RFF REPORT

An Adaptation Portfolio for the United States Coastal and Marine Environment

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Table of Contents

Introduction 1

Climate Change Impacts 3

- Ocean and Air Temperature 4
- Acidification 5
- Sea Ice, Glaciers, and Ice Sheets 6
- Sea Level Rise and Extremes 7
- Freshwater Runoff 8
- Thermohaline Circulation 8

Effects on Marine and Coastal Ecosystems 8

- Net Primary Productivity 9
- Species Distribution and Diversity 10
- Marine Disease and Invasion 12
- Coral Health 12
- Arctic Ecosystem 13
- Coastal Land Use and Erosion 14

Additional Stressors on Marine and Coastal Systems 14

- Species Diversity and Abundance 15
  - Coastal Habitat Loss and Deterioration 15
  - Fisheries 19
  - Coral Reefs 23
  - Biological Invasions 24
- Coastal Communities 25
  - Population and Demographic Pressures 26

Stormwater and Wastewater Treatment 27
Water Demands 28
Social Vulnerability 29
Adaptive Capacity and Resilience 31
Marine and Coastal Ecosystems 34
Marine Fisheries Management 36
Marine Conservation 40
Invasive Species 41
Arctic Resources 41
Estuarine Health and Coastal Land-Use Practices 42
Habitat Restoration and Permitting Decisions 42
Agricultural and Urban Runoff 44
Coastal Land Conservation 45
Setbacks, Purchases, and Rolling Easements 45
Regional Planning 46
Discussion 47
References 49

An Adaptation Portfolio for the United States Coastal and Marine Environment

David Kling and James N. Sanchirico*

Introduction

Since the beginning of the industrial revolution, the concentration of carbon dioxide (CO_2) in the atmosphere has risen approximately 35 percent (Forster 2007). This change has had a number of effects on marine and coastal environments. The additional atmospheric CO_2 has intensified the "greenhouse effect," warming both the air and the oceans (Le Truet et al. 2007). Estimates are that the global mean surface temperature has increased by approximately 0.74°C between 1906 and 2005 (Trenberth et al. 2007).[1] In just the last four decades, temperatures in the 0- to 700-meter layer of the ocean have increased by 0.1°C (Bindoff et al. 2007; Levitus et al. 2005). Current projections indicate that these trends will continue (Solomon et al. 2007). Second, the increased CO_2 in the atmosphere is changing the chemical composition of the ocean environment. Recent estimates indicate that the pH of the upper ocean decreased by 0.1 between 1750 and 1994 (Bindoff et al. 2007).

The goal of this paper is to discuss a portfolio of adaptation policies, which we define as the actions taken to enhance the resilience of human and natural systems to the effects of climate change and variability for marine and coastal environments within the United States and its territories. Associated with each policy in this portfolio are questions regarding the applicability (and need) in particular locations and the spatial scale, timing, and type of instrument to employ. For example, are adaptation policies best left to state and local governments (Tol 2005)? In light of current institutional realities in the United States, we agree in principle with Tol (2005) who argued that, compared with mitigation efforts, the federal government has a lesser role to play in adaptation policies than local governments. However, the answer to this question in the marine and coastal environment depends critically on the context. Unlike other settings, a role for government intervention is more likely because many of the natural resources impacted by climate change have public good characteristics.

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[1] Likely range 0.74 ± 0.18°C (Trenberth et al. 2007).

Understanding the context, in turn, requires a number of steps. First, the anticipated physical changes associated with climate change and the likely impacts of those changes need to be downscaled to particular locations. The set of physical and chemical impacts discussed in the "Climate Change Impacts" section includes ocean and air temperature, acidification, upwelling, glaciers, Arctic sea ice, freshwater runoff, and thermohaline circulation (THC). The "Effects on Marine and Coastal Ecosystems" section discusses how these changes are predicted to affect the land–sea margin, marine and coastal ecosystems, and the availability of mineral and natural resources in the Arctic. For example, as we discuss below, acidification of the oceans will probably increase the natural mortality of calcifying organisms (e.g., corals), lead to a greater frequency of marine disease and less resistance to biological invasions, and reduce the ecological benefits from upwelling events.

Second, whether a particular region or natural resource is more vulnerable can depend critically on the near-term state of the ecosystem. For example, is the environment in a particular location degraded or in a relatively pristine state? In the Caribbean, for example, the potential increase in the natural mortality of corals due to acidification is an additional threat to a system that is already stressed by bleaching events, habitat destruction, and overfishing (Hoegh-Guldberg et al. 2007). In the "Additional Stressors on Marine and Coastal Systems" section, we discuss the effects of non–climate change stressors on species abundance and diversity and coastal communities. Additional stressors to coastal communities include an increasing population and the aging of that population, antiquated stormwater and wastewater management systems, demands for freshwater, and current socioeconomic conditions that make a particular area less likely to be able to adapt.

After mapping the impacts and additional stressors, we discuss the potential suite of adaptation policies in the "Adaptive Capacity and Resilience" section. A sample of federal, state, and local policies we consider includes investments in habitat restoration, the purchase of coastal lands, reductions in the incentives for landowners to build in low-elevation and coastal areas subject to flooding and storm surges, controls for reducing nonpoint and point source pollution upstream of intertidal estuaries, the inspection and prevention of invasive species, the designation of marine protected areas (MPAs), and incentive-based fishery management policies.

Although each of these policies has been discussed and implemented to address a particular concern, an adaptation framework shifts the emphasis toward a risk management portfolio approach as opposed to an approach focused on a single issue at a time. Questions arise as to whether and how the instruments in our regulatory toolkit need to be redesigned to account for the scale, severity, timing, and uncertainty associated with climate change impacts. For example, the design and implementation of many of these tools has been carried out under the assumption of a relatively stable environment. How important that assumption is for the design and performance of a policy in a particular place will depend on the context, but it is becoming more evident that the underlying assumption is tenuous at best. Adaptive policies will need to be flexible with a balance between the use of incentives versus prescribed rules and "local" control over the choice of which mechanisms in the portfolio best fit the needs and risk management approach of a particular place. Too rigid a regulatory structure will lead to unnecessary costs and will be unable to respond efficiently to the changing conditions. Because there will also be many opportunities to learn along the way, policymakers at all levels should focus on policies that are designed to facilitate learning about the system.

What we consider as an undesirable that requires some level of government intervention might also need to be reconsidered. For example, we currently treat sedimentation in river systems as a pollutant and we attempt to eradicate invasive species. Sedimentation, however, is needed to maintain the height and extent of coastal wetlands that will be our first barrier to rising sea levels and sea level extremes, and a growing number of invasive species are likely to be species adapting to climate change by changing their geographic ranges.[2]

The framework also needs to consider the cumulative impacts of the stressors and the ability of the ecosystem to respond to potentially abrupt as well as gradual changes. From a climate change perspective, this is akin to preventive medicine rather than trauma care. In many cases, however, the historical mismanagement of the additional stressors has already put many of these resources on life support, such as coral reefs, coastal wetlands, and slow-growing commercially harvested species. Advocates for coastal and marine ecosystem-based management (EBM) have been calling for exactly this type of regime change in governance (McLeod et al. 2005).

Climate Change Impacts

In this section, we discuss a sample of the direct and indirect impacts of atmospheric CO_2 emissions on coastal and marine ecosystems, including changes in ocean and air temperature, acidification, upwelling intensity, glaciers and freshwater runoff, arctic sea ice, and ocean circulation. These impacts are illustrated in Figure 1. The likely direction of causality is illustrated with arrows, and the effects with more than one arrow illustrate the potential feedbacks in the system. For example, the loss of ice and snow cover is expected to generate further warming as a result of reduced albedo, or capacity to diffusely reflect sunlight, in northern latitude regions.

Figure 1 does not reflect information on which of these feedbacks and linkages is more likely for different ranges of ocean and air temperatures, the severity of the different effects, or the timescales over which these feedbacks are likely to occur. The likelihood, severity, and timing are critical information when deciding the nature of public policy responses, and we approach these issues in the next sections. For the purposes of this section, however, we focus on the potential linkages and feedbacks.

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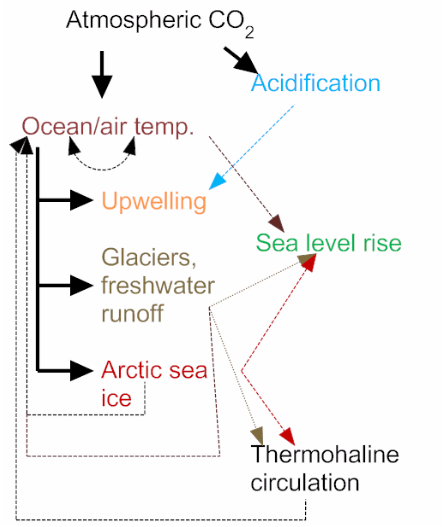
[2] We thank John Wilson from the U.S. Environmental Protection Agency for pointing this out to us.

Figure 1. Physical and Chemical Changes from Increased CO_2



Ocean and Air Temperature

In the Northern Hemisphere, mean land surface temperature has risen by about 0.9°C, while sea surface temperature (SST) has increased by close to 0.7°C over the same period (Trenberth et al. 2007).[3] The Intergovernmental Panel on Climate Change (IPCC) projects that the global average land and sea surface temperature is likely to rise by 0.2°C over the next two decades, with a low-greenhouse gas (GHG) emissions scenario seeing an increase of 1.8°C (likely range of 1.1–2.9°C) over the 1990–1999 mean by the end of the century and a high-GHG projected increase of 4°C (likely range of 2.4–6.4°C; IPCC 2007; Solomon et al. 2007).[4] Average temperatures in the upper oceans are also projected to rise, with the greatest increase expected in the Arctic and in the eastern Pacific at the equator.

Increases in ocean and air temperatures have both direct and indirect impacts on a number of processes in coastal and marine environments. For example, the warming of the oceans has implications for the carbon cycle. Atmospheric carbon concentrations today would be significantly higher were it not for the operation of land and ocean carbon sinks for anthropogenic CO_2. Between 1980 and 2005, the ocean absorbed 30 ± 7 percent of net CO_2 emissions (Bindoff et al. 2007).[5] Because the solubility of carbon decreases as the temperature of water increases, ocean warming

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[3] Figures calculated by multiplying 1901–2005 decadal trends by 10.5, retaining significant digits, and then rounding to the nearest tenth of a degree Celsius. We use estimated decadal trends published in Trenberth et al. (2007), based on original Northern Hemisphere land surface temperature data presented in Brohan et al. (2006) and Northern Hemisphere SST data from Rayner et al. (2006).

[4] These estimates correspond to the low-carbon scenario (scenario B1, 983 gigatons carbon [GtC] emitted between 1990 and 2100) and high-carbon scenario (A1FI, 2189 GtC, 1990–2100), respectively (see IPCC 2007 and, e.g., Pfeffer et al. 2008).

[5] Net of terrestrial biosphere response to emissions. See Bindoff et al. (2007).

will gradually reduce the potency of the seas as a carbon sink, leading to higher atmospheric carbon concentrations. An example of an indirect effect is the impact of warming on coastal inundation of wetlands via the increase in sea level.

Acidification

The ocean's service as a carbon sink has in turn led to adverse changes in seawater chemistry. Human activity since the industrial revolution has increased the concentration of dissolved inorganic carbon (DIC) in the ocean by increasing atmospheric CO_2 (Denman et al. 2007; Kleypas et al. 2006).[6] The carbonate chemistry of the ocean is centered on the total alkalinity and the DIC level and composition.[7,8] From the beginning of the industrial revolution to 2005, ocean pH has fallen (acidity has increased), and the composition of DIC has shifted toward bicarbonate to a degree not observed for approximately 420,000 years (Hoegh-Guldberg et al. 2007).

Atmospheric CO_2 is also a determinant of the depth of the aragonite saturation horizon (ASH), which is the limit between the layers of the sea that are saturated and those that are undersaturated with respect to calcium carbonate ($CaCO_3$). For example, between 1750 and 1994, the ASH is thought to have shoaled by as much as 200 meters in some parts of the ocean (Bindoff et al. 2007).[9] Orr et al. (2005) project that under a "business-as-usual" IPCC emissions scenario (CO_2 concentrations at 780 ppm by 2100), the ASH in the Southern Ocean and a region of the subarctic Pacific will rise to the surface, leaving those regions undersaturated, whereas in the North Atlantic the horizon may shoal by as much as 2,485 meters.[10] Figure 2 illustrates the potential patterns and shoaling of the supersaturated and undersaturated waters with specific attention to the Atlantic ocean.

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[6] DIC is the total molar sum of dissolved carbon dioxide, carbonic acid, bicarbonate, and carbonate, or CO_2, H_2CO_3, HCO_3^- and CO_3^{2-}, respectively.

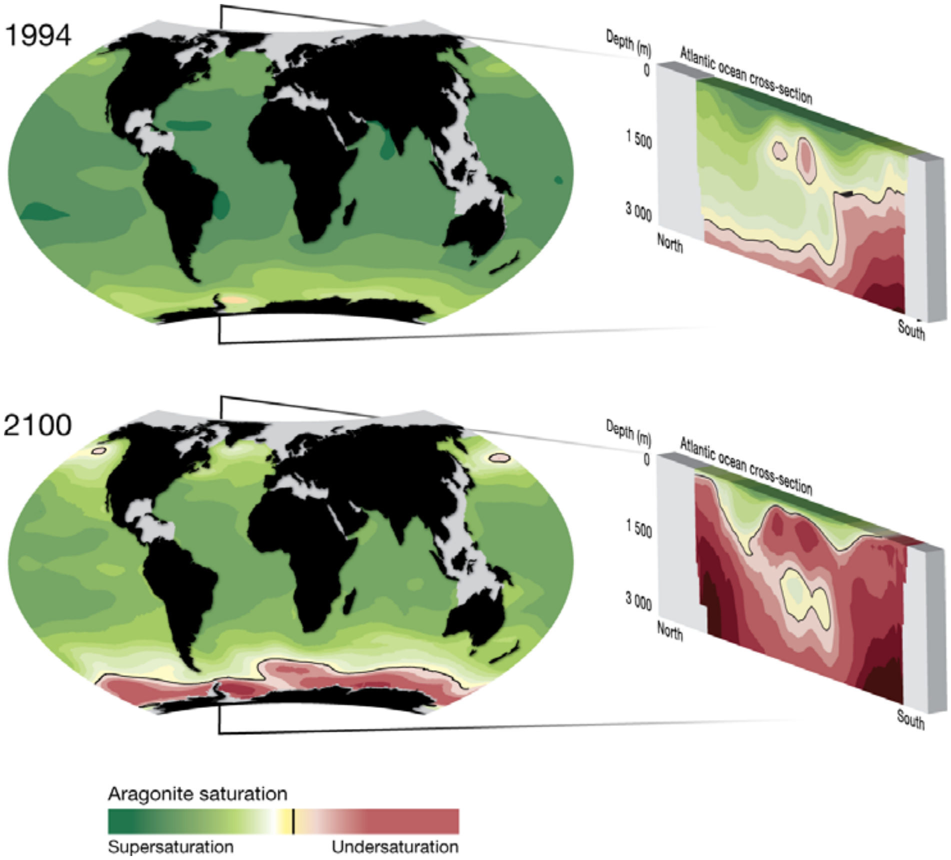
[7] Total concentration of all bases that can accept H^+ when a titration is made with hydrochloric acid to the H_2CO_3 endpoint (Le Quere et al. 2007).

[8] CO_2 absorbed by the ocean reacts with water to form H_2CO_3, which then dissociates into an H^+ ion and HCO_3^-, or loses another H^+ to form carbonate (CO_3^{2-}). As more CO_2 is dissolved in water, the balance between CO_3^{2-} and HCO_3^- is shifted in favor of HCO_3^- (Feely et al. 2004).

[9] Aragonite and calcite are two $CaCO_3$ minerals. Calcite has a substantially deeper saturation horizon.

[10] Orr et al. (2005) base these projections on the IPCC IS92a scenario.

Figure 2. Acidification and the Aragonite Saturation Level



Source: In *United Nations Environment Programme (UNEP)/GRID-Arendal Maps and Graphics Library*.[11]

Sea Ice, Glaciers, and Ice Sheets

Warming in the past century has contributed to a decrease in the extent and thickness of Arctic sea ice. According to recent IPCC findings, mean Arctic ice extent has declined by 2.7 ± 0.06 percent per decade since 1978, whereas the summer minimum extent has decreased by 7.4 ± 2.4 percent per decade since 1979 (Lemke et al. 2007). The mean September 2007 ice coverage of 4.28 million square kilometers was the lowest on record up to that point (National Snow and Ice Data Center 2007). Some projections show a near total loss of summer sea ice as early as 2040 (Serreze et al. 2007; Holland et al. 2006). One recent study finds that between 1979 and 2006, 47–57 percent of the downward trend in summer Arctic sea ice extent was due to GHG forcing (Stroeve et al. 2007).[12]

Climate change is the likely cause of the observed shrinking of the ice sheets covering Greenland and Antarctica; however, the dynamics of ice melting and accumulation in these regions

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[11] Retrieved 00:13, October 1, 2008, from http://maps.grida.no/go/graphic/acidification-due-to-climate-change-impacts-for-oceans-and-coral-reefs.

[12] In the climate change literature, *forcing* typically refers to both the direct and indirect effects of a particular agent on global mean temperature. *See* Leggett (2007).

are poorly understood (Leggett 2007). Between 1993 and 2003, the Greenland Ice Sheet is thought to have lost mass at an average rate representing 0.14–0.28 millimeter per year sea level equivalent (SLE) (Lemke et al. 2007).[13] Estimates of mass change for the Antarctic Ice Sheet during 1961–1993 range from a gain of –0.28 millimeter per year SLE to a loss of 0.55 millimeter per year SLE.

Land ice outside of Greenland and the Arctic has exhibited a clearer pattern of melting due to warming and changes in precipitation, accounting for the majority of observed ice loss (Lemke et al. 2007). During 1993–2003, glaciers and icecaps worldwide lost mass at a rate of 270 ± 79 gigatons per year (Solomon et al. 2007).[14] Close to 13 percent of the world's glaciers are located in Alaska. These bodies are among the most rapidly declining ice formations of a significant size. Using remote sensing data, Arendt et al. (2002), found that from mid-1995 to 2001, Alaskan glaciers lost volume at nearly twice the rate as the Greenland Ice Sheet. Loss of ice and snow cover is expected to lead to further warming as a result of reduced albedo in affected regions.

Sea Level Rise and Extremes

Thermal expansion of the oceans and the inflow of freshwater from glaciers arising from global warming have contributed to a rise in average sea levels during the 20th century. The IPCC places global mean sea level rise (SLR) during 1961–2003 at 1.8 ± 0.5 millimeter per year (Bindoff et al. 2007). Underlying the increase in the global average is considerable regional variability, with the western Pacific and eastern Indian Ocean seeing the largest increases. IPCC projections place the increase in the average sea level during 2090–2099 relative to 1980–1999 between 0.18 and 0.38 meter under a low-carbon scenario and between 0.26 and 0.59 meter under a high-carbon scenario (Meehl et al. 2007).[15] Because of modeling uncertainties, these estimates did not factor in possible accelerated melting of the Greenland and Antarctic Ice Sheets, although recent melting of the Greenland sheet is thought to have contributed to rising oceans during the 1990s and early 2000s (Solomon et al. 2007). A recent effort by Pfeffer et al. (2008) to include ice flow dynamics in sea level rise projections produced a central estimate of a 0.8-meter increase by 2100.

In addition to changes in global mean sea level, research suggests that the magnitude and frequency of sea level extremes might increase (Bindoff et al. 2007; Woodworth and Blackman 2004). Using data aggregated from 141 tidal gauge time series from around the world, Woodworth and Blackman (2004) find evidence that between 1975 and 2004, the magnitude of high-water events, defined as levels in the 99th percentile of within-year values, increased globally. In some areas, the projected increase in mean sea level over the next century may be accompanied by elevated and more frequent extreme sea levels. Cayan et al. (2006; 2008) find that, in certain mean sea level rise scenarios for the California coast, potentially damaging high-water events in the San Francisco Bay exceed those observed in the past two centuries.

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[13] 1 millimeter SLE = 360 gigatons. *See* Alley et al.(2005).

[14] Range was calculated by taking published figures and equating 1 millimeter SLE to 360 gigatons ice mass, adjusting for significant digits.

[15] Scenarios B1 and A1FI, respectively. *See supra*, note 2.

Freshwater Runoff

Warming is also expected to alter the global water cycle, although considerable uncertainty complicates efforts to forecast changes in precipitation and continental runoff. In certain areas, an increase in runoff levels and changes in the timing of the major spring runoff is anticipated. Runoff and river discharge has increased in northern latitude (e.g., Alaska) systems in the latter half of the 20th century (Trenberth et al. 2007; Huntington 2006). General circulation model projections show declining snow cover sustaining this pattern during the next several decades (Meehl et al. 2007).

Thermohaline Circulation

Current climate models forecast that freshening of the North Atlantic resulting from increased runoff and ice loss (lower salinity content) will lead to a slowdown of the THC. The THC is the large-scale ocean circulation conveyor belt that transports heat within the Atlantic northward via the Gulf Stream in the process warming Northern Europe (Broecker 1997). Stouffer et al. (2006) use a climate model ensemble to study the effects of a North Atlantic freshening episode similar to that anticipated as a result of climate change. Within a century after the perturbation, the THC weakens by 30 percent, leading to moderate cooling in the Northern Hemisphere.

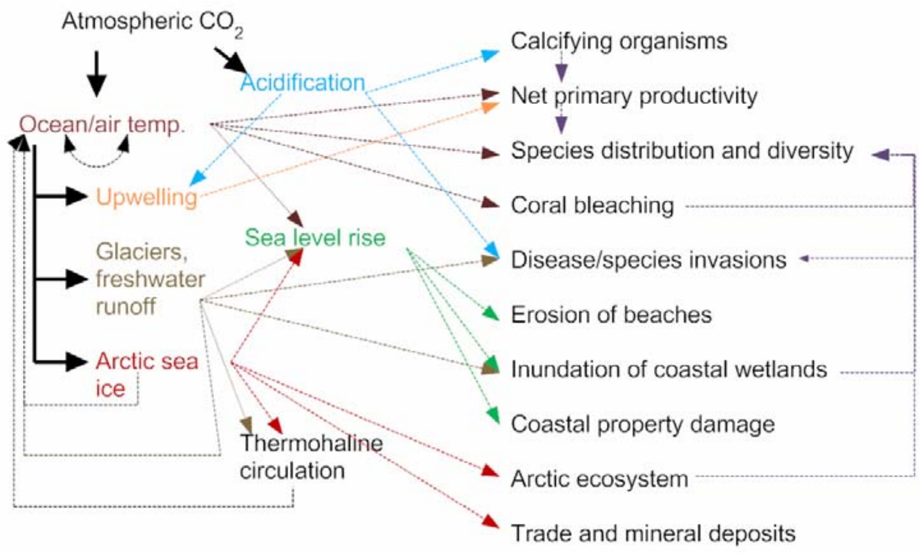
Climate scientists appear to have reached consensus in positing that a collapse or near-collapse of the THC in the next 100 years is highly unlikely (Meehl et al. 2007). The interplay between broader climate forcing and the cooling feedback associated with likely THC changes are uncertain. In the study by Stouffer et al. (2006) and in similar efforts, the cooling effect of a THC slowdown at best only mitigates the effects of anthropogenic forcing in certain regions, such as Northern Europe.

Effects on Marine and Coastal Ecosystems

Figure 3 maps the potential physical and chemical changes in ocean conditions to the potential effects on marine and coastal ecosystems. We focus in particular on ecological impacts in terms of changes in net primary productivity, survival of calcifying organisms, changes in species distribution and diversity, increased frequency of coral bleaching, diseases and species invasions, and changes to arctic ecosystems. Specific impacts on the land–sea margin include the erosion of beaches, inundation of coastal wetlands, and property damage.

The arrows in Figure 3 represent the likely direction of the impact, and the lines connecting different impacts illustrate the feedbacks in the system. As an example of a feedback, the loss of coastal wetlands affects the distribution and diversity of species, as do invasions and coral bleaching events. Unlike Figure 1, however, Figure 3 also illustrates cumulative impacts. The ecological benefit from net primary productivity is directly affected by the frequency, timing, and duration of upwelling events, which are driven in part by differentials in land and sea surface temperatures and the acidity of the ocean.

Figure 3. A Sample of the Impacts and Potential Feedbacks in Oceans and Coastal Systems from GHG Emissions



Net Primary Productivity

Phytoplankton account for close to half of the earth's net primary production (NPP) and form the base of marine food webs (Behrenfeld et al. 2006). Using ocean color data obtained from satellites, Behrenfeld et al. (2006) provide evidence that increased SST and water column stratification near the equator associated with El Niño–Southern Oscillation cycles (ENSO) have caused a reduction in ocean NPP. This finding suggests that marine primary production may be permanently reduced in equatorial and midlatitude regions as a result of global warming. NPP, however, will not be uniformly negatively impacted. For example, in colder regions (lower latitudes) where opportunities for photosynthesis rather than the supply of nutrients are binding (i.e., light-limited settings), increased stratification will probably aid phytoplankton growth.

The eastern margins of major ocean basins, including the West Coast of the United States, are highly productive because of the upwelling of nutrient-rich cold waters driven by alongshore winds. Coastal upwelling is expected to increase as a result of increasing surface air temperature-to-SST differentials brought about by global warming (Bakun 1990; McGregor et al. 2007).[16] Whether this increase leads to higher NPP in those areas, however, is not immediately evident. For example, although the intensity might increase, there is the potential that the timing of upwelling-favorable winds in coastal areas will shift to different times of the year. For example, in 2005, the California Current Large Marine Ecosystem (LME)[17] experienced a delayed upwelling event that depressed primary production at critical stages in the lifecycles of many dependent organisms.

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[16] As Harley et al. (2006) discuss, the increases in air temperature over land masses are likely to be greater than those over the ocean, and thus the pressure gradient will increase; this in turn could intensify wind fields along the ocean margin, which might lead to the greater intensity in upwelling events.

[17] The California Current LME spans from the Canadian border with Washington to slightly beyond the southern tip of Baha.

Barth et al. (2007) focused on the specific impacts to mussels and barnacles but concluded that these effects will probably move up the food web to impact other species, such as crabs and shorebirds. The poor recruitment of Cassin's auklet (see Figure 4) is attributed to the event (Barth et al. 2007). Researchers are also investigating whether the 2005 event, which included the delayed onset of upwelling with anomalously high SST and very low plankton biomass, is a potential cause of the abnormally low levels of coho and chinook salmon returns along the West Coast in 2008 (see Figure 4). The low returns led to a complete closure of the salmon fishery. Delayed and stronger upwelling events are forecast by some climate models.

Evidence has emerged that upwelling and ocean acidification combine to expose coastal marine life to undersaturated waters. The implication, as discussed by Feely et al. (2008), is that ocean acidification can cause the upwelling events to consist of water with lower pH, which can lead to a decline in the biological benefits from the strong upwelling events. Therefore, although the upwelling-favorable winds that were predicted for the eastern margins might turn out to be stronger than usual—which would normally imply greater NPP levels—a delay in the timing and a decrease in the pH levels of the mixing water can reduce the potential biological benefits.[18]

Species Distribution and Diversity

Ocean and terrestrial temperatures are fundamental drivers in the timing of events during the lifecycle of marine and coastal organisms and their location both vertically (depth) and horizontally (along the coastline; Parmesan 2006). For example, changing ocean and surface temperatures have prompted numerous species to shift their distributions either locally (e.g., a zonal shift of a benthic organism with a region) or across broad areas (thermoregulating fish; Harley et al. 2006).

The ability of biogeographically shifting populations to adapt to climate change depends on their spatial extent and the rate over which the changes occur. For example, species could be squeezed out, especially when the changes cause significant physiological stress on organisms that are adapted to live within a specific, often narrow, range of environmental conditions (Harley et al. 2006).

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[18] Still another potential issue is that increased stratification of the coastal water (depths at which the temperature changes) will cause the upwelling to consist of less colder water than it might otherwise and thereby reduce its benefit.

Figure 4. Species That Will Probably Be Affected by the Changes Due to Increased GHG Emissions

Note: Top left panel, Cassin's auklet (*source*: National Oceanic and Atmospheric Administration [NOAA]); top right panel, coho salmon (*source*: NOAA); lower left panel, shelled pteropods (*source*: Gulf of the Farallones National Marine Sanctuary); lower right panel, red sea urchin (*source*: NOAA; photo by Susan Scott).

Heterogeneity in phonological responses to climate change can lead to a mismatch in the development of species that in turn affects their survival. Costello et al. (2006), for example, present a study of two competing zooplankton species, *Acartia tonsa* and *Mnemiopsis leidyi*, in Narragansett Bay, Rhode Island. During 1951–2003, increasing temperatures induced *M. leidyi* to appear increasingly early in the Bay, by as much as two months before the long-term mean emergence date. The first occurrence of *A. tonsa* remained unchanged during the same period. The shift in timing provided *M. leidyi* with a considerable advantage, allowing it to prey on *A. tonsa* at a vulnerable developmental phase. The dominance of *M. leidyi* over *A. tonsa* in the Narragansett Bay ecosystem also had effects higher up the food chain, as fish species dependent on *A. tonsa* were placed at a disadvantage.

In general, migration in response to rising temperatures is expected to proceed toward the poles. Observations from a long-term study of an intertidal community in Monterey Bay, California, lend support to the poleward migration theory (Barry et al. 1995). Comparing resident invertebrate species during 1931–1933 with documented occurrences of these species at the same location between 1993 and 1994, Barry et al. (1995) find that the populations of eight out of nine southern species had increased significantly, whereas the populations of five out of eight northern species had decreased significantly. Climate change, along with ENSO events, brought an increase in mean winter and summer temperatures to the study site that lead to favorable conditions for the dispersal of southern species larva (Barry et al. 1995).

Anticipated changes in the carbonate chemistry of the ocean could have extremely negative implications for many forms of marine life. Calcifying organisms—such as coral, planktonic species (shelled pteropods), benthic classes including echinoderms (e.g., sea cucumbers, urchins, and sea stars), varieties of mollusks (e.g., mussels and clams), and crustaceans (e.g., Dungeness and Tanner crabs)—build their skeletons by combining calcium ions (Ca^{2+}) and carbonate (CO_3^{2-}) to form $CaCO_3$ minerals (Fabry et al. 2008; Kleypas et al. 2006; see Figure 4). This process must take place in seawater supersaturated with both Ca^{2+} and CO_3^{2-}; otherwise, calcareous structures will dissolve (Royal Society 2005). The shoaling of the ASH, therefore, may soon place species adapted to supersaturated conditions in seas that are increasingly undersaturated.

Juvenile stages of calcifying benthic species, such as mollusks, starfish, sea cucumbers, and sea urchins (Echinodermata), which form highly soluble forms $CaCO_3$ during development, have been shown to be highly susceptible to acidification (Fabry et al. 2008). Physiological processes for combating excess CO_2 in the body (hypercapnia) in a broad range of marine life may also be susceptible to acidification and may lead to reduced growth rates and metabolism in some species in the future. Changes in carbon concentrations may also represent an additional factor altering species distributions in the future; however, its relative importance as a driver of species migration is uncertain (Fabry 2008; Kleypas et al. 2006).

Marine Disease and Invasion

Temperature-related stress has the potential to render some organisms more susceptible to parasites (Mydlarz et al. 2006). Mortalities during widespread coral bleaching episodes in the late 1990s are thought to have been exacerbated by opportunistic infections (Harvell et al. 2002). Increased terrestrial temperatures and SST have been linked to expansions in the range of some marine parasites. One well-known example is the *Perkinsus marinus* (Dermo) endoparasite, which has caused high mortality in eastern oyster populations (*Crassostrea virginica*). A period of elevated maximum winter ocean temperatures enabled the tropical parasite to successfully spread north along the New England coast (Cook et al. 1998; Harvell et al. 2002).

Differences in migration patterns across shifting species along with alterations in phenological responses due to changes in water temperature are expected to result in more frequent episodes of invasion and transitional interspecies relationships (Walther et al. 2002). According to Harley et al. (2006, 234), "climatically driven changes in species composition and abundance will alter species diversity, with implications for ecosystem functions such as productivity and invasion resistance."

Coral Health

Coral reefs, among the most biologically diverse ecosystems on earth, provide a range of services to humans and are one of the marine habitats most threatened by global climate change

(Buddemeier et al. 2004). One concern is the impact of rising ocean temperatures on warm-water, reef-building corals. Recent episodes of mass, regionwide coral bleaching[19] have been linked to episodes of ocean temperatures exceeding summer maxima by just 1–2°C for three to four weeks (Hoegh-Guldberg et al. 2007). Bleaching is indicative of significant stress that can lead to diminished growth and reproductive capacity or death of the coral. Such periods of extreme high ocean temperatures are expected to occur frequently over the next 50 years (Hughes et al. 2003).

Acidification represents another threat to reef-building corals. A doubling of preindustrial atmospheric CO_2 is expected to reduce warm-water coral calcification by as much as 40 percent (Hoegh-Guldberg et al. 2007). In addition to reduced growth and colony density, declining calcification may lead corals to reduce skeletal density and divert energy away from other processes, such as reproduction, and toward calcification. The net effect would be a reduced capacity to survive and repopulate reefs following natural disturbances such as storms.

Cold-water corals, which do not obtain energy from photosynthesis through symbiotic algae, are expected to be adversely affected as well. Current projections indicate that only 30 percent of known cold-water coral reefs will be in supersaturated waters as the ASH shoals in response to climate change, with most of these in North Atlantic. Very few data exist on the effects of acidification on cold-water corals; however, they are expected to behave similarly to warm-water species (Guinotte et al. 2006). A reduction in primary productivity in regions where shell-building plankton are dominant may place further strains on cold-water corals by reducing the supply of suspended organic matter and the zooplankton on which they feed.

Corals are also likely to be impacted by the change in distribution and intensity of disease in a warming environment.

Arctic Ecosystem

Current trends in sea ice coverage in the Arctic have a number of implications for the environment, international trade, and security. First, the loss of ice has, in turn, led to further warming due to the lower albedo of the open ocean: between 1979 and 2005, the amount of solar energy absorbed has increased in much of the Arctic, in some regions by as much as 4 percent (Perovich et al. 2007).

Ice coverage and its seasonal variability is a defining aspect of the Arctic environment, and warming is likely to have an impact on the ecology of the region. One prominent example is the polar bear (*Ursus maritimus*), which was recently named a threatened species by the United States under the Endangered Species Act (Eilperin 2008, A1). The listing came as evidence emerged that warming may already be affecting the species. A study of a South Arctic polar bear population in Western Hudson Bay, Canada, attributed a decrease in juvenile polar bears to an increasingly early spring that results in earlier breakup of sea ice (Regehr et al. 2007). Largely as a result of the

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[19] Warm-water coral species are characterized by the symbiotic relationship between the coral animal and the zooxanthellae algae they recruit and house. The presence of the algae enables the composite organism to sustain itself from both feeding and photosynthesis, allowing it to survive in low-nutrient tropical regions. Coral bleaching occurs when the coral animal ejects its algae, either because it experiences a reduced ability to serve as a host or because the algae are subject to stresses or are unable to photosynthesize.

reduction in sea ice, the U.S. Geological Survey (USGS) projects that subpopulations comprising two-thirds of the species in the wild may be eliminated by 2050 (Amstrup et al. 2007).

The loss of Arctic sea ice raises a number of new issues relating to resource extraction and shipping. Arctic conditions in the coming decades are expected to allow for increasingly long periods of unfettered circumpolar navigation through the Northeast Passage (NEP) over the northern edge of Europe and Asia and the Northwest Passage (NWP) through the North American Arctic (Rayfuse 2007). Transpolar shipping during the summer months may become feasible by midcentury. Unlike the Antarctic, much of the Northern Ocean is subject to conflicting territorial claims by eight states, and at present the status of both the NEP and NWP are in dispute;[20] fishing waters and vast mineral deposits are at stake. A recent analysis estimates the undiscovered oil and gas deposits at 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids (Gautier et al. 2008).

Coastal Land Use and Erosion

Rising sea levels will be accompanied by more intense erosion of beaches and barrier islands and increasing salinity of some freshwater aquifers, taxing coastal population centers and sandy shore ecosystems in the United States (Scavia et al. 2002; Titus 1990; Brown and McLachlan 2002). Coastal marshes in the United States will also be subjected to erosion and inundation in the coming century, threatening the highly productive communities they support (Poff et al. 2002). Coastal wetland plants have adapted to survive in the intertidal zone within a narrow elevation band. This specialization makes most species vulnerable to regular short-term inundation with seawater, suggesting that wetlands may experience substantial stress and losses even if they escape being submerged. Threatened wetlands unable to migrate further ashore because of steep terrain or other impediments will need to display a high vertical accretion rate to remain, and this depends critically on the supply of sediment (Poff et al. 2002). A recent study for the Northern Gulf Coast of Florida found that, although marsh elevation was increasing over time, it was increasing at a slower rate than SLR because of low sediment supply (Ladner et al. 2000).

Additional Stressors on Marine and Coastal Systems

According to the IPCC (2007), ecosystems and coastal environments are highly vulnerable to the changing climate. This is especially true of ecosystems at the ice–sea margin (e.g., the Bering Sea) and that include both warm- and cold-water coral reefs (see Figure 9 for a map that illustrates the known distribution of warm- and cold-water coral reefs).

In this section, we focus on the cumulative impacts of non–climate change stressors that contribute to an area or resource being more or less vulnerable to climate change. Specifically, we discuss marine and coastal species diversity and abundance and coastal communities (see Figure 5). Additional stressors on species diversity and abundance include coastal habitat loss and deterioration of habitat quality, commercial and recreational fishing, destruction of coral reefs, and

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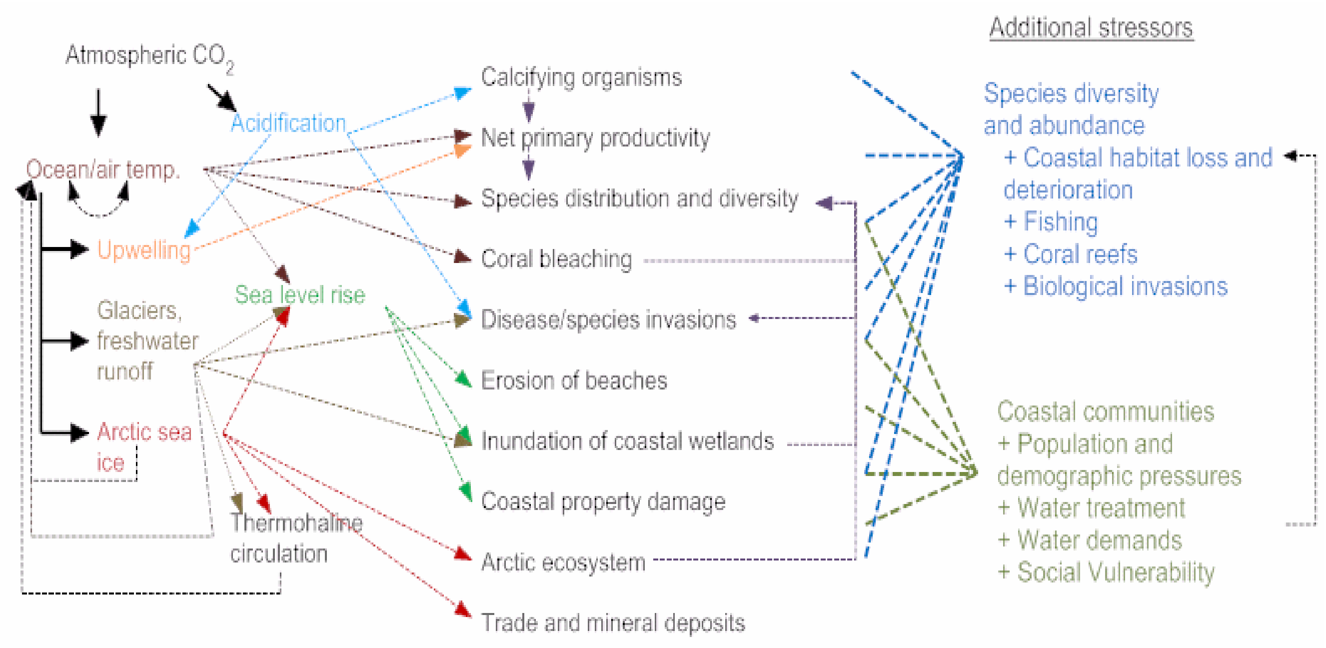
[20] The Arctic states include Canada, Denmark (through Greenland), Finland, Iceland, Norway, Russia, Sweden, and the United States.

biological invasions. With respect to coastal communities, we focus on population and demographic pressures, stormwater and wastewater treatment, water demands, and social vulnerability.

Figure 5. Mapping the Cumulative Impacts of Climate Change and Additional Stressors in Coastal and Marine Ecosystems



Species Diversity and Abundance

Many researchers point to five threats to marine and coastal ecosystems, including climate change, habitat loss, overfishing , water and marine pollution, and invasive species. We have already discussed the potential effects of climate change. In this section, we focus on the other threats in turn. A ranking of the severity of the threats is not immediately clear and will probably vary from one system to the next. What is clear, however, is that the cumulative impact places considerable stress on the living biological resources within these environments.

Coastal Habitat Loss and Deterioration

Estimates indicate that, since European colonization of North America, roughly half of inland freshwater and coastal wetlands have been lost. Within the past decade, the area of the United States covered by intertidal estuarine wetlands, which include salt and brackish marshes, flats and beaches, mangrove, and shrub forests, has continued the downward trend (Dahl 2006).[21] The most biologically productive classes of the intertidal marshes (vegetative estuaries) experienced the

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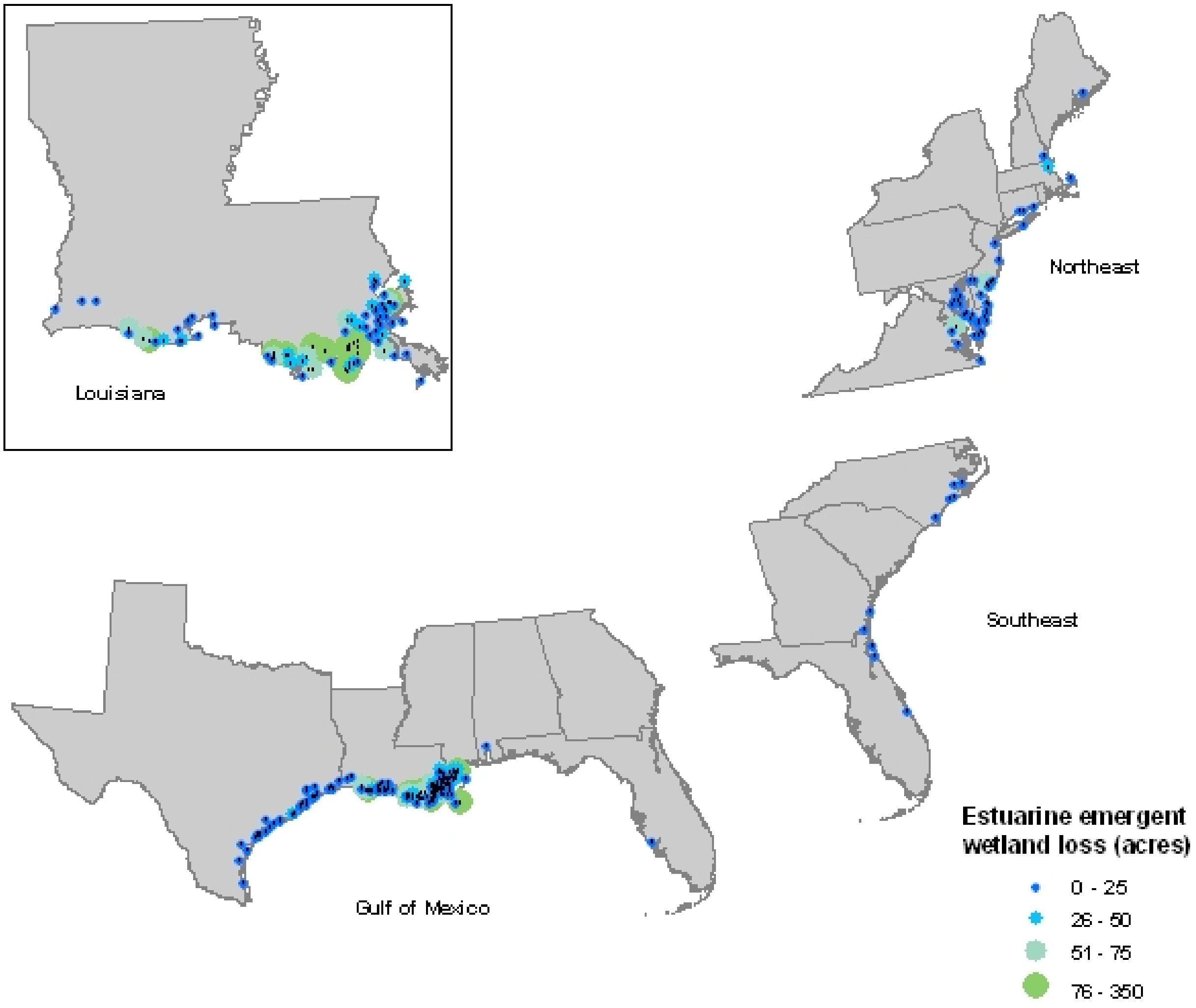
[21] The reduction between 1998 and 2004 is estimated to be 114 square kilometers out of a total of 21,527 square kilometers. These data do not include the estuaries on the West Coast because of issues with data availability and the nature of the systems.

largest reduction (Dahl 2006). The total for all intertidal marshes, however, was slightly higher than the loss in vegetative estuaries because of a small increase in flats and beaches (nonvegetative estuaries). According to Dahl (2006), these losses are mainly due to submersion by open water (93 percent) and coastal development (7 percent), where the former is caused by water control (e.g., levees), dredging, and commercial and recreational boating activities along with changes in natural flow patterns and inundation by storms.

Figure 6 illustrates the losses in intertidal wetlands along the eastern coast of the United States and in the Gulf of Mexico (Dahl 2006). The losses are scattered along the entire eastern seaboard, but the greatest frequency and size of losses occur in Louisiana. These measurements are probably underestimates as they do not include the losses due to Hurricanes Rita and Katrina.

In addition to the loss in coverage, the quality of much of what remains has been degraded as a result of seasonal runoff emanating from industrial agriculture and other sources of pollution (Poff et al. 2002). This has led to a sharp increase in the level of nutrients (eutrophication), principally nitrogen (N) and phosphorous (P), in estuaries and coastal areas (Buck 2007; Diaz and Rosenberg 2008). The resulting increase in primary production from seasonal runoff and subsequent die-off leads to reduced (hypoxic) or total (anoxic) oxygen depletion toward the bottom of the water column as oxygen-consuming bacteria break down the dead plant matter. In the absence of oxygen, mobile marine life unable to adapt flee the area, whereas sedentary species die, creating a “dead zone” nearly devoid of life. Low-oxygen zones also have the effect of limiting recruitment time for resident organisms, and chronic hypoxic conditions typically eliminate almost all microorganisms that use organic compounds for their survival and persistence (Buck 2007; Diaz and Rosenberg 2008).

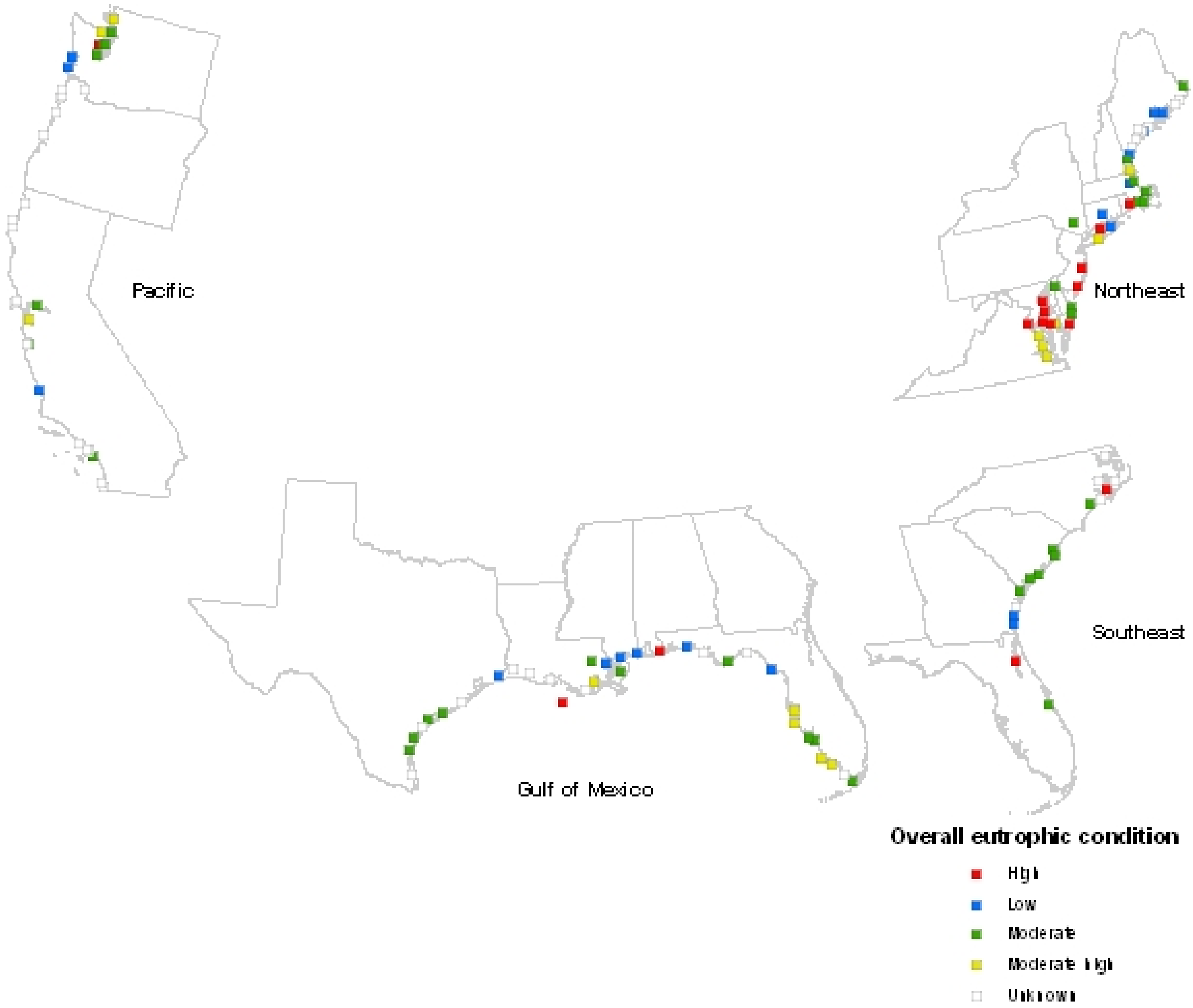
Figure 6. Loss of Intertidal Wetlands along the Eastern Seaboard and the Gulf of Mexico



Note: The figure is adapted from Dahl (2006). The data only include Estuarine Emergent Wetlands, where emergent wetlands have perennial plants, such as eel grass. The insert is an enlargement of the Louisiana area.

Figure 7 illustrates the distribution of eutrophic conditions throughout the coastal areas of the United States.. Projections for 2008 placed the maximum area of the Gulf of Mexico dead zone at approximately 20,700 square kilometers, propelled by nutrients brought down the Mississippi River at three times their 1960 level (Achenbach 2008, A2; Buck 2007). Although the evidence is mixed on the potential for stronger and more frequent storms, one potential beneficial impact of the storm surges would be increased mixing of the waters in the coastal environment. Depending on the timing of the storms relative to the summer, the storms could decrease the length and extent of eutrophic conditions.

Figure 7. Eutrophic Condition in 1999



The U.S. biofuel mandate has resulted both in agricultural lands being taken out of retirement and air and water pollution issues at the biofuel plants. The type of crop used—whether corn or switchgrass—and the geographic location of the farm will result in different requirements for N and P. These additional lands, which are more likely to be marginal and therefore require additional fertilizers to make them profitable to farm, are likely to worsen the eutrophic conditions throughout the United States. With respect to the manufacturing process, a newspaper column from the *Des Moines Register* (Beeman 2007) highlights the types of violations from biofuel plants:

> The biggest problem at the plants is meeting sewage pollution limits and preventing wastes from spilling into waterways. There were 276 violations in that category, involving 11 plants, one-third of all Iowa's plants in operation during the analysis and covered in the documents. Much of the sewage trouble came from too much iron in water withdrawn from local aquifers.

Elevated nutrients can also lead to blooms of certain types of toxic algae which, combined with hypoxia-causing events, fall under the heading of harmful algal blooms (HABs; Anderson et al. 2002; Horner et al. 1997). Toxic HABs can lead to substantial damage to fisheries through fish kills and contamination, and some varieties are poisonous to people (Knap et al. 2002). For example, a red tide diatom that occurs in shellfish in the Northwest Atlantic has a 4 percent mortality rate (Knap et al. 2002). During the period 1987–2000, a study estimated that the costs of HABs in the United States—including the public health costs from seafood poisoning, costs of cessation of commercial and recreational fishing during the blooms, and management costs—averaged $75 million per year (Hoagland and Scatasta 2006). According to NOAA, pathogens led to 20,000 beach closures in 2005.[22] One such HAB event that occurred along the New England Coast led to shellfish closures from Maine to Rhode Island and was the largest on record since 1972.

A recent assessment of the estuaries within the National Estuary Program evaluated their health across four indices: water quality, sediment quality, benthic conditions, and fish tissue contaminants (Dahl 2006). Table 1 is adapted from the assessment, where the indices are on a scale of 1 to 5, with 5 representing the highest quality. The assessment found variation within regions across the indices and across the regions. Although not represented in the table, it also found variation within regions and across the different estuaries. A simple average of the scores shows that Southeast Coast estuaries in the National Estuary Program are some of healthiest, whereas the Northeast Coast and San Juan Bay estuaries are in the worst condition.

Table 1. National Estuary Program 2007 Assessment of Estuarine Condition

Index	Northeast Coast	Southeast Coast	Gulf Coast	West Coast	San Juan Bay Estuary Puerto Rico
Water quality index	3	5	3	3	3
Sediment quality index	1	4	2	1	1
Benthic index	1	3	2	5	1
Fish tissue Contaminants index	1	4	4	1	1
Overall condition	**1.5**	**4.0**	**2.75**	**2.5**	**1.5**

Note: The Gulf Coast assessment excludes the dead zone.
Source: Dahl 2006.

Fisheries

In 2007, commercial fishermen landed at U.S. ports more than 4.8 metric tons of finfish (e.g., pollock, cod, and halibut) and non-finfish (e.g., shrimp, crab, kelp, and lobster) at a value of approximately $2.4 billion (NOAA 2007).[23] The distribution of these landings and returns at the regional and state levels are illustrated in Figure 8, panels A and B. Alaska, Louisiana, Virginia, California, and Massachusetts are the top five states in terms of volume landed, and the West Coast

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[22] The source for this information is the NOAA Coastal and Marine Economics web page (available at http://www.economics.noaa.gov).

[23] The value is the total gross revenue from the catch and does not net out the costs of fishing.

region—including Hawaii and Alaska—had the greatest catch in terms of volume. The gross revenue per pound (panel B) shows a wide distribution ranging from $2.50 in Hawaii to 0.175 cents in Mississippi. These figures are driven by the set of commercially viable species residing within a certain distance of the ports. For example, Hawaii catches include high-valued stocks, such as swordfish and tuna, shrimp are landed in Texas and Alabama (low weight, high value), and lobsters from the Long Island Sound are landed in Connecticut. In some cases, we would expect the distribution of these and other species to change as a result of the changing climate and oceanic conditions (Perry et al. 2005; Murawski 1993).

Some of the most productive fishing grounds are in the Bering Sea in Alaska, where the major commercial species include pollock, crabs, Pacific cod, halibut, and salmon. The changes in the sea ice boundary, both its spatial extent and the timing of melting and freezing, is likely to lead to changes in the productivity of the system by shifting the location and abundance of predators and prey (IPCC 2007). These fisheries, however, are relatively healthy and are therefore not as likely to be vulnerable as fisheries with overexploited stocks.

Overall, the ecological and economic record of fisheries within the U.S. exclusive economic zone (EEZ)—including migratory species that spend part of their cycle within U.S. territorial waters—is mixed with signs of improvement on both fronts. Of the 190 species monitored by the U.S. National Marine Fisheries Service (NMFS) in 2007, 24 percent were “overfished,”[24] or had a biomass below their minimum sustainable level (NMFS 2007). An additional set of stocks were subject to overfishing; this does not necessarily mean that the stocks are currently overfished, but rather that if exploitation continues at the current rate, the stocks will become overfished. Figure 8, panel C illustrates the number of vulnerable fish stocks in the U.S. EEZ. Although depleted species can be found throughout the U.S. EEZ, the highest concentration is found in the Northwest Atlantic fisheries off of New England. Some examples include bigeye tuna in the Pacific, cod in the Gulf of Maine, and red snapper, both along the Southeast Coast and in the Gulf of Mexico (Figure 8, panel D).

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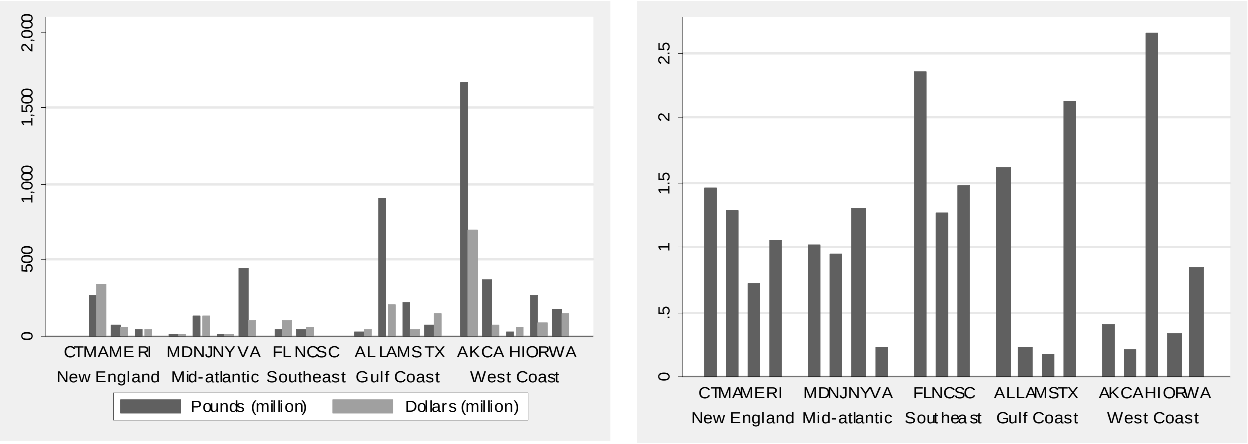
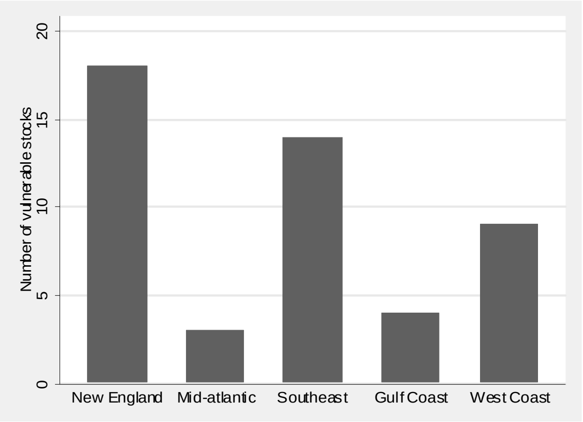
[24] Overfished stocks are those in which the fish stock has fallen below a prespecified sustainable target set by NMFS, and a stock subject to overfishing occurs when the fishing mortality rate exceeds the overfishing threshold set by NMFS.

Figure 8. U.S. Commercial Fishery Statistics for 2007



A. Commercial catch in pounds and dollars

B. Pounds per dollar



C. Vulnerable fish stocks, including overfished stocks and stocks subject to overfishing

D. Examples of overfished stocks and stocks subject to overfishing

Region	Fish stock	Over-fished	Over-fishing
NE	Gulf of Maine cod	X	X
NE	Georges Bank winter flounder		X
SE	Red snapper	X	X
SE	Black grouper		X
MA	Summer flounder	X	X
MA	Scup	X	X
WC	Boccaccio	X	
WC	Bigeye tuna		X
GC	Red snapper	X	X
GC	Gag grouper		X

Note: In panel C, the West Coast includes the Alaska region (one stock) and the Pacific region (two stocks). In all panels, the East and Gulf Coasts of Florida are in the Southeast region. In terms of fisheries management, the Atlantic Coast of Florida is part of the Southeast Fishery Management Council, and the Gulf Coast of Florida is part of the Gulf of Mexico Fishery Management Council. The landings data from NMFS are not complete, as data can be excluded because of confidentiality (one company landing at a single port), and we are only plotting the landings from major ports throughout the United States. The 2007 commercial catch data set is available from the National Marine Fisheries Service web site (www.nmfs.noaa.gov).

In addition to impacts on the abundance of the species being targeted, commercial and recreational fishing has resulted in changes to many harvested species and the ecosystems they occupy. For example, (limited) evidence supports the potential for rapid evolutionary shifts toward smaller size and earlier maturation in response to long-term exploitation (Fenberg and Roy 2008; Olsen et al. 2004). Bycatch—the mortality or maiming of animals other than the targeted animal within a fishery—is a significant threat to a number of bird, mammal, and sea turtle species (Read 2008; Tasker et al. 2000). Although marine bycatch is necessarily underreported as there are often no formal requirements to measure and record the information, Read et al. (2005) estimated a lower bound on the mean annual marine mammal bycatch in U.S. waters between 1990 and 1999 at 6,215 metric tons. For marine life that naturally exists in small and isolated populations, moderate bycatch tonnage can be harmful. Extremely high bycatch rates have had an adverse effect on what were at one time abundant species. Pelagic long-line fishing, for example, kills several thousand black-footed albatrosses (*Phoebastria nigripes*) annually, a situation that recently prompted the United States to consider listing the species as endangered or threatened (U.S. Fish and Wildlife Service 2007).

In some fisheries, removing commercially valuable top-level predatory species can have negative ecological effects. Frank et al. (2005) provide evidence that severe and persistent depletion of top-level predatory benthic fish species in the eastern Scotian Shelf—principally cod—caused a *trophic cascade*, or thorough restructuring of the food web. In response, the number of native grey seals (*Halichoerus grypus*) rose exponentially, and the size and abundance of zooplankton, as well as the populations of local crab and shrimp species, increased. Recent work has shown, however, that the pattern of fishing known as “fishing down the marine food web” (Pauly et al. 1998) is not as common as it was once thought to be (Essington et al. 2006). In addition, after a more detailed and rigorous analysis of the economic, ecological, and regulatory seascape, de Mutsert et al. (2008) show that previous estimates (Worm et al. 2006) of the health of the Gulf of Mexico and the area south of the Chesapeake Bay were too pessimistic.

The responses of marine ecosystems affected by industrial-scale fishing are not fully understood. However, a growing consensus suggests that exploited populations are likely to be more susceptible to changes in SST and primary production. Using data on exploited and unharvested species in the southern portion of the California Current system, Hsieh et al. (2008) find that the distribution of harvested populations tracked changes in climate to a greater degree than did bycatch species. Ottersen et al. (2006) similarly find that Barents Sea cod recruitment has, in recent decades, exhibited a higher degree of correlation with sea temperature as both the age and size profile of the stock have decreased.

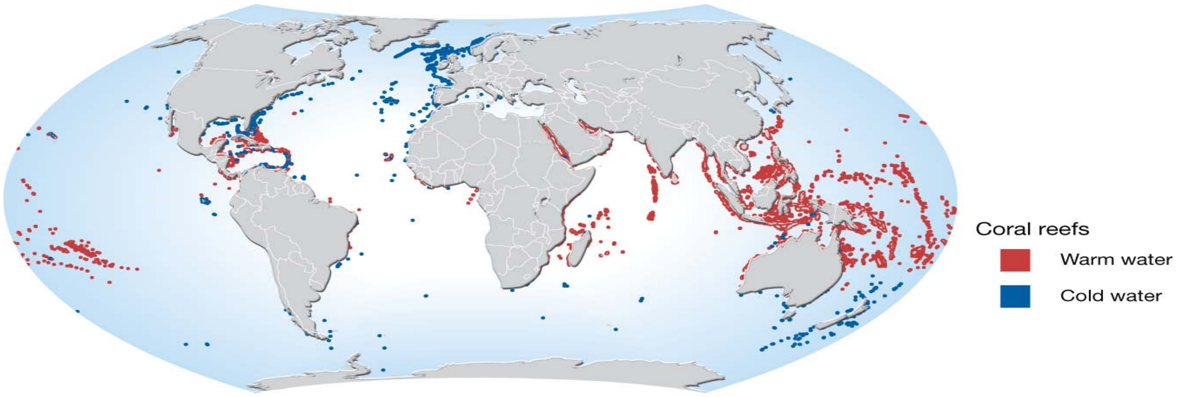
For a long time, conventional wisdom held that recreational fishing, including charter boats, private boat anglers, and shore-based fishermen, did not have a significant impact on marine fish stocks. Coleman et al. (2004), however, illustrate that the sector takes, on average, about 4 percent of the total marine fish landed and as much 10 percent when commercial fishing on pollock and menhaden are excluded. They also showed that the effects are not uniform across the United States; in particular, recreational fishing accounted for more than 60 percent of the total landings in the Gulf of Mexico and almost 40 percent in the South Atlantic. Private boat anglers, who compose the largest segment of recreational fishers and whose numbers are increasing, are one of the hardest sectors to manage and monitor because the set of anglers is so large and diffuse (Sutinen and Johnston 2003).

Coral Reefs

Significant warm- and deep-water (cold-water) coral ecosystems exist throughout the U.S. EEZ (Lumsden et al. 2007; Waddell and Clarke 2008). Algae-bearing zooxanthellate coral communities are found in the in the warmer waters of the Pacific, Gulf of Mexico, the Atlantic off of Florida, and the Caribbean (see Figure 9, red dots). Although the full extent of shallow-water coral ecosystems in U.S. territory is unknown, estimates place the total area capable of supporting them at approximately 36,813 square kilometers (Rohmann et al. 2005).[25] Deep-water coral communities are still being discovered in U.S. territory (see Figure 9, blue dots). Although fewer deep-water species are reef- or structure-building, many, including Gorgonians, form dense communities ("coral gardens") that serve as crucial habitat for marine populations, including groundfish and crab fisheries off of Alaska (Stone 2006).

Globally, warm-water coral ecosystems are in decline. Carpenter et al. (2008) found that, of the 704 reef-building species for which data were sufficient to make a determination, 231 were either vulnerable, endangered, or critically endangered according to International Union for Conservation of Nature criteria. In U.S. waters, outbreaks of disease, coastal runoff and pollution, and overexploitation threaten reefs (Bruckner et al. 2005). Caribbean corals, including those found near the U.S. Virgin Islands (USVI), are of particular concern, in part because of their relative lack of biodiversity and the weakening of reefs by major bleaching events in 1998 and 2005 (Bellwood et al. 2004; Jeffrey et al. 2005; Rothenberger et al. 2008).

Figure 9. Worldwide Distribution of Warm- and Cold-Water Corals



Source: In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved 00:08, October 1, 2008 from http://maps.grida.no/go/graphic/distribution-of-coldwater-and-tropical-coral-reefs.

In recent decades, the makeup of coral reef ecosystem in the USVI and other areas of the Caribbean has transitioned from communities based around framework-building corals, such as members of the Acropora genus, to non–framework building opportunistic species. The loss of the

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[25] Zooxanthellate corals generally cannot survive at depths greater than 30 m below the surface (Stachowicz et al. 2002).

urchin population as a result of a disease outbreak has also left Caribbean coral reefs in a vulnerable state (Gardner et al. 2003; Knowlton 2001). As Mumby et al.(2007) demonstrate, a reduction in the Caribbean of parrotfish, which graze on macroalgae, can cause the reefs to revert to an algae-dominated system. Both of these changes may make Caribbean reefs more vulnerable to shocks associated with climate change (Mumby et al. 2007), such as storm patterns and pollution. An example of the latter is the 2005 HAB event off the Gulf Coast of Florida that killed vast areas of coral reefs.

Cold-water corals are also under threat. Although it is difficult to assess the full extent of the impact of human activities, evidence suggests that fishing practices—particularly bottom trawling—are damaging cold-water corals in the Gulf of Alaska, Aleutian Islands, and Bering Sea. Between 1997 and 1999, coral bycatch amounted to approximately 81.5 metric tons annually in the region, with bottom trawls accounting for at least 87 percent of the total (Lumsden et al. 2007).

The portion of the U.S. EEZ extending out from the Florida coast contains major deep-water coral ecosystems, including communities on the continental shelf edge near eastern Florida dominated by the structure-forming Oculina varicose (ivory tree coral) and concentrations of Lophelia pertusa on the Blake Plateau (U.S. Fish and Wildlife Service 2007). Oculina reefs typically occur in the 0- to 200-meter layer of the ocean, whereas the majority of Lophelia-dominated assemblages occur at depths greater than 300 meters. Both habitats have seen physical destruction and the depletion of reef-dwelling species, such as snapper in the shelf area and wreckfish (Polyprion americanus), a deep-water species.

Biological Invasions

Nonnative invasive species (NIS) can lead to severe ecological damage and demand costly mitigation efforts (Carlton 1989; Corn et al. 2002). Key vectors for recently established marine, estuarine, and coastal NIS include shipping through ballast water exchange and hull fouling, the aquarium trade, and live species seafood and bait (Williams and Grosholz 2008). A review by Ruiz et al. (2000a) found that invertebrate and algal NIS alone constituted 298 self-sustaining populations in U.S. coastal regions. San Francisco Bay and other busy port areas in the United States have the highest incidence of NIS (Cohen and Carlton 1998).

Biological invasions can damage an affected ecosystem on multiple levels (Grosholz 2002). Once introduced, many invaders feed on local species, limiting functions performed by the targeted species in the case of heavy predation and altering preexisting trophic (predator–prey) relationships. Often, such changes in the food web can place pressure on endangered species, as in the case of predation by the red imported fire ant (*Solenopsis invicta* Buren) on endangered loggerhead sea turtle (*Caretta caretta* L.) hatchlings in Florida (Allen et al. 2001; Wetterer et al. 2007). NIS may supplant or hybridize with residents, in some cases creating even more invasive agents. Finally, invasive species such as weeds or grasses may directly alter the structure of an ecosystem by altering plant density and the distribution of plant growth.

An invasive species with stable populations in one part of the country can rapidly expand its range once introduced to a new region within the United States. Since its first appearance on the California coast in the late 1980s, the European green crab (*Carcinus maenas*) has spread north to

Canada, overpowering many indigenous crab species and placing stress on native bivalves (Yamada and Gillespie 2008). Evidence from New England, where the crab was introduced in the 19th century, attributes the decline of the commercial soft shell clam (*Mya arenaria*) populations in part to *C. maenas* predation (Kern 2002). On the West Coast, the green crab has been observed outcompeting juvenile Dungeness crab (*Cancer magister* Dana; McDonald et al. 2001). Although *C. maenas* has not yet moved into primary *C. magister* nursery areas, fisheries scientists and managers are concerned that a further advance could threaten the Dungeness fishery that totaled more than $140 million in landings in 2006 (NMFS 2008).

Temperature and salinity provide barriers to the expansion of established invasive populations and limit the number of new introductions (Stachowicz et al. 2002). Climate change may create openings for NIS to enter new ecosystems as the distribution, phenology, and trophic relationships among native species respond to altered environmental conditions (Parmesan 2006). In some cases, a loss of biodiversity due to warming and human encroachment can reduce the capacity of resident species to resist further invasion (Fridley et al. 2007).

Coral reefs in the Caribbean are currently under threat from the predatory Indo-Pacific lionfish (*Pterois volitans*). The species is thought to have been introduced via the aquarium trade into waters off of Florida. Albins and Hixon (2008) show that, within a short time after introduction, the survival of the other reef fish iwasreduced by almost 80 percent. The loss of grazers, such as parrottfish, on these reefs resulting from lionfish predation could result in the reefs becoming more algae dominated and less resilient to bleaching and other shocks.

Florida is a hotspot of marine and coastal invasive species (Florida Invasive Species Working Group 2003). In 2001, a total of 122 marine and freshwater fish species were known to have been introduced in the state, with 53 forming self-sustaining invasive populations (Benson et al. 2001). The majority of the NIS recruitments in Florida have been attributed to the aquarium trade (Padilla and Williams 2004). Infested ballast water is thought to have brought the fast-growing Asian green mussel to Florida (Baker et al. 2007; Power et al. 2004). Green mussels have been observed displacing native eastern oysters on oyster reefs in Tampa Bay, and the mussel's propensity to damage infrastructure in other regions has drawn comparisons to the notorious invasive freshwater zebra mussel (Power et al. 2004). Climate change and the attendant shifts in the distribution and phenology of native species may increase the rate of successful marine NIS recruitment in Florida.

Coastal Communities

We discuss the additional stressors to coastal communities from an increasing population and the aging of that population, antiquated stormwater and wastewater management systems, demands on freshwater supplies, and social vulnerability. The latter is an index of social and demographic variables that attempts to rank a particular location's ability to adapt to changes over time, including emergency planning and climate change (Cutter and Finch 2008).

Population and Demographic Pressures

Along with the changes to marine and coastal natural resources, coastal counties will experience to varying degrees the effects of sea level rise that include inundation, coastal erosion, flooding, and saltwater intrusion. These climate change impacts are in addition to the stressors placed on local infrastructure and resources from current population density levels. Specifically, counties within coastal watersheds, excluding Alaska, contain close to 53 percent of the U.S. population but represent only 17 percent of the total area of the country (Crossett et al. 2004). As of 2003, 153 million people live in the coastal counties; this represent a 28 percent increase over the level in 1980.

Figure 10 illustrates the distribution of this change throughout the United States. Both the Atlantic and Gulf Coasts of Florida, along with the San Francisco and Seattle metropolitan areas, have seen some of the largest percentage increases. According to the U.S. Census Bureau, California, Florida, Texas, and Washington have experienced the largest gain in coastal population during the 1980–2000 period.

Florida's dense coastal population and long coastline along both the Atlantic Ocean and the Gulf of Mexico place it among the states most vulnerable to the effects of eustatic sea level rise resulting from climate change. Titus and Richman (2001) estimate that approximately 12,251 square kilometers of the state's land lies between 0 and 1.5 meters above sea level, and a further 12,743 square kilometers has an elevation between 1.5 and 3.5 meters. Florida's coastal counties are also the most densely populated in the United States. In 2005, approximately 10.4 million people lived in the state's Atlantic coastal counties, and another 7 million lived in counties along the Gulf (Florida Atlantic University 2008).

Crossett et al.(2004) report that the coastal demographic distribution is shifting toward older, and often retired, individuals. Predictions based on this trend are that the demand for marine and coastal recreation will increase with the shift to retired populations, as this demographic has more time for recreation activities (Crossett et al. 2004). Not surprisingly, Florida and California are the top two states in terms of beach visitation (Crossett et al. 2004), and these activities can have considerable economic impact. For example, according to Leeworthy and Wiley(2006), almost $1 billion (year 2000 dollars) was spent on beach activities during a one-month period in Los Angeles and Orange Counties in California during the summer of 2000.

At the same time, rising sea levels and storm surges are expected to help fuel the loss of beaches and barrier islands, particularly on the East Coast (Hanemann et al. 2003). Morton and Miller (2005) estimate that, between 1970 and 2000, 39 percent of the 1,543 km of the Southeast Atlantic Coast surveyed eroded, despite efforts to mitigate shoreline loss and barrier island loss through nourishment and reinforcement. In communities located on shores, such as Ocean City, Maryland, or barrier islands, the process of erosion can threaten communities that provide recreational services and contain highly valuable properties (Morton and Miller 2005). Projected eustatic sea level rise will probably contribute to the loss of barrier islands and the further erosion of beaches on the Florida peninsula. The state of Florida currently classifies approximately 620 kilometers, or

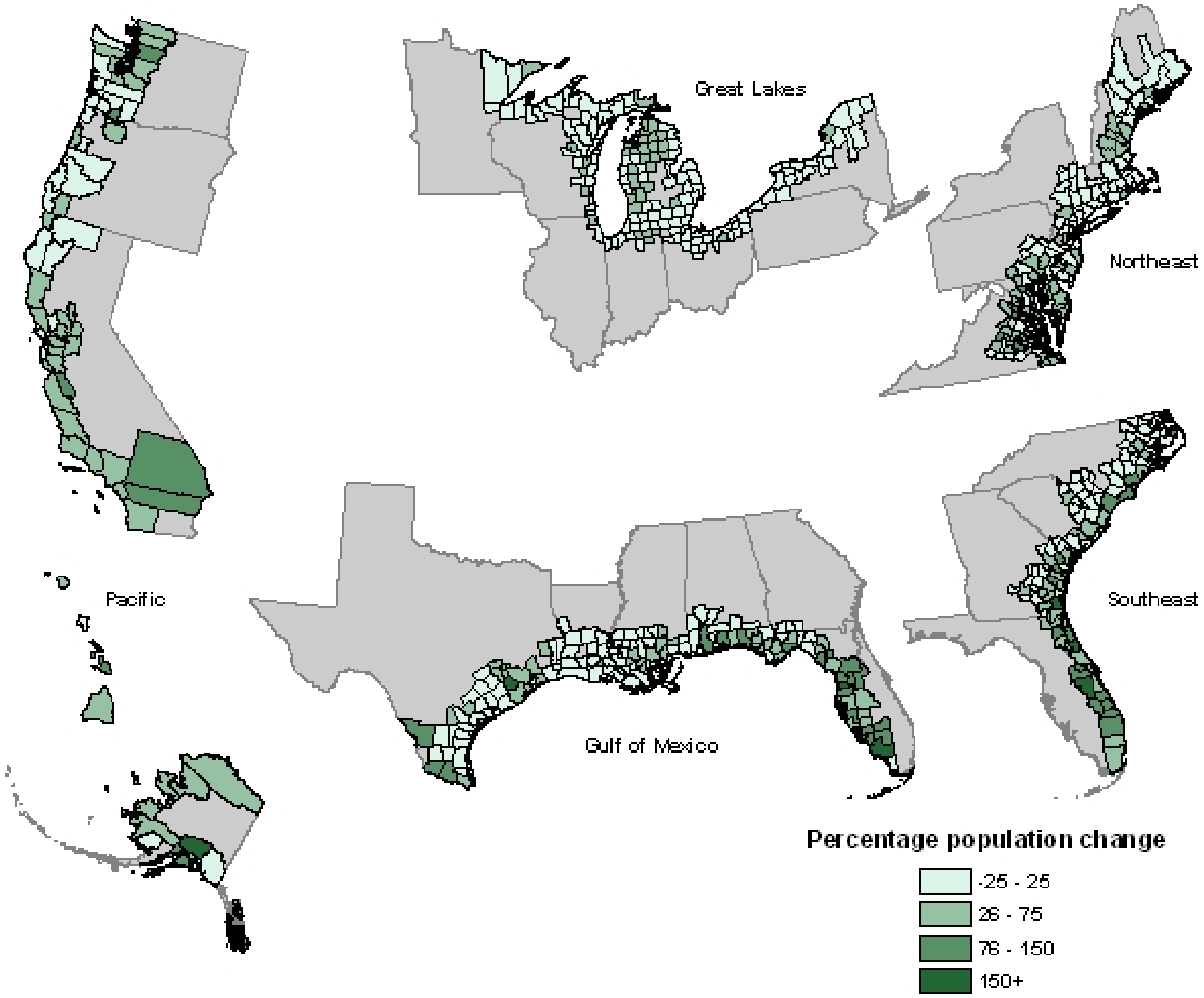
46 percent of the state's beaches, as sustaining "critical erosion" (Florida Department of Environmental Protection n.d.).

Stormwater and Wastewater Treatment

Many of the areas that are experiencing population growth and are receiving considerable economic and social returns from recreation have moderate to high eutrophic conditions. Comparing Figure 10 with Figure 7 highlights that the Gulf Coast of Florida, the San Francisco Bay Area, the Seattle region, and the Mid-Atlantic might experience greater rates of eutrophication in the future resulting from increased urban runoff.

One factor leading to greater eutrophic conditions near coastal urban areas is the design of stormwater management systems that quickly discharge water into nearby waterways, making cities and suburbs key sources of pollution runoff (Roy et al. 2008; Paul and Meyer 2001). The situation is especially dire for the more than 700 municipalities that have inherited systems that attempt to treat runoff by combining it with wastewater en route to treatment facilities during normal rain events (U.S. Environmental Protection Agency [EPA] Office of Water 2004). In heavy rain events, combined sewer systems often overflow, sending pollutants and raw sewage into local watersheds. Nutrients, metals, and other pollutants from urbanized areas have been identified as major obstacles to the restoration of important ecosystems, such as the Florida Everglades (Chimney and Goforth 2001). On the southern California coast, a number of studies have identified health hazards associated with exposure to sea water contaminated with runoff from nearby municipalities (Dwight et al. 2004; Haile et al. 1999). These types of risks may increase if alterations in the hydrological cycle brought about by climate change result in increased runoff.

Figure 10. Percentage Change in Coastal County Population from 1980 to 2000



Source: U.S. Census Bureau (http://www.census.gov/popest/estimates.php).

Water Demands

Although there is uncertainty regarding the extent of sea level rise during the next century, coastal developments will probably be subjected to increased erosion and, in some cases, inundation by the sea (McGranahan et al. 2007). Based solely on the physical attributes of the landscape, an estimated 80 percent of the New Jersey coast is highly vulnerable to inundation, coastal erosion, flooding, and saltwater intrusion from sea level rise (Cooper et al. 2005). Although greater saltwater penetration into coastal freshwater aquifers is a likely future scenario from sea level rise (Cooper 2005), the United States is in a good position to compensate for lost water; however, substantial additional costs are likely.

Future precipitation patterns and possible saltwater intrusion may lead to greater conflict between species that depend on instream flows, agricultural users, and urban water districts. Controversy over water use in the drought-prone Klamath River Basin on the California–Oregon border has been particularly intense (Powers et al. 2005; Lane 2007). Dams and other water reclamation measures in the region have been cited as significant stressors on endangered shortnose sucker (*Chasmistes brevirostris*) and Lost River sucker (*Deltistes luxatus*), and threatened coho salmon (*Oncorhynchus kisutch*). At present, coho salmon are extinct above the Iron Gate Dam, the first of the main dams on the Klamath River (Powers et al. 2005).

Social Vulnerability

Whether a particular coastal county is more or less vulnerable is likely to depend on many dynamic factors. Tracking and measuring vulnerability is based on the assumption that more vulnerable or disadvantaged regions may be less able to finance adaptation and mitigation measures to address the effects of climate change or other shocks. Researchers have built a county-level (static) social vulnerability index (SOVI) that combines many different socioeconomic and demographic variables (Cutter and Finch 2008; Cutter et al. 2003; Boruff et al. 2005).[26]

Figure 11 illustrates both the SOVI index for 2000 (Cutter and Finch 2008), where dark red implies that the county is more vulnerable, and the coastal vulnerability index computed by USGS, which ranks a coastal county's risk of sea level rise and where larger numbers imply greater risk. Figure 11 clearly shows that, despite some overlap in Florida, the Gulf of Mexico, and parts of the Mid-Atlantic, overall many of the counties that are vulnerable to a one-meter sea level rise are not as socially vulnerable as other counties. The patterns in Figure 11 are also found in Boruff et al. (2005). Figure 12 focuses in on the overlap between social vulnerability and the areas inundated by a one-meter sea level rise in Florida. We can see, in the southeastern portion, areas where the populations are vulnerable from both physical and social factors.

Per capita income is an important variable in the SOVI . According to the U.S. Census Bureau, the median income of coastal counties is greater than that of interior ones—a difference partly due to the concentrations of urban areas within coastal communities. However, many coastal counties are economically depressed (Crossett et al.2004). In the southeastern United States, for instance, counties bordering the Atlantic are less well off on average than those in the interior.[27]

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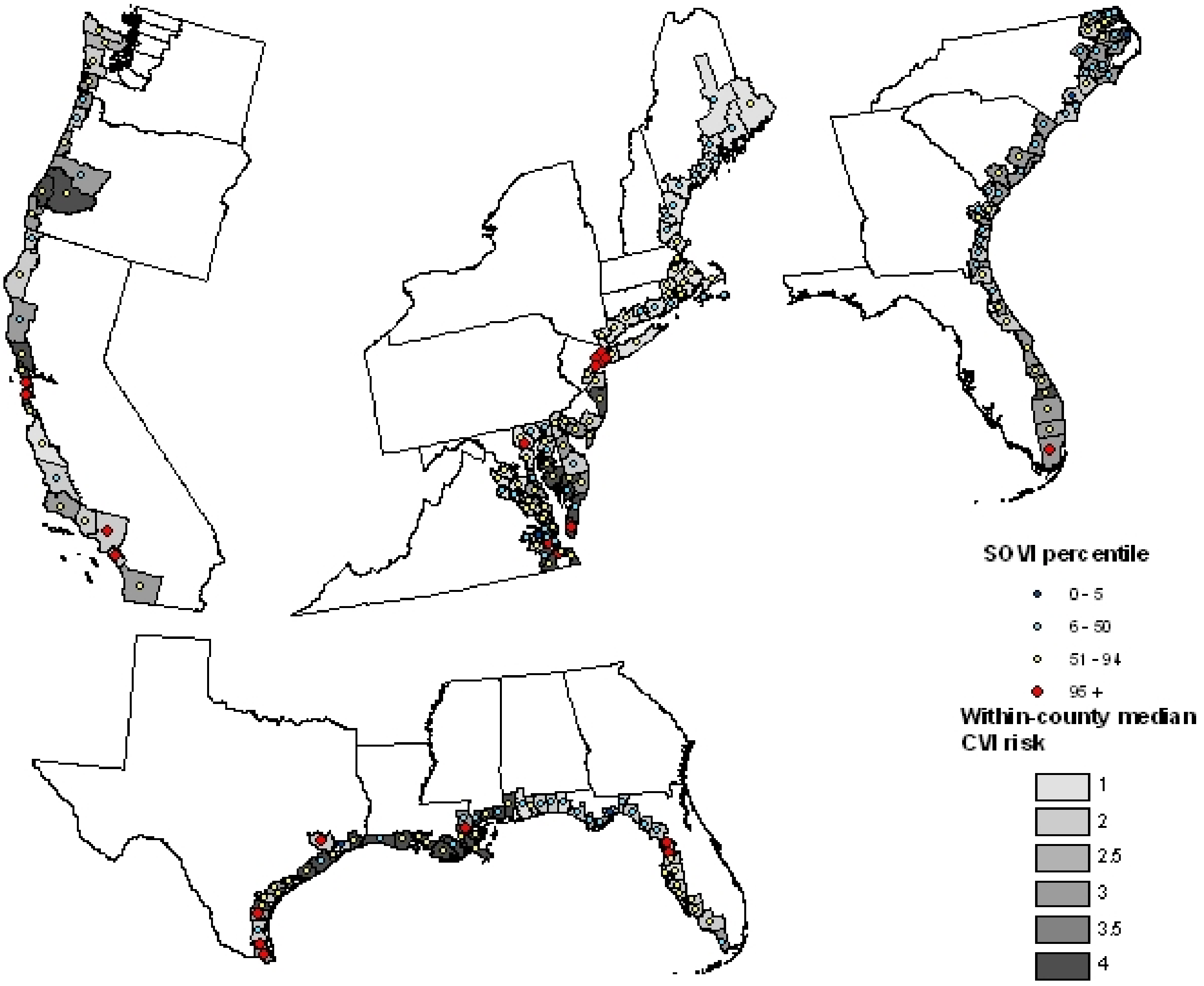
[26] Using a principal components analysis, Cutter et al. (2003) additively combine 11 out of 75 variables that explained more than 75 percent of the variance to create the SOVI. The 11 variables, in order of their contribution to explaining the variance, are per capita income, median age, density of the built environment (number of commercial businesses per square mile), single-sector economic dependence (percentage employed in extractive industries), housing stock (percentage of mobile homes), race variables, occupation (employed in service occupations), and infrastructure dependency (percentage employed in transportation, communication, or public utilities).

[27] *Southeastern* here includes the Atlantic Coast of Florida, Georgia, South Carolina, and North Carolina (Crossett et al. 2004).

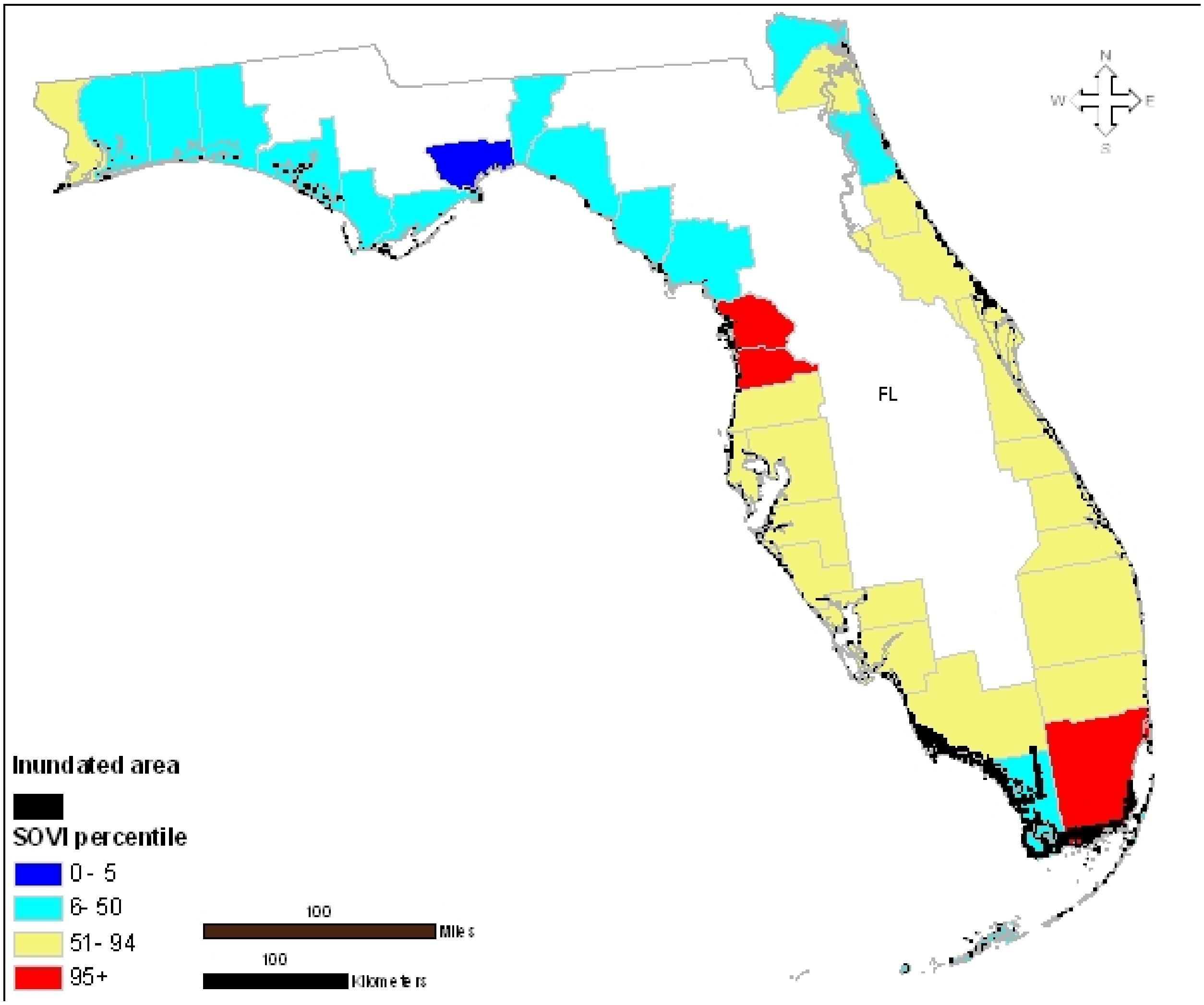
Figure 11. Social Vulnerability Index Score and Within-County Median Coastal Vulnerability Index Risk for Coastal Counties in the Lower 48 States



Note: CVI, coastal vulnerability index.
Source: USGS (http://woodshole.er.usgs.gov/project-pages/cvi/) and Hazard & Vulnerability Research Institute, University of South Carolina (http://webra.cas.sc.edu/hvriapps/SOVI_Access/Get_All_Data.aspx)

In the United States, several indigenous communities harvest marine and coastal animals and plants for subsistence, recreation-based enterprises, cultural practice, or some combination of the three (Anisimov et al. 2007; Arctic Climate Impact Assessment [ACIA] 2005). These communities are likely to face challenges due to climate warming and increasing variability. The dramatic loss of summer ice cover and the delayed onset of winter ice in the Arctic are likely to be particularly problematic for some Alaskan native communities, many of which face a difficult social and physical (dietary) transition away from partial dependence on subsistence hunting should climatic conditions render it untenable (Anisimov et al. 2007; ACIA 2005).

Figure 12. Predictions on One-Meter Sea Level Rise and County-Level Estimates of Social Vulnerability for Florida



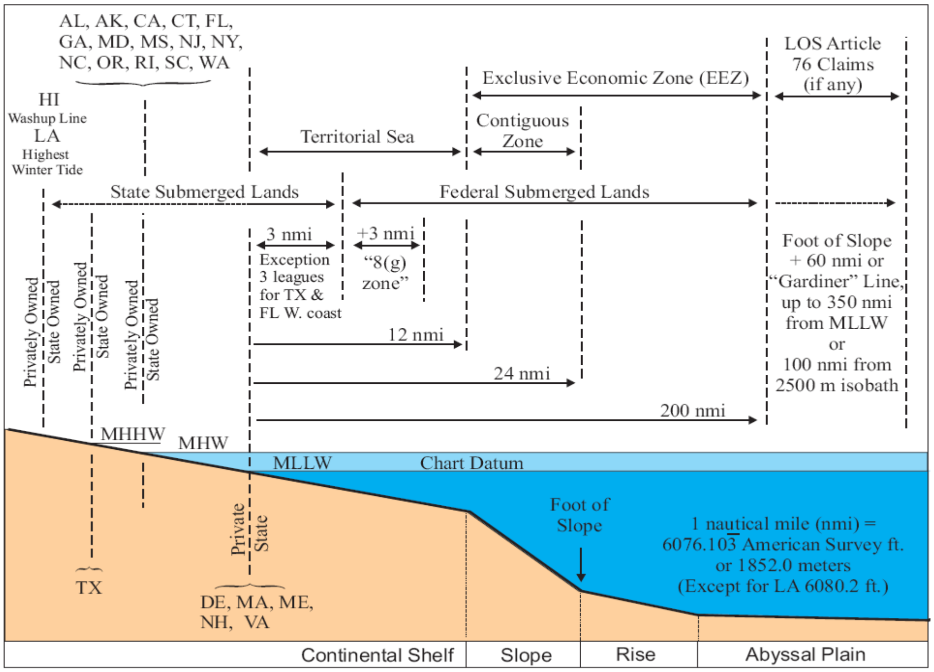
Source: Center for Remote Sensing of Ice Sheets (CReSIS), University of Kansas (https://www.cresis.ku.edu/research/data/sea_level_rise/esri_grids/)

Adaptive Capacity and Resilience

Because many marine and coastal natural resources, such as marine fish stocks and coastal open space (estuaries), are common pool resources suggests that enhancing the adaptive capacity and resilience of the system will often require government intervention. The extent and level of intervention, however, will differ based on the nature of the rights over the resource. For example, allocating rights to harvest a share of the fish stock each year is a means to provide incentives to owners of the shares to cut back their fishing to maintain larger populations that might be more resilient to climate change. Marine biodiversity, however, is a public good requiring government protection. In some cases, the federal government has a direct role (managing resources within federal waters), and in others, the local land-use planning agencies or state-level resource management agencies (which may address coastal land use or manage resources within state waters, respectively) are probably best suited to design the appropriate adaptation policy.

An important issue with respect to the role of state and federal government intervention revolves around the delineation of legal boundaries in the coastal and marine environment. Figure 13 presents a detailed picture of the different boundaries within this environment. Important distinctions among states depend on where private property rights end and state rights begin. In states such as Delaware, Massachusetts, and Maine, the boundary depends on the mean lower low-water mark; it is the mean high-water mark for states such as California, South Carolina, Rhode Island, and others; Texas uses the mean higher high-water mark; and Louisiana and Hawaii use the highest winter tide mark.

Figure 13. Private, State, and Federal Rights to Coastal and Marine Resources



Notes: LOS, Law of Sea; MHW, Mean high-water; MHHW, mean high high-water; MLLW, mean lower low-water mark.
Source: U.S. Department of Interior. Mineral Management Service.

These boundary definitions and their interactions over time with sea level rise are important for several reasons. For example, public access to the coast can become inhibited as the boundary line moves inland because of inundation and erosion. This could happen if the high tide line moves inward and onto private land. A related issue is that land currently above the boundary and in private ownership can end up on the state-owned side of the boundary with SLR (Titus 2000). As discussed in (Caldwell and Segall 2007, 553), in 1998 the California supreme court ruled that

> The high water mark is the mark made by the fixed plane of high tide where it touches the land; as the land along a body of water gradually builds up or erodes, the ordinary high water mark necessarily moves, and thus the mark or line of mean high tide, i.e., the legal boundary also moves.

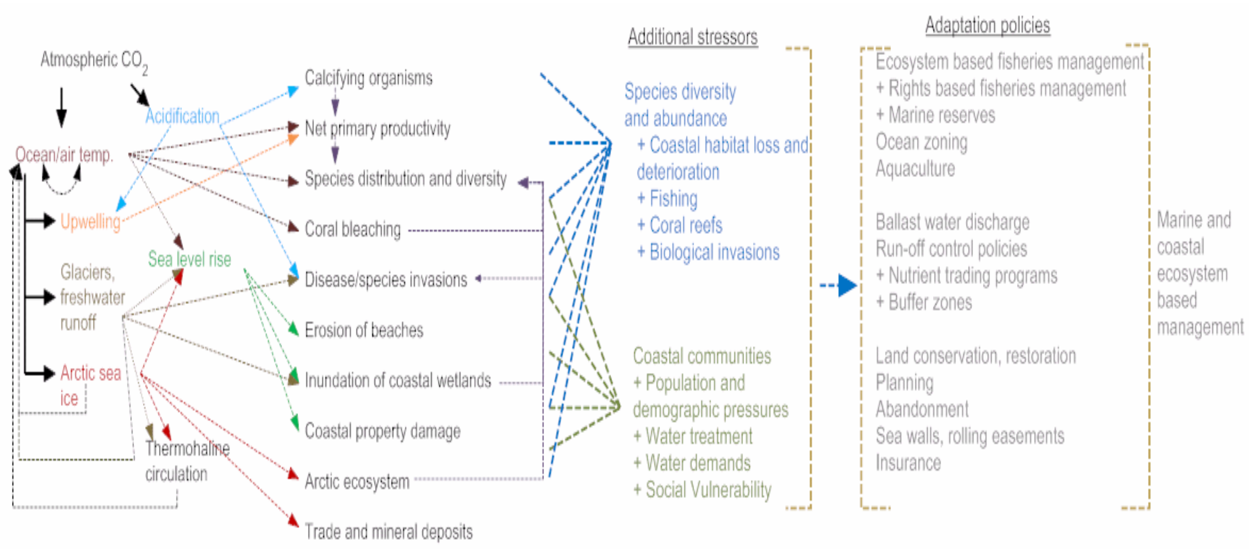
The ruling goes on to support the use of the Public Trust Doctrine as a justification for usurping private lands along the coastline as the lines move to ensure that the public has access to the beach (Caldwell and Segall 2007). Of course, incentives encourage landowners to prevent the encroachment of the sea by putting up seawalls and other barriers. We discuss these issues in further detail below.

In addition to the coastal boundaries, Figure 12 highlights the role of state and federal responsibilities in marine resources. Off of most coasts, states have jurisdiction over the area from the coast out to 3 nautical miles and the federal government regulates the area from 3 to 200 nautical miles. For federal fishery resources, NMFS works in conjunction with the eight fishery management councils to set fishery regulations. Council membership includes commercial and recreational fishing interests, tribal representatives (in some regions), state fish and game representatives, and other political appointees of the governors in the region. When considering the effects of climate change on marine resources, jurisdictions are important because of differences in the topography of the coasts, such as the location of the continental shelf and the effects of eutrophication, which occur mainly within the zero- to three-mile limit.

In many respects, none of the tools that are part of the portfolio of policy options (see Figure 13) to improve the adaptive capacity of the marine and coastal environment is novel, nor is the argument that society needs to employ the entire suite to improve the health of marine and coastal ecosystems. The use of a suite of policies and the acknowledgement that we need to manage a system rather than just the system's parts and that we need to consider the cumulative impacts of stressors is simply the implementation of EBM principles and ideals. As defined in a scientific consensus statement (McLeod et al. 2005), EBM emphasizes the protection of ecosystem structure, functioning, and key processes; is place-based, focusing on a specific ecosystem and the range of activities affecting it; explicitly accounts for interconnectedness within systems, recognizing the importance of interactions between many target species or key services and other nontarget species; acknowledges the interconnectedness among systems, such as between air, land, and sea; and integrates ecological, social, economic, and institutional perspectives, recognizing their strong interdependences.

A sample of the suite of federal, state, and local policies for marine and coastal EBM is illustrated in Figure 14 and includes: investments in habitat restoration, permitting decisions under Section 404 of the Clean Water Act, the purchase of coastal lands, controls for reducing nonpoint and point source pollution upstream of intertidal estuaries, the inspection and prevention of invasive species, MPAs, incentive-based fishery management policies, and in general a better definition of rights to marine and coastal resources that creates stewardship incentives. In what follows, we discuss mechanisms that can be used to improve the health of the marine and coastal environment in anticipation of the changes that are likely to come from climate change. From a climate change perspective, this is in a sense akin to preventive medicine rather than trauma care. In many cases, however, the historical mismanagement of the additional stressors has already put these resources on life support.

Figure 14. Suite of Adaptation Policies for Coastal and Marine Ecosystems



Marine and Coastal Ecosystems

Within the United States, a number of marine EBM activities are underway, including efforts in the Florida Keys Marine Sanctuary, Chesapeake Bay, Morro Bay, many of the estuary reserves in the National Estuary Program, and the Bay–Delta in northern California.[28] NOAA has also established integrated ecosystem assessments (IEAs) and management as a strategic priority where, according to NOAA's definition (www.noaa.gov), an IEA is "a synthesis and quantitative analysis of information on relevant physical, chemical, ecological, and human processes in relation to specified ecosystem management objectives." Components of intended IEAs include assessments of baseline conditions, the identification of stressors on the system, forecasts of business-as-usual policies, and the quantitative analysis of various policy alternatives.

Current EBM activities include top-down regulatory approaches and bottom-up grassroots attempts to bring stakeholders together. Morro Bay in Central California, for example, is a combination of a grassroots and a national effort consisting of a locally grown marine interest group, a science and ecosystem alliance community group, and the National Estuary Program. Collaborative agreements and partnerships form the bulk of the current efforts in Morro Bay. To

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[28] Other areas where more holistic approaches to ecosystem management are either underway or in the planning stages include the Gulf of Mexico Alliance, Puget Sound Partnership, Great Lakes region, and the Gulf of Maine. See the report by the Environmental Law Institute (2007) for a background discussion of these and other efforts.

date, outputs have been education campaigns, but there are some ongoing efforts to work with the California Department of Fish and Game to change local regulations on nearshore fisheries.

Most of the current examples of EBM efforts are not far along in planning and implementation and, in many instances, the bodies formed to consider multiple user impacts and coordination act in an advisory role with no regulator functions. This is especially true in the incorporation of spillovers from outside the boundaries of the defined management efforts. In the Florida Keys National Marine Sanctuary, for example, a water quality protection program "recommend[s] priority corrective actions and compliance schedules addressing point and multipoint 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 on the water"[29]. This program stems from a Congressional directive to EPA and the state of Florida. On paper, these types of collaborations are critical, but in many cases, the long-term funding to implement them are lacking. The lack of decisionmaking authority is also a serious limitation of many of the more top-down initiatives.

A broader policy tool that could be used to implement EBM is a comprehensive ocean zoning plan (Courtney and Wiggins 2003; Eagle et al. 2008). Under such a plan, state waters and the U.S. EEZ would be divided into areas with prescribed uses, such as recreation or conservation (Eagle et al. 2008). With an appropriate mix of protected and fishing areas, zoning may be a way to protect critical habitat while restructuring incentives in a way that discourages overcapitalization by harvesters and promotes fishery stewardship. Although zoning has not seen wide application in the United States,[30] large-scale zoning has been put in place within Australia's Great Barrier Reef Marine Park (Day 2002). Flexibility is a critical component in a zoning plan and can be incorporated by allowing parties to trade access and resource rights both within and across zones (Sanchirico et al forthcoming).

Although EBM is a holistic approach taking into account the multiple and diverse values derived from the resources in the system (McLeod et al. 2005), we discuss adaptive practices with respect to the management of marine fisheries and marine biodiversity separately. Of course, comprehensive planning and integration of these components is necessary to improve the health of the ecosystem at the lowest possible cost to society.

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[29] Florida Keys National Marine Sanctuary and Protection Act, Public Law 101-605 (H.R. 5909), Nov. 16, 1990. Available at http://floridakeys.noaa.gov/regs/sp_act.html

[30] In 1990, the Florida Keys National Marine Sanctuary management plan was built around a zonal framework, which is mandated under Section 7(a)(2) of the Florida Keys National Marine Sanctuary and Protection Act. The zones include existing management areas, wildlife management areas, ecological reserves, sanctuary preservation areas, and special use areas. Each of these zone types is designed to reduce damage to resources and threats to environmental quality while allowing uses that are compatible with resource protection. The zones protect habitats and species by limiting consumptive and/or conflicting user activities and allowing resources to evolve in a natural state with minimum human influence.

Marine Fisheries Management

A consensus has emerged supporting a mode of fisheries management that departs from policies aimed at maximizing the sustainable yield of commercially valuable species in a single-species framework. Ecosystem-based fishery management (EBFM), which is a subset of the broader EBM approach, provides a general orientation for policymaking aimed at realizing long-term benefits from key fisheries through monitoring and regulating human intervention at all levels of an ecosystem (Pew Oceans Commission 2003; U.S. Commission on Ocean Policy 2004). An example of how EBFM might differ from traditional approaches is the management of predator and prey species. EBFM would set aside additional prey species (through lower directed fishing on the prey) for predators in the system, where the set of predators might include marine mammals along with commercially valuable fish stocks.

Implementing an EBFM plan will involve the use of a number of existing policy instruments, such as area closures and other restrictions on fishing inputs (vessel and gear restrictions), individual fishing quota (IFQ) systems, and fishing cooperatives. Area closures have a long history in fisheries management, especially when it comes to setting aside nursery habitat.[31] Recently, the use of area closures for fishery management has gained considerable momentum (Hughes et al. 2005; Pikitch et al. 2004; Botsford et al. 1997), where closures could possibly increase fish stocks in nearby unprotected waters through outward migration of adult fish or larval dispersal. The effects of closures for fishery management remain uncertain, with some bioeconomic studies predicting that reserves may not produce harvest gains, especially when the spatial distribution of fishing effort is already resulting in de facto reserves (Smith and Wilen 2003).

IFQs and fishing cooperatives have been shown to address the economic waste (Sanchirico 2008) associated with the use of fishery resources. IFQ programs are analogous to other cap-and-trade programs, such as the sulfur dioxide allowance-trading program. They limit fishing operations by setting a total allowable catch (TAC), which is then allocated among fishing participants, typically based on historical catch. In most IFQ fisheries throughout the world, participants are able to trade their perpetual right to a share of the TAC and their annual catch equivalent.

Cooperatives, such as the Pacific Whiting Conservation Cooperative and the two in the North Pacific Pollock Fishery, are formed around a fishing sector such that the set of participants is fixed and the sector has received an allocation of the allowable catch. The allocation of the cooperative's allowable catch to each member, along with any trading among the members, is done through private negotiations and rules as outlined in their charter.

Although IFQs and cooperatives differ from an instrument design perspective and the respective roles of government intervention, both treat the cause rather than the symptoms of insecure rights to marine resources (Wilen 2006). That is, the allocation of shares of the TAC reduces the incentives to race for fish, as participants have greater certainty on their catch levels, and the ability to buy and sell shares provides flexibility for participants to adjust the scale of their

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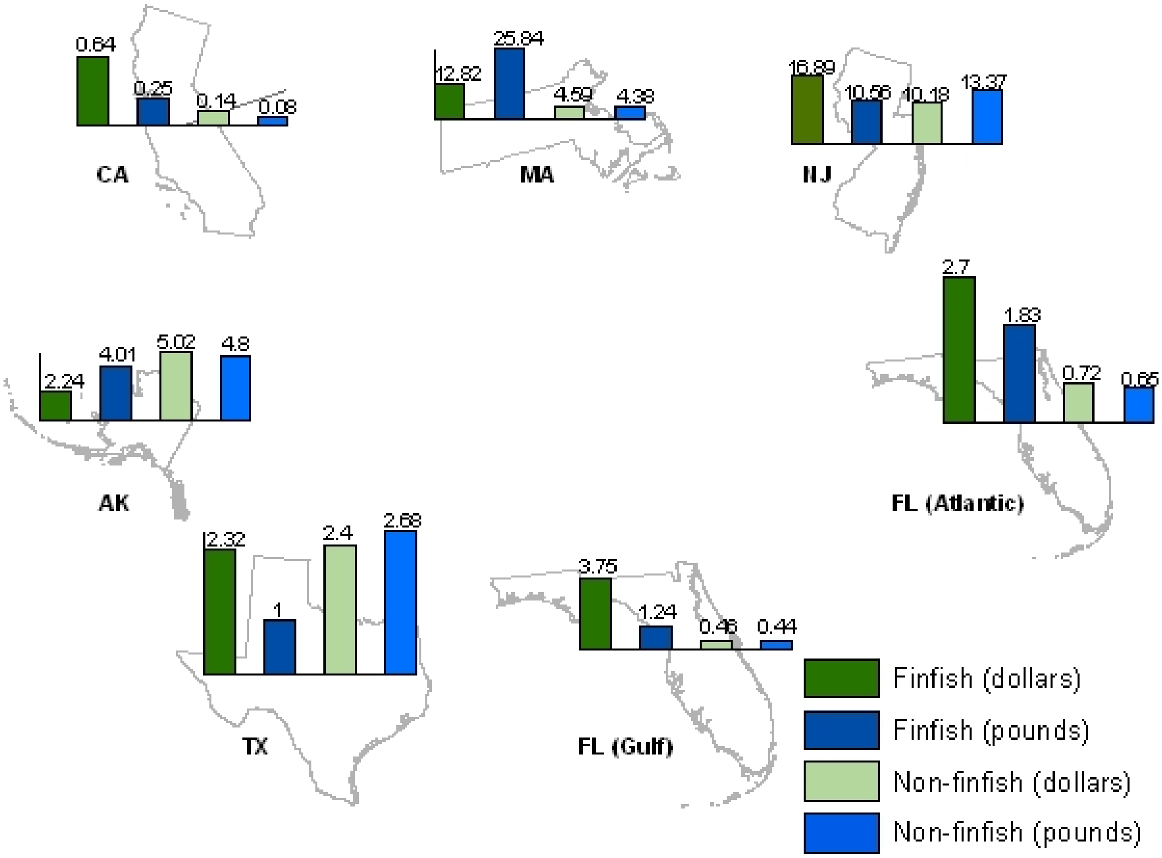
[31] For many species, nursery habitat occurs in the coastal zone that is impacted by runoff and habitat destruction.

operations. It also provides fishermen with stewardship incentives, as the value of their asset (fishing quota) depends on the ecological health of the system.

Typically, IFQs have been allocated by species–area combinations, and rules are often put in place to prohibit trades within the same species but across these species–area combinations, which makes sense in a relatively stable environment. With climate change, however, the rules that prohibit trading across species–area combinations might need to be revisited, especially as species ranges change. Other rules in these systems include the allocation of shares of the TAC to different fleets (e.g., trawler allocation for species Y) and a prohibition on converting a quota in one species to a quota in another species.[32] Each of these restrictions needs to be rethought in a changing climate.

Figure 15. Share of Commercial Landings between 0 and 3 Miles and between 3 and 200 Miles Offshore



Note: The numbers represent the ratio of catch or value from the area 3–200 miles to the catch or value from the area within 3 miles of the coast for 2007. *Source:* NMFS. 2007

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[32] An exception to the intraspecies trading rule is the cod equivalence system in place in Iceland. For more details, see Sanchirico et al. (2006).

The task of transforming existing fishery management into EBFM presents a number of challenges. First, the appropriate role of federal versus state regulators in setting policies varies across the United States because of the distribution of species and topography. For a subset of the coastal states, Figure 15 illustrates the ratio of commercial landings of finfish (e.g., salmon, halibut, Pacific cod, menhaden, and flounder) and non-finfish (e.g., crabs, urchins, lobsters, kelp, and squid) caught within the 0- to 3-mile range, which is under state jurisdiction, and between 3 and 200 miles, which falls under the management of regional fishery management councils.[33] A ratio above one implies that a larger share is caught 3–200 miles offshore. We also illustrate the share of the total revenue from each of these regions, which can differ from landings based on the differences in the price of the catch.

In California, where the continental shelf is relatively close to shore and where there is a strong coastal upwelling, the majority of finfish and non-finfish catches are within the zero- to three-mile range. Massachusetts and New Jersey are noticeable for the skewed distribution of their catches from federal waters. Florida's East and West Coasts vary with respect to finfish, but non-finfish are mainly caught within the zero to three miles; this is not surprising given the distribution of coral reefs and the species that make up the majority of the inshore catch (blue crabs, spiny lobsters, and shrimp). The location of the fishing activity implies that in California, for example, the California Department of Fish and Game has a larger role to play in setting EBFM policies than the Pacific Fisheries Management Council.[34] The location also highlights the potential vulnerability of a particular region to climate change.

Second, the jurisdiction over marine resources is often shared by state and federal authorities (Day 2002). Aspects of the EBFM approach have been included in plans for some regional jurisdictions, such as the Chesapeake Bay and South Atlantic fishery ecosystem plans (FEPs); however, the ecosystem approach has not been officially implemented at the wider regional level (Crowder et al. 2006). The preliminary efforts of the North Pacific Fisheries Management (NPFM) Council provide one example of how EBFM might in the future be achieved largely through coordinating existing regulatory bodies (Leslie and McLeod 2007). Draft work envisions the development of criteria for defining the Aleutian Islands as an ecological region and creating an FEP that would guide the management of federal and state fisheries as well as the Alaska Maritime National Wildlife Refuge.

Third, although there is general agreement among fishery scientists and managers about the need to develop FEPs, many of the hard policy questions remain on the table, such as what a "true" ecosystem management plan entails (Link 2002). It is also not clear what the ecological and economic trade-offs inherent in an ecosystem plan would be. For example, will ecosystem plans entail overharvesting some species to remove predation pressures so that others might prosper? What happens when one sector of the economy is dependent on the species whose population

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[33] The distribution of recreational fish catches is largely within the 0- to 3-mile range. Some exceptions are charter boats in New England that fish in the Gulf Stream and recreational fishing for highly pelagic species, such as tuna, off of the West Coast.

[34] Interestingly, Massachusetts is going forward with an ocean zoning regime within state waters, but as Figure 14 illustrates, a significant amount of the fishing pressure is occurring in federal waters, implying that a strong federal–state partnership is needed for EBFM to have an effect on the Northwest Atlantic ecosystem.

abundances are to be reduced? Furthermore, little information exists regarding the value to society from recreational fishing for different species and the nonconsumptive values placed on marine biodiversity, including the value of populations of forage fish and marine mammals. These are two areas where research will help managers understand the monetary values associated with EBM management.

In addition to addressing incentives in fisheries management, there is growing interest in increasing private investments in offshore aquaculture operations in federal waters. Although offshore aquaculture is not often mentioned as an adaptation policy, it can serve as a means to offset potential shortfalls in capture fisheries production due to climate change. For example, if changes in coastal upwelling processes reduce the food availability for certain species, resulting in population declines, then offshore aquaculture operations (not impacted by the coastal changes) might be able to substitute for this shortfall. Outstanding environmental issues with aquaculture operations include: the share of wild fish that is needed per pound of farm-raised fish; the impacts of concentrated wastes, including antibiotics; and the escapement and interbreeding of wild and farm-raised stocks. For many species, moving operations offshore, where water circulation and mixing are greater (that is, out of protected bays and estuaries), will reduce the latter two impacts. Over time, technological improvements and, in particular, the use of fishmeal substitutes has reduced the former.

For the past couple of years, the U.S. Congress has been debating the necessary provisions for an act that will develop guidelines for offshore aquaculture operations, including leasing and environmental safeguards. Because the uncertainty around the rules and regulations is delaying the development of the industry, passing the act seems like an important first step. Some states have begun to undertake the research necessary for the development of offshore aquaculture. For example, Hawaii formed the Hawaiian Offshore Aquaculture Research Project, through which research has been conducted on a number of species, including Pacific threadfin (Kam et al. 2003).

With respect to coral reefs, one adaptive policy would increase the protection of grazers via restrictions on fish catches and areas of fishing. This is especially true in the Caribbean where the parrotfish is the only grazer in the system (Mumby et al. 2006). Another policy is the potential reintroduction to the system of urchins (Wells 1995), the grazing prowess of which has been likened to that of sheep. The lack of grazers is believed to reduce the resilience of coral reefs to bleaching (Hoegh-Guldberg et al. 2007). To protect deep-water coral reef habitats and seamounts the NPFM Council closed approximately 280,000 square nautical miles in the Aleutian Islands to bottom trawling.

Currently, recreational fishing is managed with bag limits and time and area closures. Given that saltwater angling is a large and growing sector, along with the diffuse nature of the anglers, Sutinen and Johnston (2003) have argued for the use of angler management organizations (AMOs) as a means to better align the incentives of anglers with conservation. The concept of AMOs is similar to hunting clubs that have an incentive to maintain quality hunting grounds. The AMO would be allocated catch that it would decide how to distribute to its members, and the AMO would be responsible for monitoring and enforcing the catch rules. By creating such an umbrella organization, regulators would be able to hold the organization liable for catches in excess of its limits (e.g., by withholding catch the next year). Eagle et al. (2008) discuss how the creation of dominant use rights to areas for recreational fishing can be the catalyst for the creation of AMOs, rather than a top-down process of club creation, and can provide the AMOs with better-defined access rights. The latter is critical for establishing incentives to maintain quality fishing grounds.

Marine Conservation

A conservation ethic that is gaining momentum argues that marine biodiversity conservation is just as important as returns from seabed mining, oil and gas exploration, and commercial and recreational fishing for society's well-being and the ability to adapt to climate changes. Some argue that setting catch limits might be enough to address conservation and adaptability concerns if, for example, all species had their catches reduced by some percentage to account for in situ values. Others argue for the use of no-take areas or MPAs (Hughes et al. 2005). This is a false choice, however, as there are probably situations that would call for adjusting catch limits and the use of closures depending on the species, characteristics of the fishing industry, and other stakeholder interests (Sanchirico et al. 2005).

MPAs have been offered as a means to effectively hedge against overexploitation by protecting critical habitat and biodiversity in addition to possibly increasing the health of the system in nearby unprotected waters through outward migration of adult fish or larval dispersal (Lubchenco et al. 2003; Sale et al. 2005; Zinn et al. 2008). Existing marine reserves differ widely in their permitted uses. As with the design of incentive-based approaches, the design of MPAs needs to account for the likelihood that species ranges—at least the ranges of midlatitude species—will move toward the poles as the oceans warm.

A number of studies provide evidence of elevated biodiversity within protected areas, with the greatest benefit accruing to nonmigratory species (Halpern 2003). Harborne et al. (2008) find a greater abundance of high-value species and grazers as well as a higher degree of overall fish species diversity within the Exuma Cays Land and Sea Park (ECLSP) relative to similar unprotected reef areas in the Bahamas. Examining the same MPA, Mumby et al. (2006) find evidence of increased coral recruitment as a result of additional grazing activity within the ECLSP. Evidence of MPAs resulting in higher fish stocks in unprotected waters has been considerably less robust. Examining 18 years of data on surgeonfish (Acanthuridae) and jack (Carangidae) biomass in and around a no-take coral reef zone near Apo Island in the Philippines, Russ et al. (2004) find evidence of higher biomass of both families within 200–250 meters of the MPA boundary. Extrapolating these results to a changing ocean, however, is risky because most of these studies were carried out in relatively stable local marine environments.

In 1999, California passed the Marine Life Protection Act, which emphasizes the protection of marine life and habitats while also improving recreational and educational opportunities via the creation of a network of MPAs. The types of MPAs include marine reserves, marine parks, and marine conservation areas, where the distinction is based on the types of uses permitted. Although the Act tries to minimize the impacts on commercial fisheries, it is primarily focused on conservation. Determining the design of the marine reserve network has involved dividing the state into regions and the use of a stakeholder process that is substantial and often contentious. Oregon has also just announced plans to move forward with the development of a marine reserve network off of its coastline.

In addition to the conservation of marine areas, the persistence of many marine species in the face of climate change requires additional protections and restoration of coastal nursery habitat. West Coast salmon stocks epitomize such needs. The impacts on salmon of the management of forestry land-use practices in the Pacific Northwest, coastal land-use planning, and instream water flows will need to be considered, especially if the timing and quality of the upwelling events off of the West Coast are disturbed as a result of climate change.

Invasive Species

Climate change is expected to remove or weaken key climatic and ecosystem barriers to the spread of NIS. Given the extreme difficulty and high cost of eradication of self-sustaining marine NIS populations, the most fruitful avenues for adapting to increased recruitment probability are regulations and incentive schemes targeting key introduction pathways, including ballast water, aquaculture, the exotic pet and aquarium trade, and the seafood trade (Ruiz et al. 2000b; Williams and Grosholz 2008). Nonnative species and pathogen introductions via commercial shipping, either through ballast water or hull fowling, are of primary concern. The majority of the more than 230 self-sustaining NIS populations in the San Francisco Bay–Delta ecosystem, for example, are thought to have arrived via this route, either from overseas or from invaded estuaries elsewhere in the United States (Buck 2006; Cohen and Carlton 1998).

Practices that have proven effective in combating NIS introduction through ballast water range from low-tech options, such as ballast water exchange outside of less-saline estuaries, to biocide and the use of treatment facilities, such as those currently in place at California ports (Buck 2006). Ballast water exchange is considered by some to be an inadequate response because it is ineffective against species capable of surviving more saline water or within drained ballasts.[35] Current alternatives that would allow for the treatment of ballast water are costly; the cost of retrofitting a single commercial vessel to enable it to interface with existing port-based treatment facilities has been estimated at close to $400,000 (Buck 2006). Although robust state-level ballast water regulations have been enacted by Michigan, California, Minnesota, Oregon, and Washington, the ideal regulatory approach would involve a combination of federally funded research into low-cost ballast water treatment and robust national standards for ships entering U.S. ports (Copeland 2008). Once low-cost technologies come online, the federal government could then implement a program to induce adoption by foreign vessels using a combination of mandates, inspections, and financial incentives.

Arctic Resources

Changing sea ice conditions have renewed interest in deep-sea fossil fuel deposits as well as controversy surrounding the status of the NWP and NEP. At present, the only binding legal regime governing the claims of the eight arctic states is the 1982 U.N. Convention on the Law of the Sea (LOSC), to which all but the United States are signatories (Browne 2005; Pharand 2007; Rayfuse

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[35] Also known as “no-ballast-on-board” conditions.

2007). Maritime boundaries in the Arctic under the LOSC have become increasingly controversial because of disagreements regarding appropriate methods for drawing baselines from which a nation's 200-nautical-mile EEZ is extended. Arctic nations are also permitted to claim potentially resource-rich continental shelf outside of their EEZs under the LOSC, up to 350 nautical miles or 100 nautical miles beyond the 2,500 isobath (Rayfuse 2007).

A spate of deep-sea mapping expeditions and increased military activity in the region may forecast future confrontation over shipping and conflicting claims of sovereignty over deep-sea arctic resources (Coile 2008, A1). The United States has signed, but not ratified, the LOSC, and enforces a 12-natucialmile territorial sea limit and a 200-nautical miles EEZ through bilateral diplomatic efforts under the Freedom of Navigation Program (Browne 2005). Ratification would ground U.S. territorial claims in the treaty and integrate the nation more fully in negotiations among the arctic states. To enhance multilateral cooperation in the region, the United States could also lend its support to a new treaty for environmental protection in the Arctic, beginning with regions outside of current national jurisdictions (Rayfuse 2007).

Estuarine Health and Coastal Land-Use Practices

The suite of federal, state, and local policies that address estuaries and coastal land use include: investments in habitat restoration, permitting decisions under Section 404 of the Clean Water Act, controls for reducing agricultural and urban water pollution, reduction in the incentives for landowners to build in low-elevation and coastal areas subject to flooding and storm surges, land conservation, building of armaments or easements, and regional planning.

Habitat Restoration and Permitting Decisions

Habitat alterations made in conjunction with valuable transportation, housing, or other development change the physical structure (e.g., placement of fill) or function (e.g., diversion of flow) of the coastal landscape. The Clean Water Act provides the U.S. Army Corps of Engineers with authority, along with EPA, to grant permits and a set of guidelines for permitting applicants to avoid the placement of fill in waters and, if avoidance is not possible, to minimize and then compensate for losses. Section 404(b)(1) of the Act focuses attention on how much and what type of mitigating actions will replace the functions of any lost habitat. In determining the level of mitigation necessary, the Corps relies on a biophysical analysis that emphasizes the functional characterization of wetlands (Brady 1990).

It is important to note that these decisions are made for numerous relatively small alterations and fills every year. For many of these decisions, measuring the loss in ecological function is very difficult or virtually impossible because of a lack of information on the role of a particular hectare of a wetland in the functioning of the entire wetland. Having said that, more attention should be paid to the cumulative impacts of these seemingly insignificant decisions and the value of a particular hectare in mitigating potential damages from storm surges and inundation in permitting decisions.

The restoration of degraded ecosystems is a direct method for adapting to a decline in habitat brought about by rising sea levels and changes in the hydrological cycle (Peterson et al. 2008; Simenstad et al. 2006). An open question is whether current restoration activities should focus on restoring (a) areas that are degraded and, when restored, will contribute to current diversity protection or (b) areas that are less likely to be affected by climate change with the idea that these areas could provide refuge for shifting populations. Although both efforts will restore ecosystem functions, emphasizing the former would shift the weight toward restoring functions under the current temperature, salinity, and acidification regime. In some cases, both goals could be accomplished simultaneously. In a study of restored oyster reefs in the Neuse River Estuary in North Carolina, Peterson et al. (2008) find that restored oyster reefs in oxygenated shallow water provided temporary habitat for predatory fish species during deep-water hypoxic events in Pamlico Sound in addition to their natural filtration function. Given the presence of potential productive habitat on state and federal lands (National Estuarine Lands), restoration efforts at both levels of government will probably be necessary.

Measures may also need to be taken to restore and maintain shoreline and barrier islands (Day et al. 2005; Titus 1990). Although beach nourishment efforts are typically costly and of uncertain value as a long-run solution to rising seas, they are among the only tools available to protect certain coastal wetlands and preexisting communities.[36]

Not only are wetlands vulnerable to SLR, prior flood control projects and developments near the high tide line have interfered with natural hydrological processes that are necessary to sustain the structure, function, and extent of wetland ecosystems. One such process is the inflow of sedimentation that is necessary to maintain wetland elevation. An adaptive policy might be to reduce the diversion of water into channels and other stream diversions to permit adequate sedimentation flows to build up coastal wetlands. For example, modification of water management systems is being considered in the Everglades and the Mississippi River delta as a way to increase freshwater and sediment supply to promote wetland development. Policies to increase sedimentation flows must be weighed against the possibility that they may contradict policies meant to reduce the increased variability of precipitation on agricultural and drinking water supplies.

Recent natural disasters have underlined the role that healthy coastal wetlands can play in protecting the interior from powerful storms. Danielsen et al. (2005) show that mangrove forests and nearshore plantations in many cases shielded villages in India from the 2004 Asian tsunami, whereas unprotected neighboring settlements were completely destroyed. Although mangrove forests exist in Florida and scattered throughout the Gulf of Mexico, they are not a significant type of coastal estuary. Other coastal land features might have roles in dissipating storm surges, however. For example, in the United States, Day et al. (2007) speculate that intact barrier islands and forested coastal wetlands in the Mississippi Deltaic Plain might have absorbed some of the force and storm surges caused by Hurricanes Katrina and Rita.

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[36] Beach nourishment is a process by which sand that has eroded is replaced with sand either trucked in or pumped from the local sea floor. To maintain beaches, nourishment activities must be done repeatedly, as they treat only the symptoms and not the causes of the erosion.

Agricultural and Urban Runoff

The prospect of climate change and altered precipitation patterns exacerbating the threat currently posed by dead zones and HABs suggests that new measures to reduce runoff may be needed. Nutrients from agricultural runoff are a primary driver of coastal eutrophication (Buck 2007; Howarth et al. 2002). In the case of the large Gulf of Mexico dead zone, approximately 56 percent of the annual nutrient loading of the Mississippi River has been attributed to agricultural runoff.

A number of farming practices and land-use measures have been proposed to reduce runoff (Greenhalgh and Sauer 2003; Sharpley et al. 2000). Conservation tillage practices—such as ridge and mulch tillage techniques—can decrease soil erosion below levels associated with conventional and moldboard methods. Land set-asides and restored riparian buffers can sequester N and P during storms before it enters waterways. Farmland deemed at high risk for generating runoff can also be taken out of production through existing programs like the voluntary federal Conservation Reserve Program (Zinn 2003). Other proposed measures include the use of ambient nonpoint pollution taxes or taxing of inputs based on their N and P content (Ribaudo et al. 1999) and the restoration of wetlands to reduce runoff (Moore et al. 2000).

Options for managing urban runoff include following adaptive planning principles for future development as well as modifications to infrastructure already in place. On the planning side, a new regime of watershed-scale stormwater management has been proposed that would move away from the rapid-conveyance model embodied in older American infrastructure and toward systems that maintain as much as possible of the natural structure of receiving water bodies (Roy et al. 2008). New methods for managing runoff are designed to temporarily retain stormwater and reduce the outflow of pollutants through infiltration, bioretention, and evapotranspiration (U.S. EPA Office of Water 2004).

The stormwater management policies put in place by the City of Portland, Oregon, illustrate runoff control measures that could be implemented by other municipalities to adapt to future climate change-induced weather patterns. Compelled by EPA under the Clean Water Act to curb combined sewer overflow into the Willamette River and the Columbia Slough, the city has combined infrastructure improvements in the form of three large diversion pipes with retention measures (City of Portland 2006). These include programs to promote bioretention measures such as green streets, green roofs, and rain gardens (City of Portland 2006, 2008). Portland has also put in place a downspout disconnect program that enrolled 22,800 households between 1995 and 2005 through a combination of targeted mandatory orders and fee exemption incentives backed by technical assistance from neighborhood groups (City of Portland 2006; Learn 1999).

Coastal Land Conservation

Federal and state governments have a number of tools at their disposal to implement conservation measures for both shoreline and existing coastal wetlands. For example, the U.S. National Estuary Program, created as part of the Clean Water Act, currently manages 28 estuaries throughout the lower 48 states. Resilience of coastal wetlands could be increased through additional government purchase or private donations of wetlands. The latter is especially important because close to 74 percent of the remaining wetlands in the lower 48 states are located on private property (Zinn 2006).

Conserving lands, however, does not necessarily have to be financed by the state or federal government. In fact, between 1998 and 2006, nearly 80 percent of the 1,550 land conservation referenda that appeared on state, county, and municipal ballots across the United States passed, and they passed by a wide margin (Banzhaf 2008). These referenda encompass a broad range of conservation objectives, such as the preservation of farm land; the protection of ecologically sensitive wetlands, meadows, and forests; and the creation of new recreational sites. Some of these measures have been initiated at the grassroots level and others by public officials.

Setbacks, Purchases, and Rolling Easements

Coastal erosion is expected to threaten a large number of existing properties in the coming decades. Many of these structures are presently armored with seawalls or other hard barriers that disrupt sediment flows to the shore and may ultimately obstruct wetland accretion (Scavia et al. 2002). Although all landowners will probably fight to keep their properties and their rights to protect them, society faces an important question regarding whether and when a property should be abandoned. In some cases, the answer might be never, especially if it is a unique or high-value structure, such as a cultural heritage site. Furthermore, it seems clear that the state and federal government do not have the right to evict tenants from a property that is *already* developed, at least without due compensation (takings clause of the 5th Amendment).[37]

State and federal governments could reduce the amount or type of disaster insurance available to existing coastal landowners to reduce the incentives to invest in refurbishing and strengthening seawalls over time. The National Flood Insurance Program (NFIP) insures high-risk properties from flood damage (U.S. Government Accountability Office 2007). In 2005, the program held 4.9 million policies. NFIP policyholders are, in some circumstances, required to adopt building practices to reduce flood risk or are required to do so after filing multiple claims. To reduce the likelihood that property owners in high flood risk areas will pursue maladaptive actions in the future, the federal government could tighten standards for new NFIP policies or even stop issuing policies altogether to certain regions.

In particular, the NFIP insures many properties at nonactuarial (below expected cost) rates (Titus and Neumann 2009). Existing rules present obstacles to adjusting rates upward to reflect

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[37] See Titus (1998) and Caldwell and Segall (2007) for in-depth discussions on the issues of takings in the coastal environment under SLR.

increased flood risks: property owners who have not significantly altered structures covered under their policies have the option of maintaining rates set under Flood Insurance Rate Maps (FIRM) when presented with new maps that would raise them. This has the effect of allowing rates to be "grandfathered in," leading to a divergence between the price signal embedded in the rate and the risk to the structure. In addition, close to a quarter of properties enrolled were built prior to the local adoption of FIRM-based rates and are directly subsidized.

We would also expect private insurers to respond to increasing risk to homes and business due to climate change by increasing homeowner rates in anticipation of the damages. In this case, government intervention in the market might be needed for the prohibition of insurance discounts to landowners who reduce their risks through maladaptive practices, such as building larger sea armaments. Approximately 10 percent of the Pacific Coast in California is armored, with about a third of Southern California protected (Caldwell and Segall 2007). A role for government intervention seems warranted because neither insurance companies nor homeowners are likely to internalize the societal costs associated with seawalls and similar structures, which include the increase in erosion, the decreased ability of wetlands to adapt to the changing conditions, and interference with public access to the coast (Titus 1998; Caldwell and Segall 2007).

In the case of *future* development, states have instituted a range of policies for adapting to anticipated erosion without the use of expensive and environmentally damaging barriers. These include bans on armoring and setbacks, which prohibit development seaward of a predetermined boundary (Titus 1998). States including Rhode Island have enacted broad prohibitions on armoring (Easterling et al. 2004). Land procurement programs, such as the Coastal Blue Acres program established by New Jersey, have sought to provide undeveloped buffers for existing properties (Easterling et al. 2004). One potential issue with the use of setbacks is that once the water level reaches the setback, there is, in essence, an implicit contract that landowners will be able to build seawalls to protect their homes (Caldwell and Segall 2007). Depending on the topography of the coast, however, a setback of a certain distance might be sufficient.

A more flexible approach than seawalls and setbacks, which is tailored toward the dynamic nature of coastal erosion, has been pioneered and successfully defended in the courts by the state of Texas (New Jersey Department of Environmental Protection 2007). *Rolling easements* are intended to induce property owners to yield to advancing shorelines or wetlands. They are a type of easement that prevent property owners from holding back the sea and moves or "rolls" with the rising seas. The advantage of a rolling easement are: (1) the lack of disturbance of sedimentation transport; (2) the potential for wetlands and other tidal habitat to migrate unimpeded; and (3) continued public access to the shore (Titus et al. 1991). A rolling easement can be implemented by statute, the permitting process, and eminent domain actions (Titus 1998; Caldwell and Segall 2007).

Regional Planning

The steady reshaping of the environment projected to occur during the next century will require modifications to existing development and new planning considerations for future building (Adger et al. 2007). Low-lying infrastructure in heavily developed areas may need to be modified to withstand rising sea levels and associated storm surges (Easterling et al. 2004). Some types of public infrastructure impeding natural processes will also need to be modified to increase the resilience of threatened ecosystems. In the Mississippi delta, an extensive canal system, tributary closures, and river dredging have deprived coastal wetlands of sediment necessary for vertical accretion (Day et al. 2005; Day et al. 2007). Future restoration efforts may involve the reopening of dammed waterways and the closure of some navigation canals to increase sedimentation.

New infrastructure in the United States will need to accommodate the projected effects of climate change. An example of incorporating adaptations into planning is the Confederation Bridge, a 13-kilometer long span linking Prince Edward Island with mainland Canada (Adger et al. 2007). The bridge was built one meter higher than needed to accommodate sea level rise. Given the uncertainty surrounding climate change outcomes, planners must work to avoid overshooting in their efforts to adapt infrastructure to future conditions (Adger et al. 2007).

The California Coastal Commission (CCC) plays an important role in the land-use planning of coastal areas as formalized in the California Coastal Act of 1976 (Caldwell and Segall 2007). Along with making permitting decisions—for example, on shoreline armoring—the CCC oversees the development by local land managers of their Local Coastal Plans (LCPs), which shape coastal land-use patterns.[38]

Discussion

The common pool, or public good, nature of many marine and coastal natural resources implies that enhancing the adaptive capacity and resilience of the system will often require government intervention. The extent, level, and necessity of intervention, however, will differ based on the type and geographical location of the resources relative to jurisdictional boundaries. For example, competition for harvesting marine resources in conjunction with a lack of well-defined property rights causes stakeholders to focus their attention on the near-term benefits and costs of actions. Government intervention in this case could better define the rights to the resource to provide the harvesters with an incentive to invest in the long-run sustainability of the system. A constituency able to take a more long-run perspective is much more likely to consider adapting their management and use to reduce the vulnerability of their resource to climate change.

Coral reef ecosystems are of particular concern, as many cold- and warm-water reef-building species are in decline. For cold-water corals, an adaptation policy could simply be to reduce the use of damaging gear, such as bottom trawling, in coral habitats. Where the damage has yet to occur, protections could also be put in place until additional research can be done on the likely environmental impact of the fishing gear. In both cases, it seems prudent to determine the likelihood ofthe location of the ASH in the near future and the depth of the corals. If the corals have a high probability of being submerged in undersaturated waters, then it might be advantageous to permit the use of profitable fishing gears, as these corals are less likely to survive with the coming

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[38] As Caldwell and Segall (2007) argue on page 545, the CCC “should consider encouraging the revision of LCPs…to steer new development away from areas vulnerable to the effects of SLR.” They also discuss the importance of using rolling easements to avoid future armoring.

changes.[39] Whether these efforts need to be initiated at the federal or state level depends on the distribution of corals relative to the boundaries. We already see efforts initiated by the Regional Fishery Management Council in the Pacific Northwest. In many cases, broad-based partnerships will need to be developed that have the necessary regulatory authority to make and enforce decisions. EBM efforts to date have mostly been lacking in the authority to make regulatory decisions.

With respect to coastal land use, an important distinction when discussing adaptation policies is whether an existing property is currently protected by armaments or whether we are considering future development. In the case of the former, the emphasis should be on permitting seawalls or other armaments that minimize the potential for additional shoreline erosion in neighboring areas and loss of access for the public (Caldwell and Segall 2007). Local and state land-use planners could require that all future developments use rolling easements that permit the use of the land up to the point where it becomes inundated—that is, as long as development along the shore is proven to be a worthwhile investment in the face of the changing risks. Finally, government insurance programs that reduce the barriers for development of low-lying coastal areas should be replaced with programs that assist local land managers in developing more sustainable urban designs.

Although abandonment or the strategic retreat from a place is a politically difficult position to take that has many potential distributional and social justice consequences, the question of if and when to retreat needs to be in the forefront of the dialogue on adaptation policies. This is true for decisions regarding coastal habitat restoration in the face of sea level rise, habitat protections, and development in highly vulnerable locations such as barrier islands. With abandonment not in the feasible set of policies, cost-effective adaptation policies will remain elusive.

In general, an adaptation framework that embodies a more holistic planning and decisionmaking structure will expand on the set of factors to consider when designing policies, including the baseline from which we are measuring changes, the type of regulation or rule (e.g., liability, command and control, or an incentive-based approach), the level of control, the set of actors to consider, the time frame, and the spatial scale and scope of the policy. At the same time, adaptations to climate-driven hazards and environmental stressors must fit within a portfolio that includes mitigation efforts. The design, implementation, and assessment of the effectiveness of these different types of risky investments become exponentially harder as the dimensions under consideration increase; this increases the difficulty of developing adaptation policies. Understanding, valuing, and managing these complex risks and trade-offs will require interdisciplinary teams of researchers along with adequate representations of stakeholders.

We conclude with a recommendation firmly grounded in economic theory: because the effects of climate change on marine and coastal areas are uncertain and we will have many opportunities to learn along the way, policymakers at all levels should focus on adaptive policies that are flexible, designed to facilitate learning about the system, and that avoid large, irreversible outlays of capital.

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[39] There is the possibility, of course, that if the changes occur over an extended period of time, the corals and other organisms will adapt (through evolution) to the changes.

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