland conversion to ponds, changes in hydrologic regimes, and discharge of high levels of organic matter and pollutants into coastal waters (Eng, Paw, and Guarin, 1989; Iwama, 1991; Naylor *et al.*, 2000). Furthermore, many aquacultural practices are not sustainable because farmed species consume natural resources at high rates and the intense culture environment (*e.g.*, overcrowding) creates conditions for disease outbreaks (Eng, Paw, and Guarin, 1989; Iwama, 1991; Pauly *et al.*, 2002; 2003).

Fishery populations that are overstressed and overfished exhibit greater sensitivity to climate change and other anthropogenically derived stressors than do healthy populations (Hughes *et al.*, 2005). Overfishing can reduce mean life span as well as lifetime reproductive success and larval quality, making fished species more susceptible to both short- and long-term perturbations (such as changes in prevailing current patterns) that affect recruitment success (Pauly *et al.*, 1998; Jackson *et al.*, 2001; Dayton, Thrush, and Coleman, 2002; Pauly *et al.*, 2003; Sobel and Dahlgren, 2004; Estes, 2005; Law and Stokes, 2005; Steneck and Sala, 2005; O'Connor *et al.*, 2007). Changing climatic regimes can also influence species' distributions, which are set by physiological tolerances to temperature, precipitation, dissolved oxygen, pH, and salinity. Because rates of climate change appear to exceed the capacity of many commercial species to adapt, species will shift their ranges in accordance with their physiological thresholds and may ultimately be forced to extend past the boundaries of their "known" native range,



becoming invasive elements (Murawski, 1993; Walther *et al.*, 2002; Roessig *et al.*, 2004; Perry *et al.*, 2005; Harley *et al.*, 2006).

Commercial exploitation of even a single keystone species, such as a top consumer, can destabilize ecosystems by decreasing redundancy and making them more susceptible to climate change stressors (Hughes *et al.*, 2005). Examples of such ecosystem destabilization through overfishing abound, including the formerly cod-dominated system of the western North Atlantic (see Box 8.2), and the fish-grazing community on Caribbean coral reefs (*e.g.*, Frank *et al.*, 2005; Mumby *et al.*, 2006; 2007).

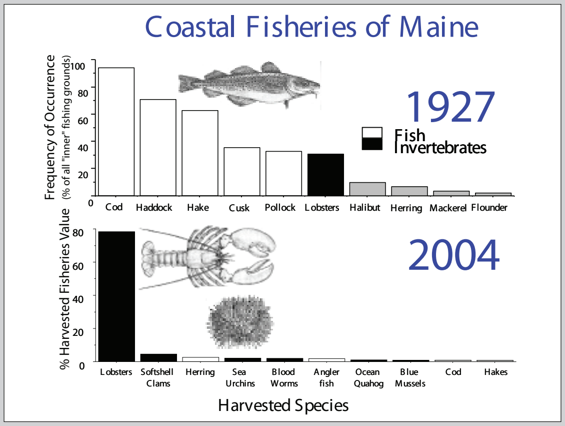
Interestingly, the theoretical framework that links protection against overfishing using no-take marine reserves to improved coral condition is hotly debated (Jackson *et al.*, 2001; Grigg *et al.*, 2005; Pandolfi *et al.*, 2005; Aronson and Precht, 2006). This framework hinges on an increase in herbivory [directly, through reduced fishing pressure on herbivores, or indirectly, through cascading effects (Mumby *et al.*, 2006, 2007)] that then reduces algal growth that can compete with coral colonies or inhibit coral recruitment. The heat of the debate is perhaps surprising because of the strong intuitive sense such arguments make. However, reserves also protect predators, so declines in herbivorous

BOX 8.2. The Western North Atlantic Food Web.

Marine carnivores of the western North Atlantic were both more abundant and larger in the past. In Maine, archaeological evidence indicates that coastal people subsisted on Atlantic cod for at least 4,000 years (Jackson *et al.*, 2001).[32] Prey species such as lobsters and crabs were absent from excavated middens in the region, perhaps because large predators had eaten them (Steneck, Vavrinec, and Leland, 2004; Lotze *et al.*, 2006).

Today cod are ecologically extinct from western North Atlantic coastal zones due to overfishing. The abundant lobsters and sea urchins that had formerly been the prey of apex predators became the primary target of local fisheries. By 1993, the value of sea urchins harvested in Maine for their roe was second only to that of lobsters. As sea urchin populations declined, so too did communitywide rates of herbivory.[32] In less than a decade, sea urchins became so rare that they could no longer be found over large areas of the coast (Andrew *et al.*, 2002; Steneck, Vavrinec, and Leland, 2004).

These and other instances of "fishing down food webs" in the Gulf of Maine have resulted in hundreds of kilometers of coast now having dangerously low biological and economic diversity. Today, bloodworms used for bait are worth more to Maine's economy than cod (see figure). The trophic level dysfunction (*sensu* Steneck, Vavrinec, and Leland, 2004) of both apex predators and herbivores leave a coastal zone suited for crabs and especially lobsters—the latter attaining staggering population densities exceeding one per square meter along much of the coast of Maine (Steneck and Wilson, 2001). The economic value of lobsters is high, accounting for nearly 80% of the total value of Maine's fisheries as of 2004 (see figure). The remaining 42 harvested species account for the remaining 20%. If a disease such as the one that recently decimated Rhode Island's lobster stocks (Glenn and Pugh, 2006) infects lobsters in the Gulf of Maine, there will be serious socioeconomic implications for the fishing industry. Prospects for such a disease outbreak may increase because of climate-induced changes in the environment such as temperature increases that favor pathogen growth (Harvell *et al.*, 1999; 2002). The figure is adapted from Steneck and Carlton (2001).



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[32] See also **Steneck**, R.S., 1997: Fisheries-induced biological changes to the structure and function of the Gulf of Maine ecosystem. In: Proceedings of the Gulf of Maine Ecosystem Dynamics Scientific Symposium and Workshop, RARGOM Report 91-1, Regional Association for Research in the Gulf of Maine, Hanover, NH, pp. 151-165.

fish and/or herbivory might occur, as opposed to increases, unless an escape in size from predation occurs for herbivores as was observed in the in the Bahamas (Mumby *et al*., 2006). Also, data from field studies provide conflicting results on the role of herbivores. Mumby *et al.* (2006) showed that increased fish herbivory in a marine reserve reduced algal growth after mass bleaching caused extensive coral mortality. However, such herbivore densities (and presumably herbivory rates) do not always increase after protection is provided (Mosquera *et al*., 2000; Graham, Evans, and Russ, 2003; Micheli *et al*., 2004; Robertson *et al*., 2005). Further, there is widespread belief that the mass mortality of the sea urchin *Diadema antillarum*—a major grazer on reefs—in 1983–1984 was a significant proximal cause of coral reef decline throughout the Caribbean. However, as reported in Aronson and Precht (2006), half the coral reef decline throughout the Caribbean reported by Gardner *et al.* (2003) occurred before the die-off of *D. antillarum*, and immediately after the die-off coral cover remained unchanged (Fig. 8.5) (Gardner *et al*., 2003). Subsequent declines in cover throughout the region were due to coral bleaching (1987, 1997–1998) and disease. It is important to highlight this complexity, because it emphasizes how much is unknown about basic ecological processes on coral reefs and consequently how much needs to be learned about whether no-take marine reserves work effectively to enhance resilience when disease and bleaching remain significant sources of coral mortality (Aronson and Precht, 2006).

Nonindigenous/Invasive Species

Invasive species threaten all marine and estuarine communities. Currently, an estimated 2% of extinctions in marine ecosystems are related to invasive species while 6% are the result of other factors, including climate change, pollution, and disease (Dulvy, Sadovy, and Reynolds, 2003). Principal mechanisms of introduction vary and have occurred via both accidental and intentional release (Ruiz *et al*., 2000; Carlton, 2000).[33] Invasive species are often opportunistic and can force shifts in the relative abundance and distribution of native species, and cause significant changes in species richness and community structure (Sousa, 1984; Moyle, 1986; Mills, Soulé, and Doak, 1993; Baltz and Moyle, 1993; Carlton, 1996; Carlton, 2000; Marchetti, Moyle, and Levine, 2004).

Some native species, particularly rare and endangered ones with small population sizes and gene pools, are unlikely to be able to adapt quickly enough or shift their ranges rapidly enough to compensate for the changing climatic regimes proposed by current climate change models (IPCC, 2007c). These native species will likely have their competitive abilities compromised and be more susceptible to displacement by invasive species, and therefore should be considered for stronger protective

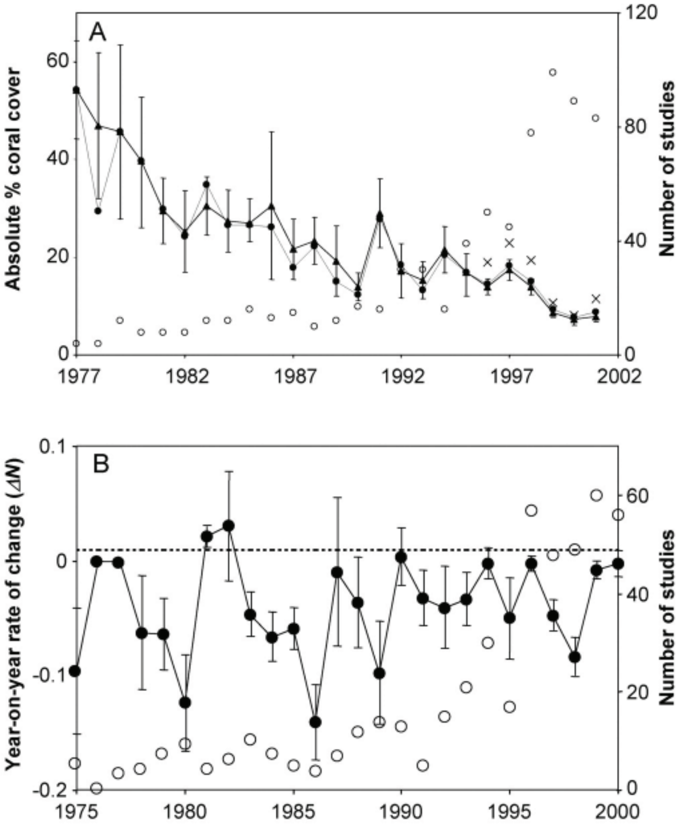
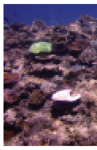


Figure 8.5. Total observed change in coral cover (%) across the Caribbean basin over the past 25 years (From Gardner *et al.*, 2003. Reprinted with permission from AAAS). A. Coral cover (%) 1977-2001. Annual estimates (▲) are weighted means with 95% bootstrap confidence intervals. Also shown are unweighted estimates (●), unweighted mean coral cover with the Florida Keys Coral Reef Monitoring Project (1996-2001) omitted (x), and the number of studies each year (○). B. Year-on-year rate of change (mean ΔN ± SE) in coral cover (%) for all sites reporting two consecutive years of data 1975-2000 (●) and the number of studies for each two-year period (○).



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[33] See also **Hare**, J.A. and P.E. Whitfield, 2003: *An Integrated Assessment of the Introduction of Lionfish (Pterois Volitans/Miles Complex) to the Western Atlantic Ocean*. NOAA Technical Memorandum NOS NCCOS 2, pp.1-21.

measures by MPA managers. Increased seawater temperatures resulting from climate change may also allow introduced species to spawn earlier and for longer periods of the year, thus increasing their population growth rates relative to natives while simultaneously expanding their range (Carlton, 2000; McCarty, 2001; Stachowicz *et al.*, 2002; Marchetti, Moyle, and Levine, 2004). Furthermore, the same characteristics that make species successful invaders may also pre-adapt them to respond to, and capitalize on, climate change. As one example, Indo-Pacific lionfish (*Pterois volitans* and *P. miles*) are now widely distributed off the southeastern coast of the United States and in the Bahamas less than 10 years after being first observed off Florida (Whitfield *et al.*, 2007; Snyder and Burgess, 2007). One of the few factors limiting their spread is intolerance to minimum water temperatures during winter (Kimball *et al.*, 2004). Ocean warming could facilitate depth and range expansion in these species.

Diseases

Disease outbreaks alter the structure and function of marine ecosystems by affecting the abundance and diversity of vertebrates (*e.g.,* mammals, turtles, fish), invertebrates (*e.g.,* corals, crustaceans, echinoderms, oysters), and plants (*e.g.,* seagrasses, kelps). Pathogen outbreaks or epidemics spread rapidly, due to the lack of dispersal barriers in some parts of the ocean and the potential for long-term survival of pathogens outside the host (Harvell *et al.*, 1999; Harvell *et al.*, 2002). Many pathogens of marine taxa such as coral viruses, bacteria, and fungi are positively responsive to temperature increases within their physiological thresholds (Porter *et al.*, 2001; Kim and Harvell, 2004; Munn, 2006; Mydlarz, Jones, and Harvell, 2006; Boyett, Bourne, and Willis, 2007). However, it is noteworthy that white-band disease was the primary cause (though not the only cause) of reduced coral cover on Caribbean reefs from the late 1970s through the early 1990s (Aronson and Precht, 2006). That outbreak did not correspond to a period of particularly elevated temperature (Lesser *et al.*, 2007).

Exposure to disease compromises the ability of species to resist other anthropogenic stressors, and exposure to other stressors compromises species' ability to resist disease (Harvell *et al.*, 1999; Harvell *et al.*, 2002). For example, in 1998, the most geographically extensive and severe coral bleaching ever recorded was associated with the high sea surface temperature anomalies facilitated by an ENSO event (Hoegh-Guldberg, 1999; Wilkinson *et al.*, 1999; Mydlarz, Jones, and Harvell, 2006). In some species of reef-building corals and gorgonians, this bleaching event was thought to be accelerated by opportunistic infections (Harvell *et al.*, 1999; Harvell *et al.*, 2001). Several pathogens—such as bacteria, viruses, and fungi that infect such diverse hosts as seals, abalone, and starfish—show possible onset with warmer temperatures (reviewed in Harvell *et al.*, 2002), and some coral species may become more susceptible to disease after bleaching events (Whelan *et al.*, 2007). The mechanisms for pathogenesis, however, are largely unknown. Given that exposure to multiple stressors may compromise the ability of marine species to resist infection, the most effective means of reducing disease incidence under climate change may be to minimize impacts of stressors such as pollution and overfishing.

8.3.3 Management Approaches and Sensitivity of Management Goals to Climate Change

Marine protected area programs have been identified as a critical mechanism for protecting marine biodiversity and associated ecosystem services (National Research Council, 2001; Palumbi, 2002; Roberts *et al.*, 2003a; Sobel and Dahlgren, 2004; Palumbi, 2004; Roberts, 2005; Salm, Done, and McLeod, 2006).[34] MPA networks are being implemented globally to address multiple threats to the marine environment, and are generally accepted as an improvement over individual MPAs (Salm, Clark, and Siirila, 2000; Allison *et al.*, 2003; Roberts *et al.*, 2003a; Mora *et al.*, 2006).[21] Networks are more effective than single MPAs at protecting the full range of habitat and community types because they spread the risk of losing a habitat or community type following a disturbance such as a climate-change impact across a larger area. Networks are better able than individual MPAs to protect both short- and long-distance dispersers, and thus have more

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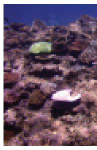
[34] See also **Ballantine**, B., 1997: Design principles for systems of no-take marine reserves. Proceedings of the the design and monitoring of marine reserves, Fisheries Center, University of British Colombia, Vancouver.

potential to achieve conservation and fishery objectives (Roberts, 1997a). Networks provide enhanced larval recruitment among adjacent MPAs that are linked by local and regional dispersal patterns, enhanced protection of critical life stages, and enhanced protection of critical processes and functions, *e.g.,* migration corridors (Gerber and Heppell, 2004). Finally, networks allow for protection of marine ecosystems at an appropriate scale. A network of MPAs could cover a large gradient of biogeographic and oceanographic conditions without the need to establish one extremely large reserve, and can provide more inclusive representation of stakeholders (National Research Council, 2001; Hansen, Biringer, and Hoffman, 2003).

While MPA networks are considered a critical management tool for conserving marine biodiversity, they must be established in conjunction with other management strategies to be effective (Hughes *et al*., 2003). MPAs are vulnerable to activities beyond their boundaries. For example, uncontrolled pollution and unsustainable fishing outside protected areas can adversely affect species and ecosystem function within the protected area (Kaiser, 2005). Therefore, MPA networks should be established considering other forms of fisheries management (*e.g.,* catch limits and gear restrictions) (Allison, Lubchenco, and Carr, 1998; Beger, Jones, and Munday, 2003; Kaiser, 2005), as well as coastal management to control land-based threats such as pollution and sedimentation (Cho, 2005). In the long term, the most effective configuration would be a network of highly protected areas nested within a broader management framework (Salm, Done, and McLeod, 2006). Such a framework might include an extensive multiple-use area managed for sustainable fisheries as well as protection of biodiversity, integrated with coastal management regimes, where appropriate, to enable effective control of threats originating upstream and to maintain high water quality (*e.g.,* Done and Reichelt, 1998).

The National Marine Sanctuary Program has developed a set of goals (Box 8.1) to help clarify the relationship between operations at individual sanctuaries and the broad directives of the National Marine Sanctuaries Act. A subset of these goals (Goals 1, 4, 5, and 6) are relevant to resource protection and climate change. Box 8.3 expands upon Goals 1, 4, 5, and 6 to display their attendant objectives, which provide guidance for management plans that are developed by sanctuary sites (see Table 8.3). Sanctuary management plans are developed and subsequently reviewed and revised on a five-year cycle as a collaboration between sanctuary staff and local communities. After threats and stressors to resources are identified, action plans are prepared that identify activities to address them. Threats and stressors may include such things as overexploitation of natural resources, degraded water quality, and habitat damage and destruction. Sanctuary management plans are designed to address additional issues raised by local communities, such as user conflicts, needs for education and outreach, and interest in volunteer programs.

Highly protected marine reserves within national marine sanctuaries have been implemented at some sites (*e.g.,* Channel Islands and the Florida Keys; Keller and Causey, 2005) to reduce fishing pressure, restore ecosystem structure and function, and protect biodiversity; the entire area of the Papahānaumokuākea Marine National Monument will become no-take within five years. These additional protective actions complement existing fishery regulations. Some sites, such as Monterey Bay and the Florida Keys, have Water Quality Protection Programs to address issues such as watershed pollution, vessel discharges, and, in the case of the Florida Keys, wastewater and stormwater treatment systems. Habitat damage may be addressed using waterway marking programs to reduce vessel groundings and mooring buoys to minimize anchor damage. Many of these activities are supported through education and outreach programs to inform the public, volunteer programs to help distribute information (*e.g.,* Team OCEAN[35]), and law enforcement.



Sanctuary management plans are intended to be comprehensive, and may take years of community involvement to develop. For example, it took more than five years to develop the management plan for the Florida Keys

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[35] **Florida Keys National Marine Sanctuary**, 2003: Florida Keys NMS Team OCEAN. Florida Keys National Marine Sanctuary Webpage, http://floridakeys.noaa.gov/edu/ocean.html, accessed on 5-21-2007.

BOX 8.3. Draft Objectives of the Goals of the National Marine Sanctuary Program That Are Relevant to Resource Protection and Climate Change (Goals 1, 4, 5, and 6 from Box 8.1).*

Goal 1: Protect Resources.

Objective 1. Prepare sanctuary-specific management plans and regional and national programs and policies that utilize all program capacities to protect and manage resources.
Objective 2. Conduct and maintain routine contingency planning, emergency response, damage assessment, and restoration activities to preserve and restore the integrity of sanctuary ecosystems.
Objective 3. Develop and maintain enforcement programs and partnerships to maximize protection of sanctuary resources.
Objective 4. Review and evaluate the NMSP's effectiveness at site, regional, and national levels, through both internal and external mechanisms.
Objective 5. Anticipate, characterize, and mitigate threats to resources.
Objective 6. Assess and predict changes in the NMSP's operating, natural, and social environments, and evolve sanctuary management strategies to address them through management plan reviews, reauthorizations, and program regulatory review.
Objective 7. Designate new sanctuaries, as appropriate, to ensure the nation's marine ecosystems and networks achieve national expectations for sustainability.

Goal 4: Improve Sanctuary Science.

Objective 1. Expand observing systems and monitoring efforts within and near national marine sanctuaries to fill important gaps in the knowledge and understanding of the ocean and Great Lakes ecosystems.
Objective 2. Support directed research activities that support management decision making on challenges and opportunities facing sanctuary ecosystems, processes, and resources.
Objective 3. Develop comprehensive characterization products of ocean and Great Lakes ecosystems, processes, and resources.

Goal 5: Facilitate Compatible Use.

Objective 1. Work closely with partners, interested parties, community members, stakeholders, and government agencies to assess and manage human use of sanctuary resources.
Objective 2. Create, operate, and support community-based sanctuary advisory councils to assist and advise sites and the overall program in the management of their resources, and to serve as liaisons to the community.
Objective 3. Consult and coordinate with federal agencies and other partners conducting activities in or near sanctuaries.
Objective 4. Use other tools such as policy development, permitting, and regulatory review and improvement to help guide human use of sanctuary resources.

Goal 6: Improve International Work.

Objective 1. Develop multilateral program relationships to interact with, share knowledge and experience with, and learn from international partners to improve the NMSP's management capacity, and bring new experiences to MPA management in the United States.
Objective 2. Investigate the use of international legal conventions and other instruments to help protect sanctuary resources, including those that are transboundary or shared.
Objective 3. Cooperate to the extent possible with global research initiatives in order to improve the overall understanding of the ocean.
Objective 4. Make NMSP education and awareness programs accessible through international efforts to increase the global population's awareness of ocean issues.

* Additional goals of the NMSP are in Box 8.1.

National Marine Sanctuary (Keller and Causey, 2005), and an additional three years were required to prepare a supplemental plan for the Tortugas Ecological Reserve (Cowie-Haskell and Delaney, 2003; Delaney, 2003). However, the focus of sanctuary management plans has been on local stressors and not on additional impacts of climate change. As suggested below, climate change will need to be included in MPA planning, management, and evaluation.

Effective management and preservation of ecosystem characteristics in the face of climate change projections is relevant to achieving NMSP Goals 1, 2, 4, and 5 (Box 8.1). The NMSP is a leader in the use of stakeholders in the development of new management approaches (Sanctuary Advisory Councils and public scoping meetings at the site level). This model of public involvement should serve well as management strategies adapt under the stresses of climate change. Exporting lessons learned to the general public, managers of other MPAs, and the international community will further address NMSP Goals 2, 3, and 6.

An additional approach of the NMSP that should further efforts toward adaptive management in the context of climate change is the development of performance measures to help evaluate the success of the program (Box 8.4). Although climate change stressors are not yet explicitly addressed in these performance measures, attainment of a number of these measures clearly will be increasingly affected by climate change. The performance-measure approach should encourage sanctuary managers to address climate change impacts using the public processes of Sanctuary Advisory Councils and public scoping meetings. In addition, national marine sanctuaries are preparing Condition Reports,[36] which provide summaries of resources, pressures on resources, current condition and trends, and management responses to pressures that threaten the integrity of the marine environment. These reports will provide opportunities for sanctuaries to evaluate climate change as a pressure, and identify management responses on a site-by-site basis as well as across the system of national marine sanctuaries.

8.4 ADAPTING TO CLIMATE CHANGE

MPA managers can respond to challenges of climate change at two scales: actions at individual sites and implementing MPA networks. At particular MPAs, managers can increase efforts to ameliorate existing anthropogenic stressors with a goal of reducing the overall load of multiple stressors (Breitburg and Riedel, 2005). For example, the concept of protecting or enhancing coral reef resilience has been proposed to help ameliorate negative consequences of coral bleaching (Hughes *et al.*, 2003; Hughes *et al.*, 2005; Marshall and Shuttenberg, 2006). Under this approach, resilience is an ecosystem property that can be managed and is defined as the ability of an ecosystem to resist or absorb disturbance without significantly degrading processes that determine community structure, or if

BOX 8.4. Draft Natural Resource Performance Measures of the National Marine Sanctuary Program.

2015: 12 sites with water quality being maintained or improved.

2015: 12 sites with habitat being maintained or improved.

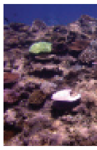
2015: 12 sites with living marine resources being maintained or improved.

2010: 100% of the System is adequately characterized.

2010: 6 sites are achieving or maintaining an optimal management rating on the NMSP Report Card.

2007: 100% of NMSP permits are handled in a timely fashion and correctly.

2010: 100% of sites with zones in place are assessing them for effectiveness.



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[36] **National Marine Sanctuary Program**, 5-21-2007: National Marine Sanctuaries condition reports. NOAA Website, http://sanctuaries.noaa.gov/science/condition/, accessed on 7-27-2007.

alterations occur, recovery is *not* to an alternate community state (Gunderson, 2000; Nyström, Folke, and Moberg, 2000; Hughes *et al.*, 2003). In short, managing for resilience includes dealing with causes of coral reef disturbance and decline that managers can address at local and regional levels, such as overfishing and pollution. These are the things that managers would want to do anyway, even if climate change were not a threat, because these activities help to maintain the ecological and economic value of ecosystems.

In addition to the approach of ameliorating existing stressors, MPA managers can protect putatively resistant and potentially resilient areas, develop networks of MPAs, and integrate climate change into planning efforts. Specific examples of adaptation options from across these approaches are presented in Box 8.5 and elaborated upon further in the sections that follow.

It is important to emphasize that variable and complex effects of climate on oceanographic processes and production (Soto, 2001; Mann and Lazier, 2006) present MPA managers with major uncertainties about climate change impacts and effective management approaches. An excellent discussion of uncertainty and scenario-based planning is provided in the National Parks chapter, sections 4.4.1 and 4.4.2.

BOX 8.5. Marine Protected Areas: Adaptation Options for Resource Managers.

- Manage human stressors such as overfishing and excessive inputs of nutrients, sediments, and pollutants within MPAs.
- Improve water quality by raising awareness of adverse effects of land-based activities on marine environments, implementing integrated coastal and watershed management, and developing options for advanced wastewater treatment.
- Manage functional species groups necessary to maintaining the health of reefs and other ecosystems.
- Identify and protect areas that appear to be resistant to climate change effects or to recover from climate-induced disturbances.
- Identify and protect ecologically significant ("critical") areas such as nursery grounds, spawning grounds, and areas of high species diversity.
- Identify ecological connections among ecosystems and use them to inform the design of MPAs and management decisions such as protecting resistant areas to ensure sources of recruitment for recovery of populations in damaged areas.
- Design MPAs with dynamic boundaries and buffers to protect breeding and foraging habits of highly migratory and pelagic species.
- Establish dynamic MPAs defined by large-scale oceanographic features, such as oceanic fronts, where changes in types and abundances of organisms often occur.
- Maximize habitat heterogeneity within MPAs and consider protecting larger areas to preserve biodiversity, ecological connections among habitats, and ecological functions.
- Include entire ecological units (e.g., coral reefs with their associated mangroves and seagrasses) in MPA design to help maintain ecosystem function and resilience.
- Ensure that the full breadth of habitat types is protected (e.g., fringing reef, fore reef, back reef, patch reef).
- Replicate habitat types in multiple areas to spread risks associated with climate change.
- Monitor ecosystems and have rapid-response strategies prepared to assess ecological effects of extreme events as they occur.
- Following extreme events, consider whether actions should be taken to enhance natural recovery processes through active restoration.
- Consider mangrove restoration for potential benefits including shoreline protection, expansion of nursery habitat, and release of tannins and other dissolved organic compounds that may reduce photo-oxidative stress in corals.

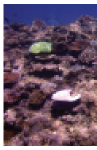
8.4.1 Ameliorate Existing Stressors in Coastal Waters

Managers may be able to increase resilience to climate change within MPAs by reducing impacts of local- and regional-scale stressors, such as overfishing; excessive inputs of nutrients, sediments, and pollutants; and degraded water quality. While this concept is logical and has considerable appeal, evidence in support of this approach is weak at best, which provides an excellent opportunity for adaptive-management research. Kelp forest ecosystems in marine reserves, where no fishing is allowed, are more resilient to ocean warming than those in areas where overfishing occurs (Behrens and Lafferty, 2004). This ecological response is a result of changes in trophic structure of communities in and around the reserves. When top predators such as spiny lobster are fished, their prey, herbivorous sea urchins, increase in abundance and consume giant kelp and other algae. When kelp forests are subjected to intense grazing by these herbivores, the density of kelp is reduced, sometimes becoming an "urchin barren," particularly during ocean warming events such as ENSO cycles. In reserves where fishing is prohibited, lobster populations were larger, urchin populations were diminished, and kelp forests persisted over a period of 20 years—including four ENSO cycles (Behrens and Lafferty, 2004).

Managing water quality has been identified as a key strategy for maintaining ecological resilience (Salm, Done, and McLeod, 2006).[37] In the Florida Keys National Marine Sanctuary and the Great Barrier Reef Marine Park, water quality protection is recognized as an essential component of management (U.S. Department of Commerce, 1996; The State of Queensland and Commonwealth of Australia, 2003; Grigg *et al.*, 2005, also see the Monterey Bay National Marine Sanctuary's water quality agreements with land-based agencies).[37] Strong circumstantial evidence exists linking poor water quality to increased macroalgal abundances, internal bioerosion, and susceptibility to some diseases in corals and octocorals (Fabricius and De'ath, 2004). Addressing sources of pollution—especially nutrient enrichment, which can lead to increased algal growth and reduced coral settlement—is critical to maintaining ecosystem health. In addition to controlling point-source pollution within an MPA, managers must also link their MPAs into the governance system of adjacent areas to control sources of pollution beyond the MPA boundaries (*e.g.*, Crowder *et al.*, 2006). Further actions necessary to improve water quality include raising awareness of how land-based activities can adversely affect adjacent marine environments, implementing programs for integrated coastal and watershed management, and developing options for advanced wastewater treatment (The Group of Experts on Scientific Aspects of Marine Environmental Protection, 2001).

Managers may be able to build resilience to climate change into MPA management strategies by protecting marine habitats such as coral reefs and mangroves from direct threats such as pollution, sedimentation, destructive fishing, and overfishing. Therefore, managers should continue to develop and implement strategies to reduce land-based pollution, decrease nutrient and sediment runoff, eliminate the use of persistent pesticides, and increase filtration of effluent to improve water quality. As noted above, the efficacy of these measures needs research in an adaptive-management context.

Another mechanism that may maintain resilience is the management of functional groups, specifically herbivores (Hughes *et al.*, 2003; Bellwood *et al.*, 2004). Bellwood *et al.* (2004) identified three functional groups of herbivores that assist in maintaining coral reef resilience: bioeroders, grazers, and scrapers. These groups work together to break down dead coral, providing sites for recruitment, graze macroalgae, and reduce the development of algal turfs to generate relatively bare substratum for coral settlement. Algal biomass must be kept low to maintain healthy coral reefs (Sammarco, 1980; Hatcher and Larkum, 1983; Steneck and Dethier, 1994). Bellwood, Hughes, and Hoey (2006) identify the need to protect both the species that prevent phase shifts from coral-dominated to algal-dominated reefs and the species that help reefs recover from algal dominance. They suggest that while parrotfishes and surgeonfishes appear to play a critical role in preventing phase shifts to macroalgae, their ability to remove algae may be limited if a



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[37] **Monterey Bay National Marine Sanctuary**, 2007: Water quality protection program for the MBNMS. Monterey Bay National Marine Sanctuary Website, http://www.mbnms.nos.noaa.gov/resourcepro/water-pro.html, accessed on 5-23-2007.

phase shift to macroalgae has already occurred (Bellwood, Hughes, and Hoey, 2006). In their study on the Great Barrier Reef, the phase shift reversal from macroalgal-dominated to a coral- and epilithic algal-dominated state was driven by a single batfish species (*Platax pinnatus*), not grazing by dominant parrotfishes or surgeonfishes (Bellwood, Hughes, and Hoey, 2006). This finding highlights the need to protect the full range of species to maintain resilience, at least in some systems. For example, Ledlie *et al.* (2007) found that a shift from coral to algal dominance occurred at a marine reserve in the Seychelles after the 1998 mass coral bleaching event, despite the presence of abundant herbivorous fishes. Many herbivorous fishes avoid macroalgae, and more research on functional groups is needed.

Although protecting functional groups may be a component of MPA management to enhance resilience, understanding which groups should be protected requires a detailed knowledge of species and interactions that is not often available for all species. Therefore, managers should strive to maintain the maximum number of species in the absence of detailed data on ecological and species interactions. For example, for managing coral reefs, regional guidelines identifying key herbivores that reduce macroalgae and encourage coral reef settlement should be developed. For kelp forests, the opposite approach may apply—managers may need to identify key predators on herbivores and limit fishing on those predators to reduce herbivory and promote growth of healthy kelp forests. These guidelines should be field tested at different locations to verify the recommendations.

8.4.2 Protect Apparently Resistant and Potentially Resilient Areas

Marine ecosystems that contain biologically generated habitats face potential loss of habitat structure as climate change progresses (*e.g.,* coral reefs, seagrass beds, kelp forests, and deep coral communities) (see Hoegh-Guldberg, 1999; Steneck *et al.*, 2002; Roberts, Wheeler, and Freiwald, 2006; Orth *et al.*, 2006). As discussed earlier in this chapter, it is likely that climate change contributes to mass coral bleaching events (Reaser, Pomerance, and Thomas, 2000), which became recognized globally in 1997–1998 (Wilkinson, 1998; 2000) and have affected large regions in subsequent years (Wilkinson, 2002; 2004; Whelan *et al.*, 2007). The amount of live coral has declined dramatically in the Caribbean region over the past 30 years as a result of bleaching, diseases, and hurricanes (Gardner *et al.*, 2003; 2005). In the Florida Keys, fore-reef environments that formerly supported dense growths of coral are now nearly depauperate, and the highest coral cover is in patch reef environments (Porter *et al.*, 2002; Lirman and Fong, 2007). Irrespective of the mechanism—resistance, resilience, or exposure to relatively low levels of past environmental stress— these patch-reef environments might be good candidates for additional protective measures because they may have high potential to survive climate stress.

Done[38] (see also Marshall and Schuttenberg, 2006) presented a decision tree for identifying areas that would be suitable for MPAs under a climate change scenario. Two types of favorable outcomes included reefs that survived bleaching (*i.e.,* were resilient) and reefs that were not exposed to elevated sea surface temperatures (*e.g.,* may be located within refugia such as areas exposed to upwelling or cooler currents). This type of decision tree has already been adapted to guide site selection for mangroves (McLeod and Salm, 2006), and it could be extended further for other habitat types such as seagrass beds and kelp forests.

In addition, thermally stressed corals exhibit less bleaching and higher survival if they are shaded during periods of elevated temperatures (Hoegh-Guldberg *et al.*, 2007). On a small scale, MPA managers may be able to shade areas during bleaching events to reduce overall stress. On a larger scale, managers should protect mangrove shorelines and support restoration of areas where mangroves have been damaged or destroyed, because tannins and dissolved organic compounds from decaying mangrove vegetation contribute to absorbing light and reducing stress (Hallock, 2005) (see

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[38] **Done**, T., 2001: Scientific principles for establishing MPAs to alleviate coral bleaching and promote recovery. In: *Coral Bleaching and Marine Protected Areas. Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Bishop Museum, Honolulu, HI, 29-31 May 2001* [Salm, R.V. and S.L. Coles (eds.)]. Asia Pacific Coastal Marine Program Report # 0102, The Nature Conservancy, Honolulu, HI, pp. 60-66.

also section 8.4.3.1). Extensive discussions of coral bleaching and management responses are provided in Marshall and Schuttenberg (2006) and Johnson and Marshall (2007).

Because climate change impacts on marine systems are patchy (with reefs that avoid bleaching one year potentially bleaching the following year), it is essential that areas that appear to be resistant or resilient to climate change impacts be monitored and tested to ensure that they continue to provide benefits (see section 8.4.4.1 for more on monitoring and research). This allows managers to target potential refugia for MPA design now, while also monitoring these areas over time so that management can be modified as circumstances and habitats change.

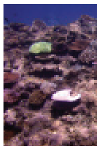
8.4.3 Develop Networks of MPAs

The concept of systems or networks of MPAs has considerable appeal because of emergent properties (*i.e.,* representation, replication, sustainability, connectivity) (National Research Council, 2001; Roberts *et al.*, 2003a),[21] spreading the risk of catastrophic habitat loss (Palumbi, 2002; Allison *et al.*, 2003), and the provision of functional wilderness areas sufficient to resist fundamental changes to entire ecosystems (Kaufman *et al.*, 2004). While MPA networks have been recognized as a valuable tool to conserve marine resources in the face of climate change, there have been a number of challenges to implementation (Pandolfi *et al.*, 2005; Mora *et al.*, 2006); nevertheless, a number of principles have been developed and are gradually being applied to aid MPA network design and implementation. These principles are described below.

8.4.3.1 Protect Critical Areas

Critical areas—areas that are biologically or ecologically significant—should be identified and included in MPAs. These critical areas include nursery grounds, spawning grounds, areas of high species diversity, areas that contain a variety of habitat types in close proximity to each other, and climate refugia (Allison, Lubchenco, and Carr, 1998; Sale *et al.*, 2005).[39] Coral assemblages that demonstrate resistance or resilience to climate change may be identified and provided additional protection to ensure a secure source of recruitment to support recovery in damaged areas. Managers can analyze how assemblages have responded to past bleaching events to assess possible resilience to climate change impacts. For example, some coral reefs resist bleaching due to genetic characteristics or avoid bleaching due to environmental factors. Managers can protect those that either resist or recover quickly from mass bleaching events, as well as those that are located in areas where physical conditions (*e.g.,* currents, shading) afford them some protection from temperature anomalies. Reefs that are resistant and reefs that are located in refugia from climate extremes may play a critical role in reef survival by providing a source of larvae for dispersal to and recovery of affected areas.[40] For coral reefs, indicators of potential refugia include a ratio of live to dead coral and a range of colony sizes and ages suggesting persistence over time. Refugia must be large enough to support high species richness to maximize their effectiveness as sources of recruits to replenish areas that have been damaged (Palumbi *et al.*, 1997; Bellwood and Hughes, 2001; Salm, Done, and McLeod, 2006).

Following extreme events, MPA managers should consider whether actions should be taken to enhance natural recovery processes through active restoration of biologically structured habitats. For example, damaged areas in seagrass beds may recover more rapidly if steps are taken to stabilize sediments (Whitfield *et al.*, 2002). Due to the loss of mangroves from many areas, mangrove restoration is another option for MPA managers that may have multiple benefits, including shoreline protection, expansion of nursery habitat (Nagelkerken, 2007), and release of tannins and other dissolved organic compounds that may reduce photo-oxidative stress in corals (Hallock, 2005).



8.4.3.2 Incorporate Connectivity in Planning MPA Networks

Connectivity is the natural linkage between marine habitats (Crowder *et al.*, 2000; Stewart,

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[39] See also **Sadovy**, Y., 2006: Protecting the spawning and nursery habitats of fish: the use of MPAs to safeguard critical life-history stages for marine life. *MPA News, International News and Analysis on Marine Protected Areas*, **8(2)**, 1-3.

[40] **Salm**, R.V. and S.L. Coles, 2001: *Coral Bleaching and Marine Protected Areas. Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Bishop Museum, Honolulu, HI, 29-31 May 2001.* Asia Pacific Coastal Marine Program Report #0102, The Nature Conservancy, Honolulu, HI, 118 pp.

Noyce, and Possingham, 2003; Roberts *et al.*, 2003b), which occurs through advection by ocean currents and includes larval dispersal and movements of adults and juveniles. Connectivity is an important part of ensuring larval exchange and the replenishment of populations in areas damaged by natural or human-related agents. Salm *et al.* (2006) recommend that patterns of connectivity be identified among source and sink reefs to inform reef selection in the design of MPA networks and enhance recovery following disturbance events. This principle applies to other marine systems, such as mangroves, as well. For example, healthy mangroves could be selected up-current from areas that may succumb to sea level rise, and areas could be selected that would be suitable habitat for mangroves in the future following sea level rise. These areas of healthy mangroves could provide secure sources of propagules to replenish down-current mangroves following a disturbance event.

A suspected benefit of MPAs is the dispersal of larvae to areas surrounding MPAs, but there are few data that can be used to estimate the exchange of larvae among local populations (Palumbi, 2004). Understanding larval dispersal and transport are critical to determining connectivity, and thus the design of MPAs. The size of an individual MPA should be based on the movement of adults of species of interest (Hastings and Botsford, 2003; Botsford, Micheli, and Hastings, 2003) and be large enough to contain the different habitats used and daily movements. The distance between adjacent MPAs should take into account the potential dispersal distances of larvae of fish, invertebrates, and other species of interest.[41]

One approach in MPA design has been to establish the size of MPAs based on the spatial scale of movements of adults of heavily fished species, and to space MPAs based on scales of larval dispersal (Palumbi, 2004). However, guidelines for the minimum size of MPAs and no-take reserves, and spacing between adjacent MPAs, vary dramatically depending on the goals for the MPAs (Hastings and Botsford, 2003). Friedlander *et al.* (2003) suggested that no-take zones should measure ca. 10 km^2 to ensure viable populations of a range of species in the Seaflower Biosphere Reserve, Colombia. Airamé *et al.* (2003) recommended a network of three to five no-take zones in each biogeographic region of the Channel Islands National Marine Sanctuary, comprising approximately 30–50% of the area, in order to conserve biodiversity and contribute to sustainable fisheries in the region.

Recent studies confirm that larval dispersal is more localized than previously thought, and short-lived species may require regular recruitment from oceanographically connected sites (Cowen, Paris, and Srinivasan, 2006; Steneck, 2006). Palumbi (2003) concluded that marine reserves tens of km apart may exchange larvae in a single generation. Shanks, Grantham, and Carr (2003) similarly concluded that marine reserves spaced 20 km apart would allow larvae to be carried to adjacent reserves. The Science Advisory Team to California's Marine Life Protection Act Initiative recommended spacing high protection MPAs, such as marine reserves, within 50–100 km in order to accommodate larval dispersal distances of a wide range of species of interest. Halpern *et al.* (2006) corroborated these estimates using an uncertainty-modeling approach.

No-take zones measuring a minimum of 20 km in diameter will accommodate short-distance dispersers in addition to including a significant proportion of local benthic fish species, thus generating fisheries benefits (Shanks, Grantham, and Carr, 2003; Fernandes *et al.*, 2005; Mora *et al.*, 2006). While this recommendation is likely to protect the majority of small benthic fish and benthic invertebrates, it is unlikely to protect large pelagic fish and large migratory species (Roberts *et al.*, 2003b; Palumbi, 2004). Recommendations to protect highly migratory and pelagic species include designing MPAs to protect predictable breeding and foraging habits, ensuring these have dynamic boundaries and extensive buffers, and establishing dynamic MPAs that are defined by the extent and location of large-scale oceanographic features, such as oceanic fronts, where changes in types and abundances of marine organisms often occur (Hyrenbach, Forney, and Dayton, 2000).

A system-wide approach should be taken that addresses patterns of connectivity among

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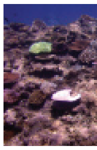
[41] **California Department of Fish and Game**, 2007: *California Marine Life Protection Act: Master Plan for MPAs.* California Department of Fish and Game.

ecosystems such as mangroves, coral reefs, and seagrass beds (Mumby *et al.*, 2004). For example, mangroves and seagrass beds in the Caribbean enhance the biomass of coral reef fish communities because they provide essential nursery habitat. Coral reefs can protect mangroves and seagress beds by buffering the impacts of wave erosion, while mangroves can protect reefs and seagrass beds from siltation. Thus, connectivity among functionally linked habitats helps maintain ecosystem function and resilience (Ogden and Gladfelter, 1983; Roberts, 1996; Nagelkerken *et al.*, 2000). Entire ecological units (*e.g.,* coral reefs with their associated mangroves and seagrasses) should be included in MPA design where possible. If entire biological units cannot be included, then larger areas should be chosen over smaller areas to accommodate local-scale recruitment.

Although maintaining connectivity within and between MPAs may help maintain marine biodiversity, ecosystem function, and resilience, many challenges exist. For example, the same currents and pathways that allow for larval recruitment following a disturbance event can expose an ecosystem to invasive species, pathogens, parasites, or pollutants, which can undermine the resilience of a system (McClanahan, Polunin, and Done, 2002). Numerous challenges also exist in estimating larval dispersal patterns. Although there have been detailed studies addressing dispersal *potential* of marine species based on their larval biology (*e.g.,* Shanks, Grantham, and Carr, 2003; Kinlan and Gaines, 2003), little is known about where in the oceans larvae go and how far they travel. A single network design is unlikely to satisfy the potential dispersal ranges for all species; Roberts *et al.* (2003b) recommended an approach using various sizes and spacing of MPAs in a network to accommodate the diversity of dispersal ranges. Larval duration in the plankton varies from minutes to years, and the more time that propagules spend in the water column, the farther they tend to be dispersed (Shanks, Grantham, and Carr, 2003; Steneck, 2006). Evidence from hydrodynamic models and genetic structure data indicates that, in addition to large variation of larval dispersal distances among species, the average scale of dispersal can vary widely—even within a given species—at different locations in space and time (*e.g.,* Cowen *et al.*, 2003; Sotka *et al.*, 2004; Engie and Klinger, 2007). Some information suggests long-distance dispersal is common, but other emerging information suggests that larval dispersal may be limited (Jones *et al.*, 1999; Swearer *et al.*, 1999; Warner, Swearer, and Caselle, 2000; Thorrold *et al.*, 2001; Palumbi, 2003; Paris and Cowen, 2004; Jones, Planes, and Thorrold, 2005). Additional research will be required to better understand where and how far larvae travel in various marine ecosystems.

8.4.3.3 Replicate Multiple Habitat Types in MPA Networks

Recognizing that the science underlying our understanding of resilience is developing and that climate change will not affect marine habitats and species equally everywhere, an element of risk spreading must be built into MPA design. To help avoid the loss of a particular habitat type, managers can protect multiple examples of all habitats (Hockey and Branch, 1994; Roberts *et al.*, 2001; Friedlander *et al.*, 2003; Roberts *et al.*, 2003b; Salm, Done, and McLeod, 2006; Wells, 2006).[21] For example, marine habitat types include coral reefs with varying degrees of exposure to wave energy (*e.g.,* offshore, mid-shelf, and inshore reefs), seagrass beds dominated by various seagrass species and in different environments, and a range of mangrove communities (riverine, basin, and fringe forests in areas of varying salinity, tidal fluctuation, and sea level) (Salm, Done, and McLeod, 2006). Reflecting the current federal goal of protecting at least 30% of lifetime stock spawning potential (Ault, Bohnsack, and Meester, 1998; National Marine Fisheries



Service, 2003), it has been recommended that more than 30% of appropriate habitats should be included in no-take zones (Bohnsack *et al.*, 2002). In 2004, the Great Barrier Reef Marine Park Authority increased the area of no-take zones from less than 5% to approximately 33% of the area of the Marine Park, ensuring that at least 20% of each bioregion (area of every region of biodiversity) was zoned as no-take (Fernandes *et al.*, 2005; Day *et al.*, 2002).

For both terrestrial and marine systems, species diversity often increases with habitat diversity, and species richness increases with habitat complexity; the greater the variety of habitats protected, the greater the biodiversity conserved (Friedlander *et al.*, 2003; Carr *et al.*, 2003). High species diversity may increase ecosystem resilience by ensuring sufficient redundancy to maintain ecological processes and protect against environmental disturbance (McNaughton, 1977; McClanahan, Polunin, and Done, 2002). This is particularly true in the context of additive or synergistic stressors. Maximizing habitat heterogeneity is critical for maintaining ecological health; thus MPAs should include large areas and depth gradients (Hansen, Biringer, and Hoffman, 2003; Roberts *et al.*, 2003a).[38] By protecting a representative range of habitat types and communities, MPAs have a higher potential to protect a region's biodiversity, biological connections between habitats, and ecological functions (Day *et al.*, 2002).

Replication of habitat types in multiple areas provides a further way to spread risks associated with climate change. If a habitat type is destroyed in one area, similar habitat in another area may provide larvae for recovery. While the number of replicates will be determined by a balance of desired representation and practical concerns such as funding and enforcement capacity (Airamé *et al.*, 2003), generally at least three to five replicates are recommended to effectively protect a particular habitat or community type (Airamé *et al.*, 2003; Roberts *et al.*, 2003b; Fernandes *et al.*, 2005). Wherever possible, multiple examples of each habitat type should be included in MPA networks or larger management frameworks such as multiple-use MPAs or areas under rigorous integrated management regimes (Salm, Done, and McLeod, 2006). This approach has the added advantage of protecting essential habitat for a wide variety of commercially valuable fish and macroinvertebrates.

While a risk-spreading approach to address the uncertainty of impacts of climate change makes practical sense, there are challenges to adequate representation. Managers must have classification maps (or local knowledge) of marine habitat types and communities to determine which representative examples should be included in MPA design. Replication of habitat types may not always be feasible due to limited monitoring and enforcement resources, conflicting needs of resource users, and existence of certain habitat types within an MPA.

8.4.4 Integrate Climate Change into MPA Planning, Management, and Evaluation

A number of tools exist to help managers address climate impacts and build resilience into MPA design and management. Ecological changes that are common in marine reserves worldwide and guidelines for marine reserve design are summarized in an educational booklet for policymakers, managers, and educators, entitled "The Science of Marine Reserves."[42] The Reef Resilience toolkit[43] provides marine resource managers with strategies to address coral bleaching and conserve reef fish spawning aggregations, helping to build resilience into coral reef conservation programs. "A Reef Manager's Guide to Coral Bleaching" provides information on the causes and consequences of coral bleaching and management strategies to help local and regional reef managers reduce this threat to coral reef ecosystems (Marshall and Shuttenberg, 2006). The application of some of these strategies is discussed in a recent report by the U.S. Environmental Protection Agency, which applies resilience theory in a case study for the reefs of American Samoa and proposes climate adaptation strategies that can be leveraged with existing local management plans,

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[42] **Partnership for Interdisciplinary Studies of Coastal Oceans**, 2005: The science of marine reserves. Partnership for Interdisciplinary Studies of Coastal Oceans Website, http://www.piscoweb.org/outreach/pubs/reserves, accessed on 5-23-2007.

[43] **The Nature Conservancy and Partners**, 2004: *R^2 - Reef Resilience: Building Resilience into Coral Reef Conservation; Additional Tools for Managers*. Volume 2.0. CD ROM Toolkit, The Nature Conservancy, http://www.reefresilience.org/.

processes, and mandates (U.S. Environmental Protection Agency, 2007).

In contrast, with regard to the impacts on marine organisms of reductions in ocean pH due to CO_2 emissions (Caldeira and Wickett, 2003), management strategies have not yet been developed. Adding chemicals to counter acidification is not a viable option, as it would likely be only partly effective and, if so, only at a very local scale (The Royal Society, 2005). Therefore, further research is needed on impacts of high concentrations of CO_2 in the oceans, possible acclimatization or evolution of organisms in response to changes in ocean chemistry, and how management might respond (The Royal Society, 2005).

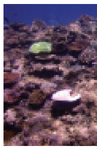
Determining management effectiveness is important for gauging the success of an MPA or network, and also can inform adaptive management strategies to address shortcomings in a particular MPA or network. To help managers improve the management of MPAs, the IUCN World Commission on Protected Areas and the World Wide Fund for Nature developed an MPA management effectiveness guidebook. This guidebook, "How is Your MPA Doing? A Guidebook of Natural and Social Indicators for Evaluating Marine Protected Area Management Effectiveness," helps managers and other decision-makers assess management effectiveness through the selection and use of biophysical, socioeconomic, and governance indicators.[44] The goal of the guidebook is to enhance the capability for adaptive management in MPAs. The "Framework for Measuring Success" (Parks and Salafsky, 2001) also provides a suite of tools to analyze community response to an MPA, and replicable methodologies to assess both social and ecological criteria.

National marine sanctuaries are preparing a series of Condition Reports for each site, which provide a summary of resources, pressures on those resources, current condition and trends, and management responses to the pressures.[36] This information is intended to be used in reviews of management plans and to help sanctuary staff identify monitoring, characterization, and research priorities to address gaps, day-to-day information needs, and new threats.

Managers in the United States can benefit from the example set by the Great Barrier Reef Marine Park Authority (GBRMPA), which is implementing a Climate Change Response Program[45] designed to: (1) understand climate change implications for the Great Barrier Reef; (2) share knowledge about climate change impacts and response options; (3) encourage and support reductions in greenhouse gas emissions; (4) maximize resilience of the Great Barrier Reef ecosystem; and (5) encourage and support Great Barrier Reef communities and industries to adapt to climate change. To further several of these objectives, GBRMPA has published a thorough assessment of vulnerabilities to climate change (Johnson and Marshall, 2007). This approach is a model for MPAs to consider worldwide.

8.4.4.1 MPA Monitoring and Research

MPAs must be effectively monitored to ensure the success of MPA design and management. If MPA design and management are not successful, then adaptations need to be made to meet the challenges posed by anthropogenic and natural stresses. As the number of pristine areas is decreasing rapidly, establishing baseline data for marine habitats is urgent and essential. Once baseline data are established, managers should monitor to determine the effects of climate change on local resources and populations. Retrospective testing of resistance to climate change impacts is difficult, so rapid response strategies should be in place to assess ecological effects of extreme events as they occur. For coral reefs, coral bleaching patterns either disappear with time or become confounded with other causes of mortality, such as predation by the crown-of-thorns starfish, disease, or multiple other stressors (Salm, Done, and McLeod, 2006). Therefore, response strategies must be implemented immediately following a



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[44] **Pomeroy**, R.S., J.E. Parks, and L.M. Watson, 2004: *How Is Your MPA Doing? A Guidebook of Natural and Social Indicators for Evaluating Marine Protected Area Management Effectiveness*. http://effectivempa.noaa.gov/guidebook/guidebook.html, International Union for Conservation of Nature and Natural Resources, The World Conservation Union, Gland, Switzerland.

[45] **Great Barrier Reef Marine Park Authority**, 2007: Management responses. Great Barrier Reef Marine Park Authority Website, http://www.gbrmpa.gov.au/corp_site/key_issues/climate_change/management_responses, accessed on 12-24-2007.

mass bleaching event or other climate-related event to determine bleaching impacts. For coral reefs, bleaching and mortality responses of corals to heat stress, the recovery rates of coral communities, and the physiological response of certain corals to bleaching should be monitored. After the degree of damage from a mass bleaching or other climate-related event has been evaluated, MPA managers can consider whether active restoration may be an option for supporting natural recovery (Marshall and Schuttenberg, 2006). For coral reefs, restoration efforts may include transplanting coral colonies, introducing large numbers of coral larvae, and increasing densities of herbivores such as the sea urchin *Diadema antillarum* (in the Caribbean) or herbivorous reef fishes.

Monitoring also can be an effective way to engage community members and raise awareness of impacts of climate change on marine systems. For example, the Reef Check program enables community volunteers to collect coral reef monitoring data to supplement other monitoring data from researchers and government agencies. Programs that engage coral reef users (such as local fishermen and tourism operators) in monitoring can help raise awareness of impacts on marine systems and can help support the need to manage for local threats. The Nature Conservancy is managing the Florida Reef Resilience Program to develop strategies to improve the condition of Florida's coral reefs and support human dimensions investigations.[46] The program includes annual surveys of coral bleaching effects at reefs along the Florida Keys and the southeast Florida coast, using trained divers from agencies, universities, and non-governmental organizations.

Changes in ocean chemistry (CO_2 and O_2 levels and salinity), hydrography (sea level, currents, vertical mixing, storms, and waves), and temperature should be monitored over long time scales to determine climate changes and possible climate trends. A location that is well isolated from local-scale anthropogenic effects and has a history of relevant investigations, such as Palmyra Atoll, is well-suited for this. Such an analysis could help determine the efficacy of MPA management in the context of climate change that is relatively independent of other anthropogenic effects, similar to the situation in the Northwestern Hawaiian Islands (see Case Study Summary 8.3).

NOAA's Coral Reef Watch program[47] provides products that can warn managers of potential impending bleaching events. In addition, Coral Reef Watch is developing bleaching forecasts that will provide outlooks of bleaching potential months in advance. These tools can help managers prepare for bleaching events so that when the event occurs, managers can have the necessary capacity in place to respond. In addition to a number of guides to help managers understand resilience and incorporate the concept in management actions, global information databases exist that consolidate climate change impacts on marine systems such as coral reefs. Reefbase[48] is a global information system and is the database of the Global Coral Reef Monitoring Network and the International Coral Reef Action Network. Coral bleaching reports, maps, photographs, and publications are freely available on the website, and bleaching reports can be submitted for inclusion in the database. Reefbase provides an essential mechanism for collecting bleaching data from around the world, thus helping researchers and managers to identify potential patterns in reef vulnerability.

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[46] **The Nature Conservancy**, 2007: Florida Keys reef resilience program. The Nature Conservancy Website, http://www.nature.org/wherewework/northamerica/states/florida/preserves/art17499.html, accessed on 7-27-2007.

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[47] http://coralreefwatch.noaa.gov/

[48] www.reefbase.org

8.4.4.2 Social Resilience, Stakeholder Participation, and Education and Outreach

In addition to identifying and building ecological resilience into MPA design and management, it is equally important for managers to address social resilience (*i.e.,* social, economic, and political factors that influence MPAs and networks). Social resilience is the "ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change" (Adger, 2000). MPAs that reinforce social resilience can provide communities with the opportunity to strengthen social relations and political stability, and diversify economic options (Corrigan, 2006). A variety of management actions have been identified to reinforce social resilience (Corrigan, 2006) including: (1) provide opportunities for shared leadership roles within government and management systems (Adger *et al.*, 2005; Cinner *et al.*, 2005; McClanahan *et al.*, 2006); (2) integrate MPAs and networks into broader coastal management initiatives to increase public awareness and support of management goals (U.S. Environmental Protection Agency, 2007; Marshall and Shuttenberg, 2006); (3) encourage local economic diversification so that communities are able to deal with environmental, economic, and social changes (Adger *et al.*, 2005; Marschke and Berkes, 2006); (4) encourage stakeholder participation and incorporate their ecological knowledge in a multi-governance system (Tompkins and Adger, 2004; Granek and Brown, 2005; Lebel *et al.*, 2006); and (5) make culturally appropriate conflict resolution mechanisms accessible to local communities (Christie, 2004; Marschke and Berkes, 2006).

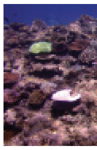
Some MPA managers may feel that engaging in supporting human adaptive capacity to climate change impacts is beyond the scope of their work. However, it is important to recognize that resource use patterns will change in response to changing environmental conditions. For example, recent studies suggest that when fishers are meaningfully engaged in decision-making processes for management of natural resources, their confidence and social resilience to changes in resource access can be increased (Marshall, forthcoming). Furthermore, as management is adapted to address changing conditions, engagement with stakeholders during this process will help MPA managers build the alliances, knowledge, and influence needed to implement adaptive approaches (Schuttenberg and Marshall, 2007). For example, national marine sanctuaries have Sanctuary Advisory Councils composed of a wide range of stakeholder representatives, who provide advice to sanctuary managers and help develop sanctuary management plans.[49] Education and outreach programs can help inform the public about effects of climate change on marine ecosystems and the pressing need to ameliorate existing stressors in coastal waters. Such programs should be strengthened in national marine sanctuaries and all agencies that manage MPAs.

8.5 CONCLUSIONS

8.5.1 Management Considerations

Adaptive management of MPAs in the context of climate change includes the concept that intact marine ecosystems are more resistant and resilient to change than are degraded systems (Harley *et al.*, 2006). Marine reserves develop less-disrupted community structure as populations of heavily fished species recover and abundance patterns and size structures return to states reflecting lower fishing mortality. Implementing networks of MPAs, including large areas of the ocean, will help "spread the risk" posed by climate change by protecting multiple representatives of habitats and communities within ecosystems (Soto, 2001; Palumbi, 2003; Halpern, 2003; Halpern and Warner, 2003; Roberts *et al.*, 2003b; Palumbi, 2004; Kaufman *et al.*, 2004; Salm, Done, and McLeod, 2006).

The most effective configuration of MPAs may be a network of highly protected areas and other types of zones nested within a broader management framework (Botsford, 2005; Hilborn, Micheli, and De Leo, 2006; Crowder *et al.*, 2006; Almany *et al.*, 2007; Young *et al.*, 2007). As part of this configuration, areas that are ecologically and physically significant and connected by currents should be identified and included as a way of enhancing resilience in



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[49] **National Marine Sanctuary Program**, 2-6-2007: National Marine Sanctuaries advisory council's information. NOAA Website, http://sanctuaries.noaa.gov/management/ac/welcome.html, accessed on 7-27-2007.

the context of climate change. Critical areas to consider include nursery grounds, spawning grounds, areas of high species diversity, areas that contain a variety of habitat types in close proximity, and potential climate refugia. At the site level, managers can build resilience to climate change by protecting marine habitats from direct anthropogenic threats such as pollution, sedimentation, destructive fishing, and overfishing; ecosystem-based management, rather than single-species or other less-holistic approaches, will become increasingly important in the context of climate change. The healthier the ecosystem, the greater the potential will be for resistance to—and recovery from—climate-related disturbances.

In designing networks, managers should consider information on areas that may be refugia from climate change impacts, as well as information on connectivity (current patterns that support larval replenishment and recovery) among sites that vary in their sensitivities to climate change. Protection of seascapes creates areas sufficiently large to resist basic changes to entire ecosystems (Kaufman *et al.*, 2004). Large reserves may benefit individual species by enabling entire adult phases of life cycles to be completed without fishing mortality, with concomitant increases in reproductive output (Sobel and Dahlgren, 2004) and quality (Berkeley, Chapman, and Sogard, 2004).

A key issue for MPA managers concerns achieving the goals and objectives of a local-scale management plan in the context of larger-scale stressors from atmospheric, terrestrial, and marine sources (Jameson, Tupper, and Ridley, 2002). Another issue concerns maintaining a focus on immediate, deleterious effects of overexploitation, coastal pollution, and nonindigenous species as climate change impacts increase in magnitude or frequency over time (Paine, 1993). A conclusion of this report is that this focus is in fact an important element of adaptation to climate change. Within sites, managers can increase resilience to climate change by managing other anthropogenic stressors that also degrade ecosystems, such as overfishing and overexploitation; excessive inputs of nutrients, sediments, and pollutants; and habitat damage and destruction. Efforts by MPA managers to enhance resilience and resistance of marine communities may at least "buy some time" against threats of climate change by slowing the rate of decline caused by other, more manageable stressors (Hansen, Biringer, and Hoffman, 2003; Hoffman, 2003; Marshall and Schuttenberg, 2006).

Resilience is also affected by trophic linkages, which are key characteristics maintaining ecosystem integrity. An approach that has been identified to maintain resilience is the management of functional groups, specifically herbivores. In some cases, the species that are necessary for recovery after a phase shift may be different from the species that had previously maintained the original state (*e.g.*, Bellwood, Hughes, and Hoey, 2006). This highlights the need to provide broad protection of species to maintain resilience and the need for further research on key species and ecological processes. However, abundant herbivores may not prevent shifts in algal-coral dominance in coral reef ecosystems (Ledlie *et al.*, 2007), and management for reduced levels of grazing may be necessary in plant-dominated systems such as kelp forests.

The challenges of climate change require creative solutions and collaboration among a variety of stakeholders to generate the necessary finances and support to respond to climate change stress. Global, regional, and local partnerships across a range of sectors such as agriculture, tourism, water resource management, conservation, and infrastructure development can help alleviate the financial burdens of responding to climate change in MPAs. Finally, effective implementation of the above strategies in support of ecological resilience will only be possible in the presence of human social resilience.

8.5.2 Research Priorities

The scientific knowledge required to reach general conclusions related to the impact of multiple stressors at community and ecosystem levels is for the most part absent for marine systems, and this gap impedes the ability of MPA managers to take management actions that have predictable outcomes. Existing levels of uncertainty will only increase as impacts of climate change strengthen. Within marine communities, temperature changes may result in new species assemblages and biological interactions that affect ecological processes such as productivity, nutrient fluxes, energy flow, and trophic webs. How such outcomes affect trophic links and other biological processes within communities is not clear, and is a high-priority area of research.

The extent of larval recruitment from local and longer-distance sources has been and must remain an active area of modeling and empirical investigations. Additional research will be required to better understand where and how far larvae travel in various marine ecosystems, to improve our understanding of where to implement MPAs and MPA networks.

The ability of corals to adapt or acclimatize to increasing seawater temperature is largely unknown (Berkelmans and van Oppen, 2006). Further, corals are sensitive to light and ultraviolet radiation, and thermal stress exacerbates this sensitivity (Hoegh-Guldberg *et al.*, 2007). The roles of temperature, light, holobiont characteristics and history, and other factors in coral bleaching are research topics of paramount importance.

Because of the greater solubility of CO_2 in cooler waters and at depth, reefs at the latitudinal margins of coral reef development (*e.g.,* Florida Keys and Hawaiian Islands) and deep-water coral formations may show the most rapid and dramatic response to changing pH. Further research is needed on impacts of high concentrations of CO_2 in the oceans, possible acclimatization or evolution of organisms in response to changes in ocean chemistry, and how management might respond (The Royal Society, 2005).

While there is no clear indication that ocean circulation patterns have changed recently (Bindoff *et al.*, 2007), future modifications could have large effects within and among ecosystems. Changing circulation would impact ecosystem and community connectivity in terms of nutrient fluxes, larval recruitment, spread of pollution, and other factors. Further modeling efforts may elucidate implications of potential changes in ocean circulation to MPA management.

Because pollution is usually more local in scope, it historically could be managed within individual MPAs; however, the addition of climate change stressors such as increased oceanic temperature, decreased pH, and greater fluctuations in salinity present greater challenges. Research in coral genomics may provide diagnostic tools for identifying stressors in coral reefs and other marine communities (*e.g.,* Edge *et al.*, 2005). MPA managers could benefit greatly from such tools, both in terms of distinguishing sources of stress and as potential "early-warning" signs for some factors such as thermal stress.

Research on marine ecosystems and climate change impacts continues to be a high-priority need, particularly in the context of using management actions as experiments in an adaptive-management framework. Although there is considerable research on physical impacts of climate change in marine systems (IPCC, 2007a), research on biological effects and ecological consequences is not as well developed.