RESTORE-ADAPT-MITIGATE:

RESPONDING TO CLIMATE CHANGE THROUGH COASTAL HABITAT RESTORATION

RESTORE AMERICA'S ESTUARIES

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Cover photo credit: Galveston Bay Foundation

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Restore America's Estuaries

2012

RESTORE AMERICA'S ESTUARIES

Restore-Adapt-Mitigate:

Responding to Climate Change Through Coastal Habitat Restoration

About Restore America's Estuaries

Restore America's Estuaries is a national 501(c)(3) nonprofit organization established as an alliance of eleven community-based conservation organizations working together to protect and restore the vital habitats of our nation's estuaries.

Acknowledgements

The authors wish to thank the many individuals who attended the March 2008 workshop that provided early input to the direction, topics, and review of this report. We are also grateful to Raymond Crew for helping with research and data collection, and to Jeff Benoit, Steven Bosak, Steve Emmett-Mattox, and Chris Lyons who assisted with preparing the final document. Final design and layout was done by Bazany Design.

This project was made possible through funding provided by the Henry Phillip Kraft Family Memorial Fund of the New York Community Trust, Marisla Foundation, and U.S. Fish and Wildlife Service-Coastal Program.

Please cite this report as:

Needelman, B.A., S. Crooks, C.A. Shumway, J.G. Titus, R.Takacs, and J.E. Hawkes. 2012 Restore-Adapt-Mitigate: Responding to Climate Change Through Coastal Habitat Restoration. B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.). Restore America's Estuaries, Washington D.C., pp. 1-63.

Published by: Restore America's Estuaries 2012

Stable URL: http://estuaries.org/reports/

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Executive Summary
Introduction

We treasure our coasts, from the tranquility of lapping waters to the thrill of the catch to the joy of a child building a sandcastle. Our lives and livelihoods are intimately connected with the health and prosperity of coastal waters and lands. Our coasts are already suffering from climate change—from the dramatic impacts of hurricanes to the incessant creep of sea level rise and ocean acidification. Climate change projections paint a dismal picture in which coastal habitats are degraded and lost over the coming decades—along with the coastal communities they support. We have an opportunity to respond to these projections with positive action to build resilient coasts and communities through conservation and proactive restoration efforts. The sooner that we take action, the less costly and more effective these efforts will be, and long-term planning is the most effective way to preserve these critical habitats and sustain our coastal communities.

This report is available online at http://estuaries.org/reports/.

The purpose of this report is to educate habitat restoration professionals, policy makers, and the public on the impacts climate change will have on coastal habitats and the possible role habitat restoration could play in mitigating those impacts. This is the first report that clearly demonstrates the opportunity to link the interconnectedness between coastal habitat restoration and adaptation and mitigation strategies related to reducing climate change impacts. They are not exclusive of each other, and if designed and managed correctly, can share mutual benefits. Much of this report is focused on policies and programs based in the United States, but many of the concepts, ideas and recommendations translate easily to other locales. In this executive summary, we summarize the findings and provide recommendations from the five chapters in this report. A glossary and a list of key organizations and publications are provided as appendices in the full report.

Chapter 1: Overview of Coastal Habitats

The United States possesses a rich diversity of coastal habitats which support the economies, cultures and ecologies of the coastal regions. This chapter provides background on the most important coastal habitats in the nation and includes examples of the primary restoration practices that are used to preserve, enhance, and re-create these ecosystems. There is also a brief introduction to ongoing efforts to quantify the economic and societal value of the many ecosystem services provided by coastal habitats.

Chapter 2: Climate Change and Coastal Habitats

Coastal habitats are already being affected by climate change and these effects are expected to increase over the next decades. This chapter presents an overview of how climate change is expected to alter several primary forces that have direct effects on coastal habitats. Coastal landscapes are inherently dynamic and therefore it is difficult to separate the effects of climate change from the effects of natural and human-induced forces. In this report, we take an integrated approach to coastal habitats and their management due to the strong linkages between climate change, coastal landscapes, and coastal communities.

Findings

Coastal habitats are being subjected to a range of stresses from climate change; many of these stresses are predicted to increase over the next century. The most significant effects are likely to be from sea-level rise, increased storm and wave intensity, temperature increases, carbon dioxide concentration increases, and changes in precipitation that will alter freshwater delivery. These climate change forces are having dramatic effects on coastal habitats and the species dependent on these ecosystems. Many of these effects are interactive, with non-linear responses sometimes characterized by critical thresholds. The fate of coastal communities and habitats are intertwined, necessitating long-term comprehensive planning.

Recommendations

- Use a multi-scenario approach to planning in the face of climate change to account for uncertainties in climate change estimates.
- Improve the management of sediment delivery to coastal habitats across climate change scenarios.
- Develop and implement management methods that will reduce elevation losses and increase elevation gains in coastal habitats.
- Understand potential mistiming between climate conditions and migration patterns.
- Develop regionally specific climate change scenarios, particularly for precipitation changes.
- Understand and identify interactions, non-linear responses, and thresholds in the response of coastal species and habitats to climate change, particularly for economically important and endangered species.

Chapter 3: Planning and Design

Considerations for Coastal Habitat Restoration in the Face of Climate Change

Restoration of coastal landscape is critical to meet the challenges of climate change and sustainable management. Purposeful restoration of wetlands began in the U.S. in the 1960s. Early restoration projects were small-scale and fragmented mitigation actions that were paid for by developers to compensate for regulatory enforcement of no-net-loss provisions. Now, an ecosystem-based perspective is proposed as a foundational element supporting U.S. policy for U.S. waters and connected lands. Restoration is now a central element to climate change mitigation and adaptation. This chapter explores key concepts and recent lessons learned in this rapidly growing field.

Findings

A number of lessons have been learned by practitioners in restoration than can be coalesced into recommendations for best practice. Overall, thoughtful planning can improve project outcomes and reduce costs. With climate change—and particularly sea level rise—there will be a need to think beyond planning for individual projects to evaluation of environmental tradeoffs across the landscape. Because of lag times in restoration and because windows of opportunity for successful restoration may close over time, there is an imperative to restore now rather than delay.

Recommendations

- Have a clear and coherent project planning approach.
- Restore at the landscape scale.
- Recognize landscape trade-offs and constraints.
- Restore physical processes and ecosystem dynamics.
- Given scarce resources, we need to prioritize our restoration activities by planning now for potential higher degrees of climate change.
- Planning for climate change is planning for land-use change with shifting boundaries and spatial frames of reference.
- Restore physical processes and ecosystem dynamics.
- Establish a design template that sets in place natural processes leading to an evolution toward a desired outcome.
- Understand the restoration trajectory.
- Restore coastal ecosystems sooner rather than later.
- Develop a learning curve by incorporating learning, experimentation, and adaptive management into ecosystem restoration.
- Recognize the value of restoration design.
- Recognize that the restoration of historic conditions is not always possible or desirable.
- Be patient—ecosystem restoration takes time, the extent of environmental disturbance may take decades to fully recover.

Chapter 4: Adapting to Climate Change by Restoring Coastal Habitat

Restoration can help coasts adapt to climate change, enabling coastal ecosystems to become more resilient. Conversely, if climate change impacts are ignored, coastal and estuarine restoration projects may fail over the long-term. Therefore, restoration must consider the impacts of climate change. In this chapter, four approaches to sea level adaptation are reviewed: Protect, Retreat, Accommodate, and Reduce Other Stressors. Responses to sea level rise and the often-overlapping impacts of shoreline erosion, increased tidal inundation, and increased flooding are also considered. The most fundamental choice for environmental managers is whether to attempt to maintain key ecosystems in their current locations or facilitate their migration, which would often require relocating most human activities away from the areas to which the ecosystems might migrate.

Findings

For restoration to succeed, we must do a better job linking humans, ecosystem services, and estuaries. Coastal communities need to be made more aware of the benefits natural habitats and species provide, and how costly it will be for them to replace the ecosystem services they provide with artificial substitutes. This requires better documentation of the economic benefits obtained at a local level from coastal resources, and it also requires outreach and education. Coastal communities also need opportunities to be directly and intimately involved with resilience and restoration efforts, to take part in visualization scenarios for their future, and to take part in the management of their coastal resources.

Recommendations

- Model estimates of resilience for different coastal habitats.
- Regionally prioritize restoration sites, considering threats, likelihood of success, and connectivity.
- Integrate restoration efforts in time and space.
- Given the uncertainties in the amount of sea level rise expected in a given region over time, identify and restore those sites likely to survive the upper range of sea level rise projected for the year 2100: 1.4 to 2 meters.
- Improve stormwater policies within coastal watersheds.
- Develop a triage for invasive species.
- Pursue the restoration of disease-tolerant native shellfish species.
- Identify and set priorities for those areas likely to benefit most from nitrogen reduction.
- Set priorities for the protection and restoration of areas threatened by coastal development.
- Restore animal/plant ecosystem engineers.
- Mitigate the adverse consequences of shoreline armoring.
- Test different approaches to adaptation.

Chapter 5: Mitigating Greenhouse Gases Through Coastal Habitat Restoration

Coastal habitats both absorb and release greenhouse gases from the earth's atmosphere. This chapter reviews the potential of coastal habitat restoration projects to create net removals of greenhouse gases such that these projects may be included in state, regional, and national greenhouse gas reduction programs and be eligible for funding through carbon crediting programs. It should be recognized that some projects may lead to a net increase in greenhouse gases; in such cases, this should be considered against other benefits of restoration.

Findings

Coastal habitats both emit and remove greenhouse gases from the atmosphere. Tidal marshes are the coastal habitat most appealing for greenhouse gas reduction goals due to their high rates of carbon sequestration (averaging 2000 lbs. C per acre per year). Some freshwater and brackish marshes emit methane, negating some or all of the carbon sequestration benefits of restoration in these systems unless project managers can control the methane emissions (e.g., through water management). The net greenhouse gas benefits of even large coastal restoration and conservation programs are likely to be relatively small when compared to national-scale emission reduction goals. Coastal habitat restoration and conservation programs may contribute significantly to state and regional-level greenhouse gas reduction goals, especially when aggregated. Carbon credits may provide a substantial funding source for coastal habitat restoration projects, particularly if restoration managers can blend carbon credit funds with revenue for other ecosystem services (e.g., portfolio funding or stacked credits), and if the value of carbon credits climbs higher.

Carbon sequestration is one of the many benefits of coastal habitat restoration. As the nation moves toward reducing greenhouse gas emissions and pursues adaptation strategies to reduce the negative effects of global warming, governments should consider the valuable contributions that coastal habitat restoration can make toward these goals.

Recommendations

- Develop cost-effective, reliable methods to estimate carbon sequestration and methane emission rates in coastal habitats, in coordination with limited direct sampling.
- Develop the capacity to predict the rate of return of carbon pools to the atmosphere following habitat loss so that avoided losses through conservation can be eligible for carbon crediting. Develop mechanisms to aggregate small and moderately sized restoration projects to allow access to carbon credit funding.
- Make carbon credits available to restoration programs that range from conservation of existing habitats to habitat creation.
- Determine the current rate of restoration in regions so that restoration practitioners can demonstrate "additionality" when they increase the pace of restoration projects using carbon credit funding.

Conclusion

The restoration and conservation of coasts is among of humanity's great challenges during this century. We are faced with tremendous uncertainty about the future, but with the knowledge that early action is necessary to sustain our coast habitats and the communities they support. We hope that this report serves as a useful resource to the communities, decision-makers, and restoration practitioners who will rise to this challenge.

Chapter 1: Overview of Coastal Habitats

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The United States possesses a rich diversity of coastal habitats, which support the economies, cultures and ecologies of the coastal regions. This chapter provides background on the most important coastal habitats in the nation and includes examples of the primary restoration practices that are used to preserve, enhance, and re-create these ecosystems. There is also a brief introduction to ongoing efforts to quantify the economic and societal value of the many ecosystem services provided by coastal habitats.

Coastal Habitats

There are a broad variety of habitats present in coastal areas—from the open ocean to near-shore woodlands. In this report we define coastal habitats as inclusive of coastal and estuarine areas. Typically the most economically and ecologically important habitats include estuarine waters, submerged aquatic vegetation, coral reefs, oyster reefs, wetlands, mudflats, beaches, barrier islands, deltas, dunes, and cliffs. Following are representative examples of each of these habitat types.

Estuarine waters

Figure 1-1 Estuarine waters exhibit a range in salinity, from fresh waters fed by rivers to salt waters primarily influenced by oceans. Estuarine waters are among the most productive in the world with a diversity of economically and ecologically important fish, shellfish, seagrass and other aquatic species. Source: Restore America's Estuaries

Seagrasses

Figure 1-2 Aquatic systems populated by seagrass and other submerged aquatic vegetation are critical ecosystems within estuaries. They improve water quality by providing oxygen to estuarine waters and trapping sediments and serve as essential habitat for fish and shellfish species. Source: NOAA

Chapter citation:

Needelman, B.A. 2012. Overview of Coastal Habitats. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore-Adapt-Mitigate: Responding to Climate Change Through Coastal Habitat Restoration. Restore America's Estuaries, Washington, D.C., pp. 7-13.

Coral reefs

Figure 1-3 Corals are small animals that produce and use calcium carbonate to build coral reef structures. Coral reefs are among the most diverse and productive ecosystems on earth. Most of the coral reefs in the United States are in southern Florida, where there are as much as 30 sq. km of potential shallow-water coral ecosystems. Source: NOAA

Oyster reefs

Figure 1-4 Oysters form large reefs that provide habitat for a wide range of marine plants and animals. Oysters feed by filtering microscopic plants from the water, in the process improving water quality and clarity. Native oyster populations are threatened by habitat loss, pollution, disease, and harvest pressure. Source: NOAA

Coastal Wetlands

Figure 1-5 Marshes are coastal wetlands vegetated primarily with herbaceous (non-woody) species. Although there is a wide diversity of marshes, many individual marshes are populated by only a few plant species. Marshes are categorized by salinity level, elevation, and landform. Seawater has a salinity of about 35 ppt (parts per thousand). Salt marshes usually have some freshwater inputs, but still have salinities greater than 18 ppt; brackish marshes have salinities of 0.5-18 ppt; freshwater marshes have salinities less than 0.5 ppt. Swamps are vegetated by woody species and are found in freshwater and some brackish systems.

Figure 1-6 Mangroves are coastal wetlands vegetated by a group of trees and shrubs of the genus Rhizophora. These species are able to tolerate salinity, unlike most tree species. Mangroves are limited in the U.S. to warmer regions, such as along the Florida and Gulf of Mexico coasts.

Mudflats

Figure 1-7 Mudflats (or tidal flats) are non-vegetated intertidal zones periodically inundated with water and characterized by fine-textured sediments. They are also high in organic matter. Mudflats are important deposition zones for sediment in estuaries and serve to protect coasts from erosion. They are important for wildlife, particularly migratory birds.

Coastal barriers and barrier islands

Figure 1-9 Coastal barriers, spits, and barrier islands protect coasts by dampening waves and mitigating storm surges. Natural barriers are often dynamic, shifting over time in response to erosion and sediment deposition during storms and through wave action. Sea level rise can erode or submerge coastal barriers and islands, a first step that leads to further degradation of coastal ecosystems.

Beaches

Figure 1-8 Beaches are highly dynamic, shifting gradually over time and rapidly due to storm events. Beaches provide nesting and feeding habitat for shorebirds. Beach erosion is a major source of habitat loss in coastal systems; the replenishment of beaches is a common and costly remediation strategy. Sheltered beaches, which are particularly important ecosystems both for their ecological and recreational values, are often an emphasis in coastal habitat restoration programs (National Research Council, 2007).

Deltas

Figure 1-10 Deltas originate from the deposition of sediment from rivers into coastal waters and often have components above and below the low tide line. The Mississippi River Delta is the largest and most ecologically important delta in the United States, but there are smaller deltas throughout coastal areas. A primary cause of delta habitat loss is isostatic subsidence—where the weight of the deposited sediment causes the delta to slowly sink unless the sediment is continually replaced. River channelization decreases this sediment delivery.

Dunes

Figure 1-11 Dunes form when sandy coastal soils are stabilized by vegetation. They are critical habitat for nesting shorebirds and a variety of other dune-dependent species. Dunes are highly susceptible to damage from vehicle and pedestrian traffic and other human activities. Source: USGS

Cliffs

Figure 1-12 Cliffs, bluffs, and rocky shore platforms constitute about three-quarters of the world's coasts. Cliffs are generally receding under the effects of erosion and weathering. Although they are not as biologically rich as other coastal ecosystems, cliffs and shore platforms are important habitats for many species.

Coastal Habitat Restoration

In this report, we define restoration as the manipulation of the physical, chemical, or biological characteristics of a site with the goal of enhancing, creating, or returning self-sustaining natural or historic structure and functions to former or degraded habitats. Habitat restoration projects can often be designed to provide additional value to an area such as preventing erosion, reducing flooding, and helping to reduce greenhouse gasses.

Many local and regional conservation organizations work in partnership with local businesses and state and federal agencies to restore the nation's coasts and estuaries. While restoration projects can involve a variety of habitat types involved, most efforts fall into one of the following categories:

Shellfish Restoration

Figure 1-13 Oyster bar restoration. Source: Elsa Carlisle

Shellfish restoration has become an important component of coastal ecosystem restoration efforts as a means to replenish native populations that have declined from a combination of overharvesting, poor water quality, and substrate removal. Typically, restoring shellfish bivalves within an estuarine system is accomplished through one of two methods, or a combination of both. One common method is to grow young "seed" shellfish in a protected environment to a sufficient size when they are then relocated to a suitable growing area in the estuary. The other common approach is to create or restore habitat that favors the natural "recruitment," or attraction, of waterborne shellfish larvae to settle and grow to maturity (Figure 1-13). For example, young oysters will attach themselves to collections of old oyster shells, often referred to as "oyster beds," "oyster reefs" or "oyster bars," or other suitable materials that offer protection as they grow. Oyster reefs can be created or enhanced by the use of old oyster shells, typically just dumped or scattered in deep water or sometimes placed in net bags and arranged in rows closer to shore. Also in use today are marine-friendly concrete domes which are placed to provide habitat for growing oysters.

Living Shorelines

Photo credit: Chesapeake Bay Foundation

Figure 1-14 Saltmarsh protected by low sill. Source: Restore America's Estuaries

Living shorelines are an innovative approach in which natural (or "living") habitat elements are used to control shoreline erosion, while restoring and/or preserving the characteristics of the estuarine habitats and upland buffers. Living shorelines typically use a low profile sill to absorb wave energy. Sills are generally constructed of rock, bags of shell or sand, concrete domes, or biodegradable materials (Figure 1-14). Behind the sill, wetland vegetation is planted to restore the lost habitat, provide a stormwater buffer, and reduce erosion. Living shorelines improve water quality by trapping sediments and filtering pollutants; provide shallow water habitat and a diversity of plant species for aquatic and terrestrial animals; provide shade to keep water temperatures cool, helping to increase oxygen levels for fish and other aquatic species; look natural rather than human-built and artificial; absorb wave energy so that reflected waves do not scour the shallow sub-tidal zone and hamper the growth of underwater grasses; and are often less costly than constructing wooden bulkheads and rock walls.

River and Stream Restoration

Figure 1-15 Restoration of Bride Brook in Niantic, CT has allowed herring to return for spawning. Source: Save the Sound

Rivers and streams provide important habitat, food, and spawning grounds for numerous fish species. They also deliver fresh water, sediment, and nutrients to estuaries. However, thousands of culverts, dikes, water diversions, dams, and other barriers have changed the natural flow of rivers and have blocked the passage and migration of fish to traditional spawning areas. The repair of collapsed culverts and the removal of dams that are no longer in use has proven to be an effective method to restore long stretches of streams and rivers (Figure 1-15). Where dams cannot be removed, the installation of structures that allow fish to pass around the obstruction, such as fishways and ladders, also help to restore fish passage and access to native spawning grounds.

Marsh Restoration

Figure 1-16

Marsh communities are critically important habitat systems that grow on the intertidal fringe of a bay, preventing erosion, buffering uplands from storms, absorbing pollutants, and providing shelter and nursery areas for many fish and wildlife species. However, many marshes have been lost due to stresses such as sea level rise, storms, and residential and commercial development and pollution. Marshes can be planted using nursery-grown or transplanted shoots of grass, or in some areas, mudflats are carefully prepared and marsh grass is allowed to re-establish through a natural seeding process (Figure 1-16). In either case, it is critical that the surface of the planting area is at the proper elevation to allow the marsh to grow and thrive.

Invasive Plant Removal

Figure 1-17

Invasive plants that are threatening native species are removed in this restoration technique (Figure 1-17). Invasive species such as the Himalayan Blackberry and Scotch Broom in Washington and the Brazilian Peppertree in Texas are removed to allow native plant species to re-colonize a restoration site.

Seagrass Restoration

Figure 1-18

Seagrass beds are a primary source of food and shelter to an abundance of marine life, including economically important finfish and shellfish. Seagrass grows in relatively shallow water and can be easily destroyed by boat propellers cutting long furrows creating "prop scars" across the beds. Impaired water quality—particularly poor water clarity—is another common cause of seagrass decline in some estuaries. Prop scars and seagrass beds are generally restored by harvesting shoots from healthy seagrass beds and transplanting them into damaged or depleted beds (Figure 1-18).

Ecosystem Services Provided by Coastal Habitats

Ecosystem services are the benefits that humans derive from natural systems, often without the need for human maintenance or any energy input other than the sun. Ecosystem services include harvestable goods such as wild fish, game, and lumber. However, ecosystems also provide many other valuable services to society such as cleaning the air and filtering water, decomposing wastes and recycling their nutrients, lessening erosion, and helping to regulate the water cycle. There are also aesthetic, cultural, and scientific benefits of natural places.

Coastal managers and communities need a better understanding of the relationship between ecosystem service value and cost in order to determine when ecosystem restoration would be cost-effective. This is an active area of research by academic and governmental agencies. The largest international project in this area is called the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005). In general, the first step is to categorize the various ecosystem services, quantify their values, and then compare the values of these services versus the cost of a given restoration strategy (de Groot et al., 2002; Farber et al., 2002; National Research Council, 2004). Quantifying ecosystem services poses significant scientific and policy challenges. One method to quantify ecosystem services is to measure services on a plot-scale in various ecosystem types and then use a model to estimate the changes in the land areas of these ecosystems across climate change scenarios (Craft et al., 2009). However, many ecosystem services do not easily scale from plot to regional scales or cannot be directly measured.

When it is not possible to assign monetary values to ecosystem services, other methods of comparison can be used to evaluate ecosystem services as long as the same method is applied to both services being compared. By rating or ranking ecosystem services based on their Net Primary Productivity (net production of biomass) or Net Environmental Benefit (Efroymson et al., 2004), trade-offs between services can be assessed (Pendleton, 2008). A combination of valuation methods are then used to identify the total economic value that an ecosystem provides for human well-being (Millennium Ecosystem Assessment, 2005; Pendleton, 2008).

Restored ecosystems rarely provide the same ecosystem services as natural ecosystems. For this reason, restoration projects should aim to achieve well-stated goals that are part of a broader process of planning, development, implementation, and evaluation (Millennium Ecosystem Assessment, 2005). It is imperative to understand the linkages between ecosystem restoration projects when buying and selling credits in environmental markets (Palmer and Filoso, 2009).

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Chapter 2: Climate Change & Coastal Habitats

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Chapter citation: Needelman, B.A., 2012. Climate Change and Coastal Habitats. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore-Adapt-Mitigate: Responding to Climate Change Through Coastal Habitat Restoration. Restore America's Estuaries, Washington, D.C., pp. 14-22.

This chapter presents an overview of how climate change is expected to alter several primary forces that have direct effects on coastal habitats. Coastal habitats are already being affected by climate change and these effects are expected to increase over the next decades. Coastal landscapes are inherently dynamic and therefore it is difficult to separate the effects of climate change from the effects of natural and human-induced forces. In this report, we take an integrated approach to coastal habitats and their management due to the strong linkages between climate change, coastal landscapes, and coastal communities.

Climate scientists are monitoring and modeling a variety of forces that will be altered by climate change that will dramatically affect coastal habitats. In many cases, we can be highly certain that these changes will occur, but it is difficult to make precise predictions. For example, the exact rate of future sea level rise is unknown, yet there is a high degree of certainty that sea level rise is accelerating. Planners will likely need a multi-faceted approach to develop responses for a range of climate change scenarios.

Sea Level Rise

We are in a geological period of rising seas. Most scientists agree the rate of sea level rise is accelerating as a result of climate change. The increasing rate of sea level rise may be the single most important impact of climate change on coastal habitats.

Eustatic sea level rise

Eustatic sea level rise refers to the increase in volume of the world's oceans, which occurs primarily through thermal expansion (water expands when it warms) and additions of water. Sea level rose at an average rate of 0.07" (1.8 mm) per year from 1961 to 2003. From 1993 to 2003, however, that rate of rise accelerated to an average of 0.12" (3.1 mm) per year (IPCC, 2007b). While this data shows an upward trend in sea level rise, predicting future sea level rise remains a challenge due mostly to uncertainty over the rate at which land-based ice sheets will melt, such as those in Greenland and Antarctica.

The IPCC has published a series of global-scale sea level rise scenarios based on various climate change scenarios ranging from an increase of 0.6 to 1.9 feet (0.18 to 0.59 m) by 2100 (IPCC, 2007b); however, these scenarios do not account for land-based ice melting. When estimates attempt to account for land-based ice melting, predictions of eustatic sea level rise are often about 3.3 feet (1 m) and range up to nearly 6.6 feet (2 m) by the end of this century (Pfeffer et al., 2008). Such a large sea level rise would cause catastrophic inundation of many coastal landscapes and communities in the U.S. and the rest of the world. The current scope of planning time horizons makes it difficult to account for the range of possible sea level rise scenarios.

Relative sea level rise

The elevation of coastal land surfaces can change significantly over even short time scales. Therefore, coastal planners are ultimately concerned about the elevation of a land surface relative to sea level—termed relative sea level rise—rather than just the elevation of the sea itself. The relative elevation of coastal landscapes is highly dynamic in relation to the

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For more detailed reviews of this topic, see the U.S. Climate Change Science Program's chapter on National Estuaries in their report Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources (Peterson et al., 2008), the IPCC's chapter on "Coastal Systems and Low-lying Areas" in their report Climate Change 2007: Impacts, Adaptation and Vulnerability (Nicholls et al., 2007), and the chapter "Future Coasts" in the text Coastal Geomorphology (Bird, 2008). For details on the Gulf Coast Region, see the report Confronting Climate Change in the Gulf Coast Region: Prospects for Sustaining our Ecological Heritage (Twilley et al., 2001).

elevation of the seas. Coastal landscapes themselves are constantly rising or lowering in response to deep and shallow geologic and geomorphologic processes. Therefore, sea level rise must be understood in the context of the many factors influencing the elevation of the land relative to the sea, both world-wide (eustatic), regionally, and locally. [For a detailed review of this subject, see the U.S. Climate Change Science Program's report Coastal Sensitivity to Sea-level Rise: A Focus on the Mid-Atlantic Region (CCSP, 2009).]

The elevation of coastal landscapes—and entire regions—is affected by both long-term and short-term processes. Isostatic rebound is a long-term process in which large regions of land are rising or lowering following the retreat of glaciers, like a slow-motion see-saw. The glaciers that covered parts of North America were heavy enough to depress the underlying crust of the earth; areas south of the glacial line tipped up (the high end of the see-saw) in response. Now that the glaciers have retreated, the glaciated areas are rising back up while those areas south of the glacial line are sinking back down. This effect causes sinking of about 0.6 inches per year in the Mid-Atlantic region and 0.4 inches per year in parts of the Gulf of Mexico. On the opposite side, the Hudson Bay in northeastern Canada is rising at a remarkable rate of about 4 inches per year.

Coastal landscapes themselves are constantly rising or lowering in response to deep and shallow geologic and geomorphologic processes.

There are also deep short-term processes that can cause the land to subside. The greatest rates of land subsidence in the nation are found along the Gulf of Mexico. A suite of processes cause subsidence along the Gulf of Mexico including pressure from the weight of accumulated sediment, sediment compaction, and the extraction of groundwater, oil, and gas.

Surface and shallow subsurface processes can have both negative and positive effects on the elevation of coastal landscapes. Any materials deposited within or lost from coastal landscapes will affect their elevation. Accretion occurs when deposition outpaces loss; erosion or subsidence occurs when losses are greater than deposition. Accretion can be significant in coastal wetlands, mud flats, the leeward side of barrier islands, and other landscapes with high rates of sediment and/or organic material deposition. Subsidence occurs in coastal wetlands when organic matter decomposes, becomes denser, and shrinks a soil. Conversely, root growth in coastal wetlands can expand soil volume, physically raising the soil surface. Coastal habitat management actions can influence these surface and shallow processes. More research is necessary to develop and implement management methods that will reduce elevation losses and increase elevation gains in coastal habitats.

Effects of sea level rise

Sea level rise has direct and indirect effects on coastal habitats. The most direct effect is to increase inundation—deepening the mean water level in a habitat. The increased water level can drown plants and decrease light availability. The degree of this effect depends on the tidal range within tidal ecosystems. Tidal range is the distance between high and low tides and it varies substantially across coastal landscapes (McKee and Patrick, 1998). Sites with a large tidal range may be relatively unaffected by moderate changes in relative sea level. However, sites with a small tidal range can be strongly affected even by small changes in relative sea level. The location of a coastal landscape relative to the tidal range has been termed elevation capital (Cahoon and Guntenspergen, 2010). It is possible that tidal ranges will increase as oceans deepen (Bird, 2008).

Sea level rise will generally increase the amount of flooding and erosion of coastal habitats. The frequency and intensity of storm events are the primary drivers of flooding and erosion, but the deepening of near-shore waters can increase this effect (Bird, 2008). Coastal erosion is also affected by altered wind patterns, reduced sediment inputs, and changes to offshore bathymetry (subsurface topography) resulting from climate change and human activities. Beach erosion will become more severe and extensive with associated damage to coastal dunes (Bird, 2008). Increased erosion along cliffs and shore platforms is expected to increase the frequency of landslides and slumping (Bird, 2008). Rising seas will also increase the flow rates of currents though tidal channels.

Among the coastal habitats most affected by sea level rise and increased storms are barrier islands (Peterson et al., 2008). These islands are naturally dynamic: storms can move some islands leeward (toward the coast); storms can also break through islands, creating new passages between the sea and bays. The preservation and restoration of barrier islands is critical to the protection of coastal ecosystems. Islands such as those in the Northwestern Hawaiian Islands and Florida Keys that provide habitat for many endangered species and are threatened by sea level rise may require priority preservation (Janetos et al., 2009).

An indirect effect of sea level rise is saltwater intrusion. As the relative level of seas rise, saltwater reaches further inland in estuarine waters and coastal habitats. The associated increase in salinity can stress plants and animals and may even eliminate species when the salinity level crosses the tolerance threshold of a species. Freshwater wetlands are particularly susceptible to saltwater intrusion because salt can stress freshwater species and increase rates of organic matter decomposition, causing shallow subsidence.

Coastal habitat transgression or migration

Within natural systems, coastal habitats often transgress, or migrate inland, with rising sea levels if the land upslope has an appropriate elevation (e.g., a gentle and constant slope). Even coral reefs may be able to migrate landward in response to sea level rise, colonizing newly inundated zones. This has not been widely observed, however, and is likely to be hindered by temperature and acidification stresses on corals (Bird, 2008).

In many places the topography of the coast will not allow for habitat transgression (Titus et al., 2008). Moreover, sea level rise

may occur too quickly to allow for habitat transgression, resulting in habitat loss (such as the conversion of swamps to open water without being converted to marsh).

Sea level rise may squeeze out these areas, eventually eliminating habitats that are essential to the productivity of coastal ecosystems. Many coastal habitats are prevented from transgressing naturally due to human settlements, infrastructure, and natural barriers (see Chapter 4).

The facilitation of habitat migration is an evolving mechanism for restoration and adaptation (see Chapter 4). Habitat restoration practitioners are emphasizing the preservation of undeveloped coastal upland areas for future habitat migration and the maintenance of corridors to allow macrospecies to migrate inland. There are several tools to allow for coastal habitat migration (see Chapter 4). Setbacks are a regulatory tool that prevents development within a certain distance of the coast. This works best when there is a steep slope near the coast, such that the setbacks allow for a relatively long-term or high sea level rise rate. Land preservation trusts are showing an interest in buying coastal land that will allow for future habitat transgression. Alternatively, coastal preservationists and governments can purchase rolling easements that pay coastal landowners to forfeit any attempts to hold back the sea as the sea-levels rise and storm events erode the coast.

Storms and Waves

Storms can have dramatic effects on coastal habitats, causing the complete loss of habitat, shifting habitats from one type to another, and sometimes even greatly benefiting a habitat.

Climate scientists expect climate change to heighten the frequency and intensity of large precipitation events and increase hurricane rainfall volume and wind speeds. This will drive associated changes in storm surges (Karl et al., 2008), intensifying flood, wave, and wind damage in coastal habitats.

A comparison of satellite images from before and after landfall of Hurricanes Katrina and Rita found that open water area increased by 217 mi^2 (Barras, 2007). The hurricane's storm surge created new open water areas by eliminating wetlands, increasing transitory water areas, removing aquatic vegetation, scouring marsh vegetation, and pushing water levels beyond ordinary tidal variations (Barras, 2007).

On the benefit side, storms can deposit much-needed sediment and wrack onto habitats such as marshes and beaches. Although wrack deposits can be so thick as to suffocate existing vegetation, the wrack may decompose and become part of the native soil organic matter, providing valuable elevation gains. In some instances, wrack deposits can lead to increased biodiversity when new species colonize these exposed zones.

Temperature

The IPCC's best estimates of changes in the mean global surface air temperature are an increase between 3.4 to 7.2 °F (1.8 to 4.0°C) by the end of the 21st century, with increases possibly ranging from 1.98 to 11.5°F (1.1 to 6.4 °C) (IPCC, 2007). The IPCC estimates that surface sea temperatures will rise from 1.7 to 4.7 °F (1.5 to 2.6 °C) (Nicholls et al., 2007). These shifts will vary geographically with greater rises generally anticipated closer to the poles and smaller rises near the equator (IPCC, 2007b). Also, scientists predict more abnormally hot days and nights, more heat waves and high temperature extremes, and fewer cold days, nights and frosts (Karl et al., 2008).

The increase in air temperature will affect coastal landscapes in several ways. The rates of many biological processes will increase as will the productivity of many plant and algal species, causing increases in net primary productivity. Greater temperatures will also lead to a longer growing season, further increasing primary productivity. However, moisture loss associated with greater temperatures could cause plant stress and drought, dampening the positive effects of production. Organic matter decomposition rates will increase in soils and sediments, liberating more nutrients but also potentially decreasing organic accretion rates.

Water temperature increases will affect many aquatic organisms, particularly when the temperature shifts outside of the preferred range of a species or crosses their tolerance thresholds. Rising sea surface temperatures are also expected to increase algal productivity and blooms, causing decreased light and oxygen availability for other species. There is already evidence of poleward marine species shifts and changes in the timing of plankton blooms (Janetos et al., 2008). Stream temperatures will also likely increase due to climate change, particularly during low flow periods (Lettenmaier et al., 2008).

The effects of increased sea temperatures are dependent on shifts in ocean current and atmospheric circulation patterns called oscillations. These oscillations include the El-Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO). These oscillations can shift rapidly and dramatically with substantial effects on marine ecosystems. Additional effects of climate change on ocean physical

processes include decreases in convective overturning, increases in stratification, longer growing seasons, and decreases in salinity (Peterson et al., 2008 for a review). [Please refer to the U.S. Climate Change Science Program's report on The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity for a detailed review of the effects of climate change on oscillations with associated effects on marine ecosystems (Janetos et al., 2008).]

Scientists expect coral reefs to be among the habitats most affected by temperature change. Coral bleaching—the whitening of corals due to the expulsion or loss of color of symbiotic algae—occurs when sea surface temperature increase approximately 2°F (1°C) above its seasonal maximum. The associated increase in solar radiation has an impact as well. Coral death occurs when temperatures increase beyond 4°F (2 °C) (Nicholls et al., 2007). Bleaching is already widespread. In one study, researchers observed a coral mortality rate of 50% in the U.S. Virgin Islands National Park from the effects of bleaching followed by disease (Janetos et al., 2008). Ocean acidification, sea level rise, increased storms, and an increase in dust (iron fertilization) are also expected to harm coral reefs. These stresses also make corals more susceptible to disease.

One of the most serious effects of increased carbon dioxide levels will be the acidification of the oceans.

Carbon Dioxide Concentration

The increase in atmospheric carbon dioxide concentration resulting primarily from the burning of fossil fuels is one of the main causes of climate change (see Chapter 5). It is also a climate change force—the increase in carbon dioxide concentrations will affect the chemistry of coastal waters and will affect coastal plant communities.

The concentration of carbon dioxide in the atmosphere has risen from 280 ppm (parts per million) before the industrial revolution to 379 ppm in 2005, which is greater than the maximum concentration over the past 650,000 years (300 ppm) (IPCC, 2007b). The IPCC has developed a set of scenarios designed to imagine possible future greenhouse gas emissions, with future carbon dioxide levels ranging from 540 to 970 ppm by the year 2100 (IPCC, 2001). The U.S. Climate Change Science Program has also developed a reference scenario and a set of stabilization scenarios to better understand future greenhouse gas emissions and atmospheric concentrations (Clark et al., 2007). Their stabilization scenarios were designed to understand what would need to occur to achieve carbon dioxide levels from 450 to 750 parts per million by 2100.

One of the most serious effects of increased carbon dioxide levels will be the acidification of the oceans. The IPCC estimates that ocean pH will lower by 0.14 to 0.35 units by 2100 in addition to the lowering of 0.1 unit already observed (IPCC, 2007a). When carbon dioxide (CO_2) dissolves into water it becomes carbonic acid (H_2CO_3), which lowers the pH of water. This increase in acidity is dramatic, with a 30% rise observed over the past 200 years and an expected increase of 300% by the end of the century (Ravens et al., 2005). Organisms that are made from calcium carbonates will be most affected, including corals, crustaceans, mollusks, echinoderms, and foraminifera. The solid part of these organisms is a simple combination of calcium and carbonate (which is a form of carbonic acid). The problem is that calcium carbonates dissolve at lower pHs. Small shifts in the pH of aquatic systems can have profound effects (Peterson et al., 2008). Increased dissolved CO_2 levels in estuarine waters may also provide a fertilization effect, increasing the frequency of harmful algal blooms (Nicholls et al., 2007).

Plants in coastal habitats may actually benefit from the increase in atmospheric carbon dioxide. Plants need carbon dioxide to photosynthesize (see Chapter 5), so the more of it that is available in the air the less work they need to do to get it (they also are able to conserve more water). Plants can be categorized into groups based on their mechanisms of photosynthesis—the two main groups in coastal areas are C3 and C4. In general the increase in carbon dioxide levels will help C3 plants more than it will help C4 plants because C3 plants are less efficient at extracting carbon dioxide than are C4 plants (Peterson et al., 2008). It is possible that the increase in carbon dioxide concentration will have some negative effects on native plant communities—for example, if an invasive species is able to compete better.

Precipitation Changes, Freshwater Delivery, and Pollutants

Climate change is expected to alter the net precipitation of geographical areas and the variability of precipitation. Most parts of the United States have already experienced increases in precipitation and streamflow and decreased drought periods, with the exception of increased drought severity and duration in the southwestern and western U.S. (Lettenmaier et al., 2008). Although climate scientists expect fewer discreet precipitation events, they predict that individual events will deliver a greater volume of water than historic averages. Correspondingly, scientists anticipate a higher frequency of intense large storms and hurricanes (IPCC, 2007b; Karl et al., 2008). Increased runoff is predicted for the eastern U.S. while decreased runoff is predicted for the west coast (Lettenmaier et al., 2008). Drought is expected to increase in the southwestern U.S. (Karl et al., 2008). These changes will increase the frequency of flood and drought-related stresses on coastal habitats, such as drought-induced sudden marsh dieback. Coastal dunes may be particularly affected: drier conditions will weaken vegetation and destabilize dunes while wetter conditions may facilitate plant growth.

Climate change-induced freshwater delivery effects on Chesapeake Bay salinity and stratification

Researchers used four different climate models to predict temperature and precipitation changes in the Chesapeake Bay watershed that would result from a doubling of current CO2 levels in order to predict changes in the Bay's salinity and stratification (Gibson and Najjar, 2000). The most significant effects they predicted were increased temperature and changes in freshwater additions from the Susquehanna River (the Bay's primary freshwater source).

Three of the four models used predicted that the flow of the Susquehanna River would increase, with estimates between 27 and 32%. The primary cause of this increase was warming-induced snowmelt in fall and winter. However, the fourth model predicted a decrease of flow by 4%, due mostly to warmer temperatures and less precipitation in springs and summers.

Increased freshwater inputs to the Chesapeake Bay would decrease its salinity and increase stratification within the Bay's water column. The models predicted that salinity would decrease 23-28% near the mouth of the Susquehanna River and fall less than 1% closer to the mouth of the Bay. This corresponds to salinity decreases of 0.8–1.8 parts per thousand (ppt), varying with depth and latitude. The models predicted that the salt wedge would recede about 2% of the length of the Bay near the river (6.3 km) and as much as 17% of the length of the Bay near the middle (55 km).

These changes could be significant to the ecology of the Chesapeake Bay. Water stratification retards the mixing of oxygen-rich surface waters with nutrient-rich deeper waters. Some economically important organisms can only survive within a limited range of salinities. For example, the soft shell clam cannot survive in salinities less than 8 ppt; the hard shell clam and the blue crab cannot live in salinities below 12 ppt and 20 ppt, respectively. The effects of climate change predicted in their models would shift the habitable range of these salt-sensitive species.

Due to the regional variance embedded in these predictions, scientists need to develop regionally specific precipitation scenarios (Davis et al., 2007). The U.S. Climate Change Science Program has published a summary and review of regionally specific information in their chapter on the effects of climate change on fresh-water supply and quality (Lettenmaier et al., 2008).

Precipitation changes will alter the delivery rate of freshwater to coastal habitats (as well as direct precipitation inputs), driving shifts in water table and salinity levels in coastal ecosystems (see box) (Peterson et al., 2008). Moreover, as freshwater delivery rates change so will pollutant input rates to coastal systems. An increase in water volume will increase pollutant loads, particularly sediment and phosphorus, which are among the primary pollutants responsible for eutrophication. Sediment has severe impacts on estuarine environments including pollutant transport and reduced light penetration, decreasing photosynthesis in sub-marine plants. This increase in pollutant loads, paired with other climate change factors, would exacerbate the risk of hypoxia in coastal waters (Peterson et al., 2008).

As with other climate impacts on coasts, the results may not be all negative. Projects such as erosion-reduction schemes and dams threaten coastal wetlands by decreasing sediment delivery. Thus, greater sediment delivery can benefit coastal wetlands and other sediment-supported coastal habitats (e.g., barrier islands and beaches), helping to build elevation and providing valuable nutrients. If policymakers are to manage coasts effectively, they will need more research on sediment delivery across climate change scenarios.

Species Changes, Biodiversity, Invasive Species, and Disease

The warming climate will generally shift the geographical range of species poleward and/or upwards along elevation gradients, which will stress species whose ranges shift away from their current locations. Consequently, warming allows invasive and other species to enter new habitats (Janetos et al., 2008; Peterson et al., 2008). Furthermore, warming will enhance conditions for disease organisms and parasites in coastal habitats while lowering host species stress thresholds (Peterson et al., 2008). It is generally easier for aquatic and avian species to move with the changing climate, so these impacts will likely be rapid in coastal systems.

Observations of longer growing seasons and increased net primary production, particularly at higher latitudes (Janetos et al., 2008) lead scientists to foresee the re-positioning of whole habitats: for example, mangroves will invade zones dominated by tidal marshes while tidal marshes will establish in areas closer to the poles.

Migratory species face additional challenges as their multiple habitats experience varying climatic shifts. Scientists have witnessed climate change's direct effects on the spring migration of migratory birds and butterflies, but expect indirect impacts—such as the mistiming of reproduction relative to food supplies—to be more important (Janetos et al., 2008). Research on the mistiming between climate conditions and migration patterns is a critical need.

The issue of species changes is further complicated when considering ecosystem-wide systematic shifts. It is a pressing research need to develop methods to understand and predict these ecological shifts, particularly as they will affect economically important and endangered species.

Interactions and Thresholds

Scientists are studying the interactions between climate change and other natural forces to gain a better understanding of ecosystem thresholds.

An interaction occurs when the sum of two forces is not equal to the sum of its parts. For example, an estuarine marsh's accretion rate may keep pace with sea level rise, allowing the system to survive this pressure; rising temperatures may reduce the marsh's organic matter but not end its productivity. When the marsh experiences both impacts, however, the habitat may no longer be sustainable. Two forces interacting may also boost a habitat's chance for withstanding climate change—for example, some coastal systems may only be able to keep pace with sea level rise if they receive more storm-driven sediment inputs.

Coastal systems commonly exhibit non-linear responses to change (IPCC, 2007), which mean that the interactions between components of the system (i.e. biological, hydrological, geological) are not directly proportional (Burkett et al., 2005). Understanding non-linear responses of ecosystems is an extremely important aspects of adaptation planning (Burkett et al., 2005).

A threshold is the level of an ecosystem variable (such as the maximum temperature) at which dramatic change occurs. Gradual or seemingly small changes can stimulate threshold changes (Fagre and Charles, 2009). Increasing the understanding of coastal ecosystem thresholds will allow managers and engineers to better plan for the protection of coasts (IPCC, 2007a). It is a critical research need to understand and identify interactions and thresholds in the response of coastal habitats to climate change (Peterson et al., 2008).

Human Activities, Climate Change, and Coastal Habitats

Human populations along the coasts have increased dramatically during the 20th century, a trend expected to continue. This human development has profound effects on coastal ecosystems.

Although people serve many critical functions as land stewards, many human-induced pressures exacerbate the effects of climate change on coastal habitats (Nicholls et al., 2007). Dredging waterways and creating artificial inlets for navigation disrupt natural hydrological pathways, allowing storm surges to penetrate deeper inland. The draining of coastal wetlands—to create space for agriculture and development—reduces flood storage and water filtration capacity. Damming streams and rivers reduces sediment inputs to coastal habitats. Freshwater extraction allows saltwater to intrude surface and ground waters. Communities discharge nutrients and contaminants into coastal waters, introduce invasive species, and over-harvest coastal resources. These human-induced pressures exacerbate many of the effects of climate change on coastal habitats (Nicholls et al., 2007).

Climate change has serious deleterious effects on the goods and services provided by coastal ecosystems (Nicholls et al., 2007). Loss of coastal habitat from sea level rise would reduce availability of fish and game species for commercial and recreational users; loss of habitat would reduce storm and flood protection for coastal communities.

The capacity of coastal communities to adapt to climate change impacts is intertwined with the fate of the coastal habitats that human development has damaged. Low-lying urban areas and small islands along the coasts are particularly vulnerable to climate change. The implementation of optimal adaptation strategies will be a particular challenge in regions with limited economic resources. In general, the costs of adaptation are less than the costs of inaction, even when only considering potential climate change impacts on lives and property (Nicholls et al., 2007). The benefits of adaptation are even greater when accounting for potential climate change impacts on businesses, communities, natural resources, and habitats. Layering on the cost of rising insurance rates and the threat of losing insurance coverage altogether may give communities more incentive to act. [See Chapter 4 for further discussion.]

Findings and Recommendations

Coastal habitats are being subjected to a range of stresses from climate change; many of these stresses are predicted to increase over the next century. The most significant effects are likely to be from sea-level rise, increased storm and wave intensity, temperature increases, carbon dioxide concentration increases, and changes in precipitation that will alter freshwater delivery. These climate change forces are having dramatic effects on coastal habitats and the species dependent on these ecosystems. Many of these effects are interactive, with non-linear responses sometimes characterized by critical thresholds. The fate of coastal communities and habitats are intertwined, necessitating long-term comprehensive planning.

Recommendations

Use a multi-scenario approach to planning in the face of climate change to account for uncertainties in climate change estimates.

There is great uncertainty in many climate change projections. However, we are confident that these changes will occur and in most cases know that the magnitude of these changes will significantly affect coastal habitats. Planners shouldn't let the uncertainty prevent them from taking action. A multi-scenario approach will be useful to guard against uncertainty, for example the protection of habitats across varying elevations would allow for species to migrate successfully across climate change scenarios.

Improve the management of sediment delivery to coastal habitats across climate change scenarios.

Sediment delivery is critical for the maintenance of elevation gain in some coastal habitats and is also among the most important pollutants of coastal waters. Climate change is expected to change sediment delivery rates and distribution due to a variety of factors including precipitation changes and sea level rise. Although there is great complexity in the management of sediment delivery, this is a critical need for the sustainability of coastal habitats.

Develop and implement management methods that will reduce elevation losses and increase elevation gains in coastal habitats.

The rate of elevation gain of many coastal habitats will determine their sustainability in the face of sea level rise. A triage approach is needed to determine which lands may benefit from management and restoration practices that increase elevation gain. Continued research is needed to better understand the utility and cost-efficiency of management practices applied with a goal of increasing elevation gain.

Understand potential mistiming between climate conditions and migration patterns.

Small changes in habitat climatic conditions may have profound effects on migrating species. The prediction and associated restoration response of mistiming situations is a complex but critical research need.

Develop regionally specific climate change scenarios, particularly for precipitation changes.

Climate science is more advanced for the estimation of climate change at global scales than at regional and local scales, but these regionally specific data are needed for planning and management. Climate scientists have recognized this need and are working toward providing locally relevant climate change information.

Understand and identify interactions, non-linear responses, and thresholds in the response of coastal species and habitats to climate change, particularly for economically important and endangered species.

Coastal habitats are complex ecological systems, making it difficult to predict the combined affects of climate change and other perturbations. The identification of critical ecological thresholds is an important tool to predict cases where relatively small climatic changes may cause substantial ecological change.

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Chapter 3: Planning and Design Considerations for Restoring Coastal Habitat In the Face of Climate Change

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Chapter citation: Crooks, S. 2012. Planning and Design Considerations for Coastal Habitat Restoration in the Face of Climate Change. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore-Adapt-Mitigate: Responding to Climate Change Through Coastal Habitat Restoration. Restore America's Estuaries, Washington, D.C., pp. 23-32.

Purpose of Restoration

The goal of coastal restoration is to achieve a sustainable coastal system, often within an urban and agricultural landscape, that is resilient to human impacts and resilient to climate change and extreme weather conditions.

Restoration of coastal landscape is critical to meet the challenges of climate change and sustainable management. Purposeful restoration of wetlands began in the U.S. in the 1960s. Since then, there has been a shift in impetus for restoration as the need for forward-thinking and integrated approaches became increasingly central foci in landscape planning (Williams and Faber 2001). Early restoration projects were small-scale and fragmented mitigation actions that were paid for by developers to compensate for regulatory enforcement of no-net-loss provisions. With growing ecological and systems level awareness, resource agencies have taken more of a leading role in projects that restore wetlands. By the turn of the millennium, the goals of restoration had risen again to include examples of large-scale restoration as a component of restoring key ecological processes for the entire ecosystem of an estuary.

Now, an ecosystem-based perspective is proposed as a foundational element supporting U.S. policy for U.S. waters and connected lands. In a recent policy perspective, Lubchenco and Sutley (2010) describe sustainable management of coastal ecosystems to "require an understanding of the functional connections between living and non-living components, the position of non-linear thresholds, and the ways in which ecosystems could change under different management scenarios. Precaution is needed to avoid unintentional losses of ecosystem resilience or diversity. Increased knowledge of complex relationships takes on real value when ecosystems can be managed sustainably, without reaching or exceeding critical tipping points."

Restoration is now a central element in climate change mitigation and adaptation. In this chapter, we shall explore key concepts and recent lessons learned in this rapidly growing field.

Planning Coastal Restoration in the Modern World

Coastal systems are naturally resilient to climate change. Over the past two million years—the Quaternary period—the global climate has swung from full glacial to interglacial conditions more than 20 times, as well as through numerous sub-cycles. During these shifts, enormous ice sheets have waxed and waned, shifting the location of polar, temperate, and tropical regions. Sea level has fallen so low as to expose entire continental shelves and it has also achieved an elevation perhaps fifteen to thirty feet above present levels. Throughout these cycles, mosaics of coastal habitats have shifted in extent, location and composition, but remained geomorphically and ecologically coherent. Key to this natural global ecological resilience to enormous climatic shifts was the availability of space—across which a rich mosaic of habitats could shift—and the relatively unimpaired health of ecological systems.

Modern times are very different. An era has now emerged—increasingly becoming known as the Anthropocene—whereby the human species is having a dramatic and unprecedented impact on the Earth's landscape, atmosphere, and oceans.

Pervasive human disruption has greatly impaired the capacity of coastal habitats and species to respond resiliently to climate change. It is in this broader context of a linked and co-evolutionary human and ecological world that we must place our plans for coastal restoration.

Environmental Setting of Coastal Habitats

Coastal habitats are found in a diverse range of geomorphic settings sheltered from embayments and estuaries to deltas, coastal plains and exposed open-shore areas. The coast that we see now reflects one phase in an evolution that began with the end of the last glacial period (around 18,000 years ago), when sea level lay around 400 ft. below present elevations. During the early Holocene, sea level rose rapidly—perhaps 0.5-1 inch per year—and by around 6000 years ago seawaters once again reclaimed the wide expanses of the continental shelves and reached the outer boundaries of river mouths that would later become estuaries. Sea level rise continued to slow. As a consequence, continuous rising oceans rolled the interface between rivers and the open ocean inland. Sediments reworked by tides and waves began to accumulate on the open shore, along coastal plains and in drowned river valleys to build wetlands, beaches and dunes. By 2000 years ago a coastal mosaic had developed that we would broadly recognize from 19th century maps and was firmly established in most coastal regions. Coincidentally, the past two millennia have been particularly stable periods, experiencing global sea level rise of only about 0.04 inches per year.

Projections of Sea Level Rise

Projecting future sea level rise presents special challenges. Scientists have a well-developed understanding of the contributions of thermal expansion and melting glaciers to sea level rise so the models used to project sea level rise include these processes. However, the causes of past and future sea level rise from ice sheets are far less well understood. Recent observations of the polar ice sheets show that a number of complex processes control the movement of ice to the sea and affect the contribution of ice sheets to sea level rise. Because these processes are not well understood, it is difficult to predict their future contribution to sea level rise. (See Chapter 2 for a more detailed discussion).

Self-Organization of Landscapes—A Critical Concept for Restoration

Geomorphologists and ecologists have long made reference to landscape evolution, reflecting a progressive change over time toward some form of steady state. It is now increasingly recognized that many landscapes can sustain more than one form of environmental configuration (or system state) under a given set of environmental conditions. The establishment of any particular landscape configuration or habitat type is strongly influenced by inherited pre-existing conditions during an early phase of system evolution. Once established, positive feedbacks in the landscape interactions result in a high degree of system self-organization and a landform that is sustainable over decades to multiple century and millennial timescales. Such landscapes are potentially resilient until thresholds are crossed beyond which a new persistent system state develops.

> ***The success of restoration depends upon a restoration project developer's understanding of the physical and ecological interactions, the implications of inheritance, and the existence of thresholds at the project and host landscape level.***

Often, as time goes by, landscapes and ecology build up in complexity, redundancy, and capacity to absorb occasional shocks, stresses, and trend changes. These systems possess feedbacks as a natural resistance to crossing a threshold that results in a new system state. The resilience of the landscape depends upon the sensitivity of the system to environmental disturbance and the existence of thresholds beyond which a system converts through structural arrangements to another stable form.

Pervasive disruption to historic landscape processes and fragmentation of elements reduces ecosystem capacity to respond resiliently to trend changes—such as climate change—and increases sensitivity to disturbance events. The impacts of reduced system resilience may not be observed for a considerable length of time—perhaps multiple decades—as increasing sensitivity to a rare event builds up, and/or state thresholds are approached. Once a landscape passes a threshold, it can begin an accelerated conversion from one form to another (e.g., from forest to grassland, from lake to dry bed, or from marsh to open water).

The success of restoration depends upon a restoration project developer's understanding of the physical and ecological interactions, the implications of inheritance, and the existence of thresholds at the project and host landscape level. Project managers must know if individual projects will increase system-level resilience and if they will be susceptible or resilient to larger trend changes (e.g., precipitation levels, sea level rise or sediment supply) and thresholds (see Chapter 1).

Self-organization in Coastal Systems

Coasts are highly dynamic systems that at times appear to behave chaotically. In fact, many coastal systems possess considerable capacity for self-organization. This capacity is provided through the reallocation of sediment in response to long-term trends in changing environmental conditions, such as sea level rise and catchment sediment supply, as well as short-term (e.g., seasonal) cycles and events.

Fundamentally, coastal geomorphology and its ongoing evolution in response to climate change is manifested through the distribution of coastal landforms (see Chapter 2). The evolution of geomorphic features resulting from natural change and human impacts defines the quality and quantity of associated habitats and the nature of their ecosystem linkages, and also the level of vulnerability of people and infrastructure in coastal areas.

Coastal landscapes are nested together; larger landforms (e.g., deltas, estuaries) are an amalgamation of interacting smaller landforms (e.g., beaches, dunes, intertidal flats, marshes, mangroves) as they respond to energy conditions. Change in prevailing energy conditions redistribute sediments that make up smaller landforms, resulting in smaller landforms' movement and a translocation or change in the form of the larger landform.

Beaches and dune fields respond together to seasonal change in wave climate through cycles of erosion and accretion, but over the long-term, remain resilient. Winter waves erode sand from the upper shore and elongate the shore profile, which in turn acts to enhance attenuation of wave energy. During quiescent summer periods, shoaling waves push sand shoreward to rebuild the upper beach and dune edge. The system is "stable" in that the beach-dune interface oscillates around a particular location as long as the recovery time in which an equilibrium condition is reestablished is less than the return interval for the disturbance events.

Should the shoreline's recovery capacity diminish (say, through reduction in sediment availability or through sea level rise changing the impinging wave energy), then the shoreline responds by relocating until a new

equilibrium is established. This form may be a simple relocation of the beach-dune complex or, if a geomorphic threshold is crossed, a different morphology that balances sedimentary and energy conditions. Salt marshes and intertidal flats interact broadly in a similar manner as beach-dune complexes but the morphological differences reflect grain-size-related particle interactions that shape the response to the disturbance dynamics.

At the large-scale, coastal systems are resilient to large occasional events, such as hurricanes or earthquakes. Given an adequate supply of sediment the shore will eventually respond to rebuild the disturbed habitats. For example, the losses of barrier islands and wetlands that we see around the Mississippi Delta when a hurricane strikes are often perceived as being a consequence of the storm itself. In actuality, this change in the distribution of landform (from barrier islands and marshes to subtidal mudflats) reflects the progressive change with sea level rise and a reduction in resilience bought about by human impacts to sediment supply. The shoreline is adjusting to a new equilibrium form and a hurricane provides a rapid, episodic jump toward that new form.

On the open coast, we can expect the shoreline to relocate as increased water levels shift the focus of wave action and sediment transport, causing erosion and re-contouring of the shore. Sea level rise results in more than just inundation changes in areas with expansive coastal cliff systems. Much of the Pacific West Coast, for example, is geologically young and uplifted with steep rises in elevation within and near the coastline. Here conflicts occur between development high on eroding cliff edges and down-drift habitats that depend on the supply of sediment from the eroding cliffs. Coastal landowners armor the cliffs to protect their properties, reducing sediment supply from these cliffs and weakening the down-drift habitats resilience to sea level rise (PWA 2009).

Geomorphic Tools to Predict the Response of Natural and Restored Coastal Systems to Sea Level Rise and Human Impacts

The tools that allow coastal scientists to examine the geomorphic response of coastal systems to sea-level rise (Table 3-1, next page) range across qualitative and quantitative conceptual models, analysis of historic change, and development of top-down and bottom-up numerical models. Our capacity to predict the future configuration and ecology of a coastal system is greatest if the system is unlikely to be approaching a critical threshold (e.g., marsh accretion response to sea level rise given adequate sediment supply; shoal volume and inlet dynamics response due to change in estuarine tidal prism). It is in this realm of gradual trend changes that process-based models are most effective.

However, geomorphic systems are loaded with latent and interacting environmental thresholds where reinforcing non-linearities result in difficult to predict outcomes. Thus, confidence in predicting an environmental system's future configuration diminishes when an analysis must incorporate thresholds between system states. To date, the use of process-based, bottom-up, environmental models are challenged and are often compromised by the sensitivity of system response predictions to non-linear interactions at thresholds. While scientific studies and models are in development to improve our understanding of environmental thresholds, we should continue to recognize our limited capacity to predict these events when analyzing contemporary model results.

A number of quantifying tools are coming online that illuminate the existence of conceptualized thresholds.

Examples include the potential breakdown of barrier island complexes to open shore under conditions of sea level rise (Rosati and others, 2008), or the implications of concentrated peak wave-power at intertidal elevations that define whether an evolving mudflat transitions to marsh as a non-linear function of sediment supply (Defina and others, 2007).

Predicting geomorphic change is most effective when multiple tools are used in concert (PWA and others, 2008). Conceptual models are useful in setting the context of understanding for testing hypotheses. System-level models and historic trend analysis provide a means to refine understanding of trends and thresholds. Process-based models allow coastal geomorphologists to examine cause-and-effect

Table 3-1 Tools for the prediction of geomorphic change in coastal areas

Geomorphic Assessment	Description	Advantages	Disadvantages
Expert Assessment /			
Professional Judgment	Geomorphic and ecological processes are governed by poorly quantified laws—particularly thresholds—but are influenced by multiple competing local interactions. An expert who has seen many similar systems in various states of behavior can draw comparisons, highlighting behavioral convergence and variance.	Capacity to synthesis understanding from a combination of qualitative and non-quantitative information sources.	Conjectural; requires experienced individuals.
Conceptual Modeling	Sediment budget analysis, integrated ecological and physical concepts.	Communication of hypotheses, not resource–intensive.	May be untested or unvalidated until suitable analytical techniques become available.
Historic Trend Analysis	Analysis of time series data to identify past trends in environmental processes or evolution.	Provides temporal context.	Requires long datasets.
Systems Analysis (top-down approaches)	Conceptual, empirical and numerical approaches that describe broad interactions between forcing variables and resulting characteristic morphology.	Often based upon simplified relationships, they provide means of framing system processes, examination of trends, thresholds, and forcing functions. Low cost, rapid assessment.	Often general, may be difficult to apply in detailed geographic or temporal assessments or to calibrate (simplifying assumptions should be clearly stated).
Process Modeling (bottom-up approaches)	"Bottom-up" approaches employ models that are based on a representation of physical principals of environmental processes and provide a representation of morphological change.	Credibility based upon calibration and validation with appropriate field measurements. Such approaches are valuable in explicitly representing hydrodynamic and sediment transport processes, leading to morphodynamic change.	Long-term predictive capacity is questionable, as 1) numerical errors accumulate with long-term runs, 2) difficulty in modeling system threshold responses because of non-linearity between forcing functions and response. Complicated and costly to set up.
Hybrid Modeling	Combined "bottom-up" and "top-down" approaches. The bottom-up component provides an understanding of the forcing processes and top-down approach provides information on system state and boundaries.	Integration of models provides refined understanding of system responses to forcing conditions.	Resource-intensive to set up.

relationships. Increasingly, analysts are employing a hybrid approach using system-level models in conjunction with process-based models to constrain the error range in numerical modeling. But models have limited ability to account for environmental complexity, necessitating their interpretation by experienced geomorphologists and ecologists with a reference largely derived from field experience. Expert opinion seeks to distill global laws of geomorphic response which are shaped by local contingencies.

How much sea level rise can coastal habitats accommodate?

The resilience of tidal wetlands, dunes, and beaches to sea level rise is defined by how the wider coastal system as a whole responds to sea level rise. Some estuaries, deltas, and coastal plains will continue to respond very resiliently to sea level rise because they have "sufficient" sediment in circulation (adequate to fill any created accommodation space) and have space for wetlands to migrate. But many coasts are not as resilient to sea level rise because the amount of sediment in circulation is insufficient to fill the space created by rising water levels. They may also be subject to engineering activities that have created internal sinks within the estuary that draw and remove sediment from circulation that would otherwise feed marshes and mudflats (such as channel dredging). Coasts that are sensitive to sea level rise may also be vulnerable to sudden changes in morphology as geomorphic thresholds are crossed resulting in system wide redistribution of sediment from vegetated marshes creating expansive shallow mudflats.

Maintenance Dredging creates artificial sinks for sediment circulating around the system. A portion of sediments that migrate to fill these artificial sinks will be derived from adjacent mudflats and marshes. Typical maintenance dredging protocols call for removing sediment from the local area, which impacts adjacent wetlands. Maintenance dredging may also impact estuarine hydrology and sediment circulation patterns. Various estuaries experiencing chronic marsh breakdown during the 20th century share common attributes: low sediment availability, maintenance dredging of deep approach channels, and export of material to deep-water disposal (e.g. Elkhorn Slough, CA; Jamaica Bay, NY; Chesapeake Bay, Stour-Orwell estuary, UK; Mississippi Delta, LA).

Consequences of human disturbance on the landscape

Human disturbance to the landscape can affect the natural resilience of coastal systems. Loss of space by diking not only causes a direct loss of habitat but also modifies or disrupts hydrologic and geomorphic processes. Artificial structures on shores block sediment movement. As a result, sediment pathways adjust away from historic sinks to new locations, adjusting the self-organization of the landscape. This may increase the sensitivity of remaining habitats to the impacts of climate change. Examples of human impacts that have cumulative impacts on coastal environments include dike construction, channel dredging, nutrient loading, and soil erosion.

The Challenge for Planners

In restoring coastal habitats to meet the challenges of climate change, restoration planners are doing something that does not sit comfortably within existing land-use planning constraints. Planning for climate change is planning for land use change with boundaries that move and spatial frames of reference that shift. The goal is to reestablish adequate space for coherent dynamic processes to migrate landward of their existing position on a landscape dominated by a patchwork of static land-use planning. These are challenging concepts for land-use planners and regulators.

Uncertainties also abound regarding the magnitude of climate change. Predictions of future sea level rise vary. Scientists recognize that ecosystems will respond to and may be threatened by a combination of climate change and human impacts but cannot accurately forecast how ecosystems will respond. Yet restoration must move forward with due consideration of these uncertainties.

In recognition of the inherent uncertainty, some large project implementers have adopted programmatic approaches to planning. One example is evident in the restoration of 15,000 acres of salt marsh and mudflats at the South Bay Salt Ponds Project. With a 50-year timeline for phased restoration, project managers will monitor and—through an adaptive management and consultative process review—will adjust the final mix of tidal wetlands restored. The project has adequate space, allowing managers to create a mosaic of targets under varying environmental conditions.

Findings and Recommendations

A number of lessons have been learned by practitioners in restoration than can be collated into recommendations for best practice. Overall, thoughtful planning can improve project outcomes and reduce costs. With climate change—and particularly sea level rise—there will be a need to think beyond planning for individual projects to evaluation of environmental tradeoffs across the landscape. Because of lag times in restoration and because windows of opportunity for successful restoration may close over time, there is an imperative need to restore now rather than delay.

Recommendations

Have a clear and coherent project planning approach.

Successful restoration is most likely when a project has a coherent planning process that identifies goal and objectives, opportunities and constraints; adopts the best available conceptual models; and sets performance metrics to track project performance relative to achievable success criteria.

Restore at the landscape scale.

When planning to restore coastal habitat, planners should take the largest possible view of landscape processes. They should, for example:

- Know how sediment dynamics respond to human impacts and changing climatic conditions;
- Consider the effects nutrient loads have on ecosystem resilience;
- Understand the size buffer required to protect habitat from direct human disturbance and how to provide for a migrating buffer, if required.

Restoring expansive connected areas, rather than a patchwork of isolated projects, provides a capacity to address many of aforementioned pressures. Providing space creates resilience to gradual change as well as the capacity to respond to disturbance events, such as an infrequent flood or a storm. Landscapes mosaics also offer a degree of ecosystem redundancy which is critical to maintaining resilient populations of species. For example, shorebirds need a wide variety of high tide roosting sites that are accessible under different environmental conditions. A study in Humboldt Bay documented 30 species of shorebirds to use some 240 different roosting sites. Of these sites, 4% were used 80% of the time, but when environmental stresses arose (such as a storm or predator disturbance), other roosts became critical (Colwell and others, 2003). Restoring shorebird feeding and roosting areas at inappropriate distances apart results in underutilization of both habitats. Restoring at the landscape level, where elements are shaped by natural processes, allows for creation of habitats that fit with native species, and allows for natural migration over time.

In planning restoration activities, planners must be cognizant of the range of the potential climate change impacts and integrate these with the ongoing response of coastal systems to human impacts.

In urbanized settings that do not offer large-scale restoration potential, strategic location of a restoration project can offer scaled ecosystem benefits. Creation of a fringe of wetlands can help attenuate nutrients leaching from adjacent lands. Sited at key staging locations, wetlands may provide food or refuge for migrating fish or birds.

When planning a restoration to incorporate the landscape context, planners should consider: (1) The interconnection among landscape processes and the functions of the restoration projects; and (2) the potential sustainability of the project in a landscape with modified processes (e.g., disturbed sediment pathways, space for migration, etc).

A failure to consider landscape context will likely limit the cumulative performance of restoration projects over time. Opportunistic, ad hoc, selection of restoration sites is likely to offer partial ecosystem rehabilitation, at best. Only strategic, spatially explicit restoration planning that incorporates landscape scale processes is likely to create a synergistic and complimentary cumulative response (Simenstad et al., 2006).

In planning restoration activities, planners must be cognizant of the range of the potential climate change impacts and integrate these with the ongoing response of coastal systems to human impacts. Uncertainties abound, and so restoration must be robust and adaptive and account for risk by creating additional ecological capacity within the landscape.

Recognize landscape trade-offs and constraints.

Not all coastal areas will respond resiliently to climate change and sea level rise. Given scarce resources, coastal planners need to prioritize restoration activities. At higher rates and magnitudes of climate change, many existing coastal ecosystems may cease to respond resiliently; habitats may evolve to other habitat types (e.g., vegetated wetlands to mudflat) or be lost entirely (e.g., coral bleaching). Planners should begin preparing now for potential higher degrees of climate change by taking the following precautions and actions:

- Locate restoration projects in a way that accounts for landscape evolution and target locations that will be sustainable under potential future conditions.
- When planning for adaptation, including restoration, seek to (1) reduce habitat exposure, (2) reduce sensitivity, and (3) increase resilience of coastal habitats and the built environment to pressures of long-term climate change and infrequent high-magnitude shocks and stresses (e.g., El Nino events, large storms, brown marsh events, etc).
- Adaptation planning, including restoration, should seek to increase capacity of all coastal systems to respond resiliently to climate change, but particular focus of effort may be warranted at sites that could become refugia should greater rates of climate change occur.
- Provide protection to areas adjacent to coastal areas that would provide future habitat migration with sea level rise.
- Manage sediment as a resource. (For instance, estuaries and wetland areas that naturally receive high sediment loading in the catchment may be the most resilient to sea level rise, though some may appear unlikely candidates under current conditions.)
- Do not squander sediments dredged from channels; reuse them within an estuary or within an appropriate coastal area. Reduce offshore disposal of dredged sediments.
- Seek to lower contamination of sediments in preparation for future use. (Sediment contaminated with pesticides or nutrients may restrict the use of some agricultural land for restoration or limit the re-use of catchment-derived sediment.)
- Recognize that the configuration or quality of modern landscapes may prevent historic ecosystems from being restored and that other beneficial habitats types may be preferable.

Restore physical processes and ecosystem dynamics.

Natural processes and dynamics underlie coastal ecosystems' delivery of environmental goods and services. Natural adjustments in the structure and composition of coastal ecosystems result from natural environmental fluctuations and disturbance dynamics. Attempting to control these natural processes will result in a fragile degraded ecosystem that will not respond resiliently to climate change.

Manipulated systems do not function as well as naturally connected ecosystems, particular when seeking to rehabilitate functions that support wider landscape processes (e.g., fisheries, flow of carbon, nutrient assimilation, etc.).

Establish a design template.

Any restoration project should be based on a suitable site "template," establishing natural processes that drive the evolution toward a desired outcome. It is generally an oversimplification to believe that passive actions will necessarily result in full restoration of coastal functions. Some wetland restorations are easier than others. Technical complexity is reduced if:

1. The site has experienced neither deep subsidence nor fill placement;
2. The natural sediment supply necessary to raise surface elevations is plentiful;
3. Remnant channel drainage systems exist on-site;
4. Site modifications (borrow pits, drainage channels, infrastructure) are minimal;
5. Internal wave climate is acceptable;
6. Invasive species are not prevalent within the region;
7. Planners have learned lessons from prior restoration activities at the site; and
8. There are no external constraints (confined channels; sediment budget issues, water quality issues; erosion or flood risks to adjacent lands, etc.).

It is occasionally possible to just breach a sea wall and restore a fully-functioning tidal wetland. Such may be the case in a recently embanked site that has not been modified. Typically some level of design is required either to provide cost-effective environmental enhancements (e.g., pilot channels and transitional ecotones). In urbanized settings, flood management requirements and other concerns can constrain a restoration project so a suitable environmental assessment is necessary. In the case of multiple restoration projects, a cumulative impact assessment is necessary.

Planning complexity can increase when restoring large areas, though very attractive beneficial ecological and socio-economic economies of scale may result. In estuaries with a limited sediment supply, large-scale restoration can impact the sediment budget of the whole estuary, disturbing tidal flow patterns and impacting patterns of sedimentation and erosion (PWA and others, 2008). Large restorations are subject to higher levels of internally-generated wave activity which may retard sedimentation and degrade or threaten external levees (Williams and Orr, 2002).

Understand the restoration trajectory.

History has demonstrated a high potential for success when restoring minimally-disturbed habitats or landscapes. The potential for success is poor when attempting to re-create habitat from scratch. The greater the disturbance, the greater the time frame and extent of intervention required to rehabilitate the landscape.

Human activities may also leave an ecological and geomorphic legacy that is difficult or impossible to override through restoration. Built infrastructure in an environment places constraints on any restoration project.

Ecological and geomorphic thresholds are perhaps the most difficult aspect of habitat restoration to accurately predict, but are recognized to exist. While thresholds may be an issue within a restoration site, they are usually a greater concern at the wider and longer-term level, especially when the system hosting the restoration project is already under stress. Examples of significant thresholds in coastal areas include bleaching of reefs because of temperature change and salt marsh shifting to open mudflat due to sediment starvation.

Difficulties arise when accommodating thresholds into restoration planning because: (1) Empirical datasets are small, (2) causes and effects may not manifest themselves for many decades after the environmental change (e.g., Elkhorn Slough, OR), and (3) deterministic, process-based models (e.g., sediment transport simulations) are very poor at recognizing environmental thresholds. Nevertheless, historic analysis, field evidence, and conceptual geomorphic and ecological models have demonstrated their presence. Yet many practitioners are unaware that critical thresholds that will impact the sustainability of their project even exist.

We must consider our restoration projects in the context of the wider landscape. Does the landscape show evidence of approaching an environmental threshold? Will our restoration project reduce or increase the probability that that threshold will be crossed? Is

the new system state desirable or undesirable? Will active long-term maintenance be required to maintain the coastal system and restoration project in the preferred state? Should we site the restoration project in a more resilient coastal setting?

Geomorphic and ecological environmental indicators may provide evidence that a system is changing and approaching a system threshold. A system-wide increase of mudflat area within a salt marsh complex (e.g., sustained increase in pan area or channel area) may indicate that sediment supply and vegetation growth is unable to keep pace with sea level rise. Similarly, sustained thinning of beaches on a barrier island complex may be an indication of increasing risk of barrier loss and impending conversion to open coast.

Despite these complications, pre-disturbance restoration targets remain worthy goals in many contexts. Restoration planners must determine when such goals remain viable and, conversely, when to consider alternative targets.

Management for change is at the root of dealing with climate change. In doing so, planners must direct restoration projects toward desirable outcomes. In constrained settings, such as urbanized estuaries, planners may decide that restoration should target new forms of habitat, or habitats that include engineered elements because the historic condition is unachievable.

Restore coastal ecosystems sooner rather than later.

The magnitude of climate change impacts are likely to increase with time. The further ecosystems fall behind on restoration trajectories, the greater the likelihood that ecosystems will cross a threshold, preventing or limiting restoration of that habitat type. A strategy of restoring coastal ecosystems sooner rather than later would improve coasts' resiliency to climate change forces.

With the rate of sea level rise likely to accelerate toward the middle of this century, planners have a window of opportunity to restore coastal ecosystems in the near-term. Restoring a system to a level of maturity both reduces ecosystem sensitivity and enhances resilience to climate change. For example, the restoration of salt marsh and mangroves typically progresses—via the buildup of sediment—from newly created mudflat to a vegetated marsh. Once the wetland attains a suitable elevation, vegetation establishes, accompanied by the inclusion of organics as part of the marsh accumulation processes. This increases resilience to both sea level rise and surface scour. Extraction of water from soils and binding by root mats also occur, both enhancing marsh cohesion which reduces the marsh's sensitivity to wave attack associated with offshore deeper water.

Develop a learning curve.

Given the young state of restoration science and the inherent uncertainties in ecosystem restoration, it is incumbent on restoration programs to incorporate learning and experimentation (Simenstad and others, 2006).

Restoration should be based upon overt and peer-reviewed conceptual models linking restoration actions—through physical processes to desired ecological outcomes. Appropriate conceptual models help achieve stakeholder and regulatory agreement and approval. Moreover, they establish project success criteria and a basis for adaptive management decision-making should the project fail to follow the desired restoration path.

Monitoring and adaptive management are needed when the outcomes are uncertain. Monitoring for periods of five to ten years—commonly required to satisfy permit conditions—may provide an indication of whether the site is evolving as anticipated. However, this period is generally not long enough to inform improvements in planning and design of future projects. Once several projects have a record of restoration success, site managers can reduce monitoring and target elements identified in the restoration conceptual model to track restoration progress. To achieve this record of success and improve future decision-making, it is important to document project design, management decisions, and monitoring actions appropriately.

Restoration should be based upon overt and peer-reviewed conceptual models linking restoration actions—through physical processes to desired ecological outcomes.

Adaptive management is quite applicable to restoration—it's an objective process that characterizes scientific uncertainties, develops strategies to test hypotheses, measures the response, and incorporates the results into future decision-making.

Recognize the value of restoration design.

Investing in design work is sometimes seen as an unnecessary expense. However, an appropriate level of engineering design can save construction costs, reduce the need for adaptive management or post-project remediation, and greatly improve the ecological value of the restored habitat. Given that land acquisition costs are often the largest financial burden to a restoration project, there is a positive benefit-cost ratio to restoring higher quality habitat per unit area of land. In the end, it is on the outcome of the success of the project will be judged, which in turn will influence future public support and funding.

Restoration of historic conditions is not always possible or desirable.

In many cases, disturbances to the landscapes began over a century ago, resulting in prolonged divergence from historic ecosystem conditions. A landscape that has adjusted and incorporated the human environment may lose its capacity to be restored to historic conditions. Moreover, climate change and ongoing non-native species invasions to coastal waters are leading to community assemblages with a mix of species that historically did not coincide.

We should plan for the future; where resilient historic conditions are restorable, we should seek to do so, particularly to support endemic species. At other sites we should seek to restore for the future, recognizing that past conditions are no longer attainable.

Be patient.

Ecosystem restoration takes time. Depending on the extent of environmental disturbance, a system may take decades to fully recover. Monitoring programs rarely extend beyond a decade; thus, few capture the total outcomes of restoration. Planners must understand the restoration trajectory and track its progress while recognizing the timeframes of natural processes do not conform to human time constraints.

Avoid transplantation of non-indigenous species and diseases/ pests.

Numerous examples exist of invasive species, diseases, and pests being introduced as part of coastal management activities. Levels of awareness are now much higher but care should always be taken to minimize risks.

Chapter 3 References

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Chapter 4: Adapting to Climate Change by Restoring Coastal Habitat

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** The views are those of the authors, and do not necessarily represent the official positions of either The Nature Conservancy or the U.S. Government.*

*** The Sections on Protect and Retreat are excerpted from Titus and Craghan (2009).*

Chapter citation: Shumway, C.A., J.G. Titus, and R. Takacs. 2012. Adapting to Climate Change by Restoring Coastal Habitat. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore-Adapt-Mitigate: Responding to Climate Change Through Coastal Habitat Restoration. Restore America's Estuaries, Washington, DC, pp. 33-48.

Restoration can help coasts adapt to climate change, enabling coastal ecosystems to become more resilient. Conversely, if climate change impacts are ignored, coastal and estuarine restoration projects may fail over the long term. Therefore, restoration must consider the impacts of climate change. For example, restoration can absorb wave damage due to sea level rise in low-energy sites, benefiting both natural and human communities. One paper (Costanza et al., 2008) estimated the monetary value of U.S. wetlands from the standpoint of hurricane protection alone as a mean value of 23.3 billion dollars per year.

In this chapter, four approaches to sea level adaptation are reviewed: Protect, Retreat, Accommodate, and Reduce Other Stressors (Figure 4-1). While the impacts of climate change on present coastal and marine habitats and species have been clearly demonstrated (Rosenzweig et al., 2008), a recent review of 113 papers addressing biodiversity management in the face of climate change noted the dearth of specific, actionable recommendations that managers could undertake immediately (Heller et al., 2009). With this in mind, suggestions and recommendations in this chapter are practical and doable.

> ***"Ecology and restoration science must, as the character Wendy in J.M. Barrie's play [Neverland], grow to face change."***
> ***—(Duarte et al., 2009)***

This chapter also considers responses to sea level rise and the often-overlapping impacts of shoreline erosion, increased tidal inundation, and increased flooding. The available research on adapting to sea level rise is more extensive than for other estuarine impacts of climate change. Many of the same principals, however, apply to other impacts of climate change in the upstream portions of watersheds. The most fundamental choice for environmental managers is whether to attempt to maintain key ecosystems in their current locations or facilitate their migration, which would often require relocating most human activities away from the areas to which the ecosystems might migrate.

From the standpoint of human use and enjoyment of coastal areas and resources, a second fundamental choice concerns public access. Under the public trust doctrine, the public generally has the right to access along open waters and tidal shores. If a response measure (e.g., bulkhead) tends to eliminate intertidal lands, preserving public access along the shore requires a public easement along lands that are private today. If a response measure (e.g., beach nourishment) creates additional land to which the public has access, then nearby property owners may prefer that public officials take measures to prevent significant increases in foot traffic (see e.g., Stop the Beach Renourishment, Inc. v Florida Department of the Environment).

Adaptation Approaches to Sea Level Rise

The Intergovernmental Panel on Climate Change (IPCC 1990; IPCC 1996) and others have long divided the responses to sea level rise into three alternative pathways:

1) Protect – protect land and structures from erosion, inundation, flooding, and other consequences of sea level rise (a) through the use of structures (e.g., dikes, biologs); (b) by elevating land surfaces (e.g., beach nourishment); or (c) some combination of the so-called hard and soft approaches;
2) Retreat – allow wetlands, beaches, other shores, and species to migrate naturally and move people out of harm's way and/or prevent new construction in vulnerable areas;
3) Accommodate – make no additional efforts to prevent tidal inundation, erosion, or flooding. Instead of moving people out of harm's way, develop coping strategies that enable continued human habitation in spite of the increased hazards. In the long run, this approach generally would give way to either protection or retreat.

A fourth category of responses is also considered that can be useful, regardless of the general response pathway chosen for a given area:

4) Reduce other stressors – reduce other factors that threaten the resilience of the area.

The following section discusses, in turn, each of these three approaches to adapting to sea level rise.

Protect

The term "shore protection" generally refers to a class of coastal engineering activities that reduces the risk of flooding, erosion, or inundation of land or structures (U.S. Army Corps of Engineers 2002). The term is somewhat of a misnomer because the activities protect land and structures immediately inland of the shore rather than the shore itself. Note that "shore protection" does not necessarily mean environmental preservation. Although shore protection can have environmental goals, it can also eliminate wetlands, beaches, and other habitat. Thus, a key restoration objective is often to design shore protection so as to minimize adverse effects on habitat.

Shore protection measures can be broadly divided into two categories: shoreline armoring and elevating land surfaces. Shoreline armoring replaces the natural shoreline with an artificial surface; areas inland of the shore are generally untouched. Elevating land surfaces, in contrast, can maintain the natural character of the shore, but may involve rebuilding a very large area of dry land and wetlands. Some methods are hybrids of both approaches—including many "living shoreline" methods. (For a comprehensive discussion, see the Coastal Engineering Manual [USACE 2002] and Mitigating Erosion Along Sheltered Shores [National Research Council 2007]) Table 4.1 (next page) presents some of the most common techniques and their environmental consequences.

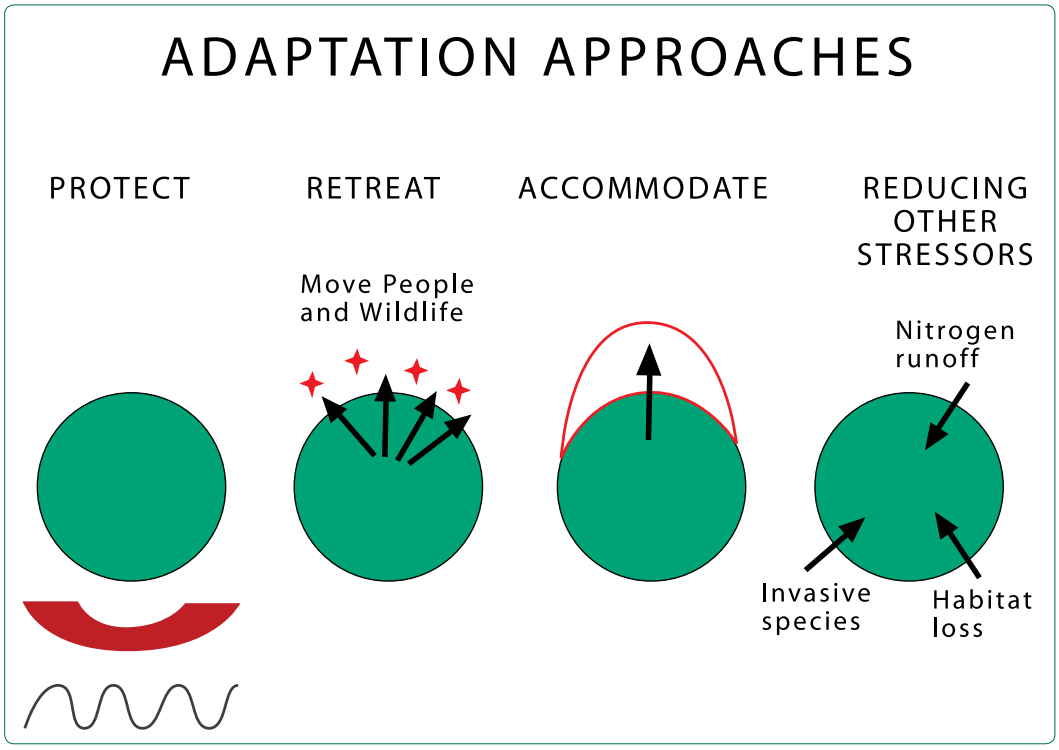


Figure 4-1 The four types of adaptation approaches.

Shoreline Armoring

Shoreline armoring involves the use of structures to keep the shoreline in a fixed position or to prevent flooding when water levels are higher than the land. Although the term is often synonymous with "shoreline hardening," some structures are comprised of relatively soft material, such as earth and sand.

Keeping the shoreline in a fixed position

Seawalls are impermeable barriers designed to withstand the strongest storm waves and to prevent overtopping during a storm. Seawalls are often used along important transportation routes such as highways or railroads (Figure 4-2a). A key problem is that the beach in front of the seawall is often eliminated or lost due to erosion.

Table 4-1 Selected Shore Protection Measures for Responding to Sea Level Rise: Objectives and Environmental Effects

Response		
Measure	Objective for Protection or Retreat	Key Environmental Effects
Shoreline armoring that interferes with waves and currents		
Breakwater	Reduces erosion.	May attract marine life. Causes downdrift erosion.
Groin	Reduces erosion.	Same effects as breakwater.
Shoreline armoring used to define a shoreline		
Seawall	Reduces erosion. Protects against flood and wave overtopping.	Elimination of beach. Causes scour and deepening in front of wall. Exacerbates erosion at terminus.
Bulkhead	Reduces erosion. Protects new landfill.	Prevents inland migration of wetlands and beaches. Wave reflection erodes bay bottom, preventing submerged aquatic vegetation SAV. Prevents amphibious movement from water to land.
Revetment	Reduces erosion; Protects land from storm waves. Protects new land fill.	Prevents inland migration of wetlands and beaches. Traps horseshoe crabs and prevents amphibious movement. May create habitat for oysters and refuge for some species.
Living Shoreline	Reduces erosion. Protects land from storm waves. Protects new land fill	Prevents inland migration of wetlands and beaches. Creates or restores habitat within the footprint of the shore protection project.
Shoreline armoring used to protect against floods and/ or permanent inundation		
Dike	Prevents flooding and permanent inundation (when combined with a drainage system).	Prevents wetlands from migrating inland. Thwarts ecological benefits of floods (e.g., annual sedimentation, higher water tables, habitat during migrations, productivity transfers)
Tide gate	Reduces tidal range by draining water at low tide and closing at high tide.	Restricts fish movement. Reduced tidal range reduces intertidal habitat. May convert saline habitat to freshwater habitat.
Storm surge barrier	Eliminates storm surge flooding. Could protect against all floods if operated on a tidal schedule	Eliminates necessary storm surge flooding in salt marshes.
Elevating land		
Dune	Protects inland areas from storm waves; provides a source of sand during storms to offset erosion.	Can provide habitat. Can set up habitat for secondary dune colonization behind it.
Beachfill	Reverses shore erosion and provides some protection from storm waves.	Causes short-term loss of shallow marine habitat. Could provide beach and dune habitat.
Elevate land and structures	Avoids flooding and inundation from sea level rise by elevating everything as much as sea rises.	Deepens estuary unless bay bottoms are elevated as well.
Retreat		
Setback	Delays the need for shore protection by keeping development out of the most vulnerable lands.	Impacts of shore protection delayed until shore erodes up to the setback line. Impacts of development also reduced.
Rolling easement	Prohibits shore protection structures.	Impacts of shore protection structures avoided.
Density or size restriction	Reduces the benefits of shore protection and thereby makes it less likely.	Depends on whether owners of large lots decide to protect shore. Reduces impacts of intense development.
Source: Titus and Craghan 2009		

Figure 4-2 Seawalls and Bulkheads (a) Galveston Seawall in Texas [May 2003] and (b) Bulkheads with intervening beach along Magothy River in Anne Arundel County, Maryland [August 2005]. Copyright Risingsea.net (2009). Used by permission.

Bulkheads are vertical walls designed to prevent the land from slumping toward the water (Figure 4-2b). They must resist waves and currents, but unlike seawalls they are not designed to withstand severe storms and are not high enough to keep out floods. They are usually found along estuarine shores where waves have less energy, such as marinas, and residential areas where homeowners prefer a vertical shoreline. Like seawalls, their seaward sides may be inland of a beach (or marsh) or in the water. If they are built landward of an eroding shore, eventually the remaining wetlands and beaches in front of the bulkhead erode and the intertidal habitat is eliminated. Reflection of wave energy off the face of bulkheads can scour the shallow bottom areas near the bulkhead and thereby increase turbidity and reduce the ability of the these shallow areas to support submerged aquatic vegetation (SAV).

Revetments are walls whose sea side follows a slope (Figure 4-3). Like the beach they replace, their slope makes them more effective at dissipating the energy of storm waves than bulkheads and seawalls. Revetments are also less likely than the other methods to cause erosion of the adjacent seaward beach (USACE 2002) and less likely to fail during a storm (Basco 2003; USACE 2001). Revetments have many of the same adverse environmental consequences as bulkheads, but some intertidal habitat is created on and in between the stones. Oyster restorations have been integrated into revetments in some cases.

Figure 4-3 Two types of stone revetments (a) near Surfside, Texas and (b) at Jamestown, Virginia. Copyright Risingsea.net (2009). Used by permission.

Protecting Against Flooding or Permanent Inundation

Dikes are high, impermeable earthen walls designed to keep the area behind them dry. They can be set back from the shoreline if the area to be protected is a distance inland. Dikes usually require an interior drainage system to remove water. Land below mean low water requires a pumping system to remove rainwater and any water that seeps through the ground below the dike (Figure 4-4). Although the most common use of dikes has been to protect developed lands from flooding and inundation, dikes are increasingly used to maintain habitat by managing salinity and water elevation levels. Along the Delaware Estuary, for example, dikes with tide gates were originally built as part of an effort to convert tidal marsh to farmland (Craghan et al., 2010). As sea level rose, however, the land was too waterlogged for crops. The dikes are now used to maintain freshwater wetlands below sea level adjacent to brackish portions of the estuary.

Figure 4-4 A dike in Miami-Dade County, Florida. Copyright Risingsea.net (2009). Used by permission.

Tide gates are barriers across small creeks or drainage ditches. By opening during low tides and closing during high tides, they enable a low-lying area above the mean low water level to drain without the use of pumps (Figure 4-5). By reducing tidal range, they may reduce the area of intertidal habitat. As sea level rises, however, they may also be used to reduce the duration of high tide and thereby delay the risk of wetlands drowning for several decades.

Figure 4-5 The tide gate at the mouth of Army Creek on the Delaware side of the Delaware River. The tide gate drains flood and rainwater out of the creek to prevent flooding. The five circular mechanisms on the gate open and close to control water flow (Source: NOAA Photo Library).

The cumulative environmental effects of extensive shoreline armoring using hardened structures to protect real property assets from erosion and land loss are now widely understood. Bulkheads and seawalls create vertical walls at the land/water interface that usually eliminate any intertidal or wetland habitat remaining along the shore, and preclude the use of much of this area by aquatic organisms. Likewise, armoring through the use of riprap, revetments, or other shore-based placement of hard materials often limits the use of these areas by crabs, fish, and reptiles, which no longer have access to the fringe marsh areas eliminated by building these structures. Nevertheless, shoreline armoring using hardened structures can have some environmental benefits. Preventing the erosion of an undeveloped buffer zone, for example, can indirectly reduce runoff of pollutants. A newer, more natural approach to shoreline armoring—living shorelines—has considerable promise in low-energy areas.

Elevating land surfaces

A second approach to shore protection is to elevate land and structures. Tidal marshes have long naturally adapted to sea level rise by elevating their land surfaces to keep pace with the rising sea (Cahoon et al., 2009). Elevating land and structures by the amount of sea level rise can keep a community's assets at the same elevation relative to the sea and prevent them from becoming more vulnerable as sea level rises. These measures are sometimes collectively known as "soft shore protection."

Beachfill, also known as "beach nourishment" or "sand replenishment," involves the purposeful addition of the native beach material (from an offshore or inland source) to a beach to make it higher and wider and to provide a buffer against wave action and flooding (USACE 2003; Dean and Dalrymple 2002). Placing sand (or gravel) onto an eroding beach can offset the erosion that would otherwise occur; but erosion processes continue, necessitating periodic re-nourishment. Beaches along Delaware Bay are sometimes nourished for the primary purpose of preserving horseshoe crab habitat. Elevating land and structures is the equivalent of a beachfill operation in the area landward of the beach.

Enhanced wetland accretion is the equivalent of a beachfill operation for wetlands. A thin-spray of fine sediment can imitate the natural process of wetland accretion through sedimentation. In Louisiana, river diversions have been proposed to provide sediment to wetlands.

Dredge and fill was common until the 1970s, but it is rarely used today because of the resulting loss of tidal wetlands. Channels were dredged through the marsh, and the dredge material was used to elevate the remaining marsh to create dry land (e.g., Nordstrom, 1994). The overall effect was that tidal wetlands were converted to a combination of dry land suitable for home construction and navigable waterways to provide boat access to the new homes. The legacy of previous dredge-and-fill projects includes numerous very low-lying communities along estuaries, including the bay sides of many developed barrier islands. Recently, some wetland restoration projects have used a similar approach to create wetlands, by using material from dredged navigation channels to elevate shallow water up to an elevation that sustains wetlands (USFWS 2008).

Communities often use a combination of shoreline armoring and elevation. Many barrier island communities apply beach nourishment on the ocean side while armoring the bay side. Ocean shore protection projects in urban areas sometimes include both beach nourishment and a seawall to provide a final line of defense if the beach erodes during a storm. Beach nourishment projects along estuaries often include breakwaters to reduce wave erosion (Figure 4-6a) or a terminal groin to keep the sand within the area meant to be nourished (Figure 4-6c).

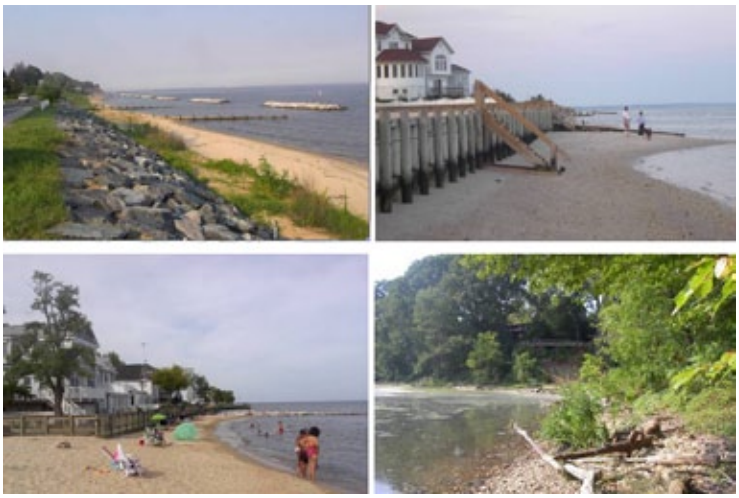


Figure 4-6 Hybrid approaches to shore protection. (a) Breakwaters and groins along Chesapeake Bay in Bay Ridge (near Annapolis) Maryland [July 2008]. The rock structures parallel to the shore in the bay are breakwaters; the structures perpendicular to the shore are groins; (b) wooden groins and bulkhead along the Peconic Estuary on Long Island, New York [September 2006]. The beach is wider near the groin and narrower between groins; (c) a nourished beach with a terminal groin at North Beach, Maryland [September 2008] (d) a dynamic revetment placed over the mud shore across Swan Creek from the Fort Washington (Maryland) unit of National Capital Parks East. Logs have washed onto the shore since the project was completed [July 2008]. Copyright Risingsea.net (2009). Used by permission.

Living shorelines and other hybrid approaches to shore protection

There is now widespread recognition that while traditional shoreline armoring approaches can provide protection for the land behind the immediate shoreline, this approach causes a loss of habitat connectivity and tidal habitat. Recently, several state agencies, scientists, environmental organizations, and property owners have begun to employ techniques designed not only to reduce erosion along estuarine shores, but to preserve more habitat instead of building bulkheads and revetments (see Box 4-1).

"Living shorelines" is a term used to define a number of shoreline protection options that allow for natural coastal processes to remain through the strategic placement of plants, stone, sand fill, and other structural and organic materials. Living shorelines often rely on native plants, sometimes supplemented with stone sills, on-shore or off-shore breakwaters, groins or biologs to reduce wave energy, trap

sediment, and filter runoff, while maintaining (or increasing) beach or wetland habitat (National Research Council, 2007). Several of these techniques are hybrids of traditional shoreline armoring and the softer approaches to shore protection. The goal is to retain much of the wind, tide, and storm-related wave protection of a hard structure, while maintaining some of the features of natural shorelines.

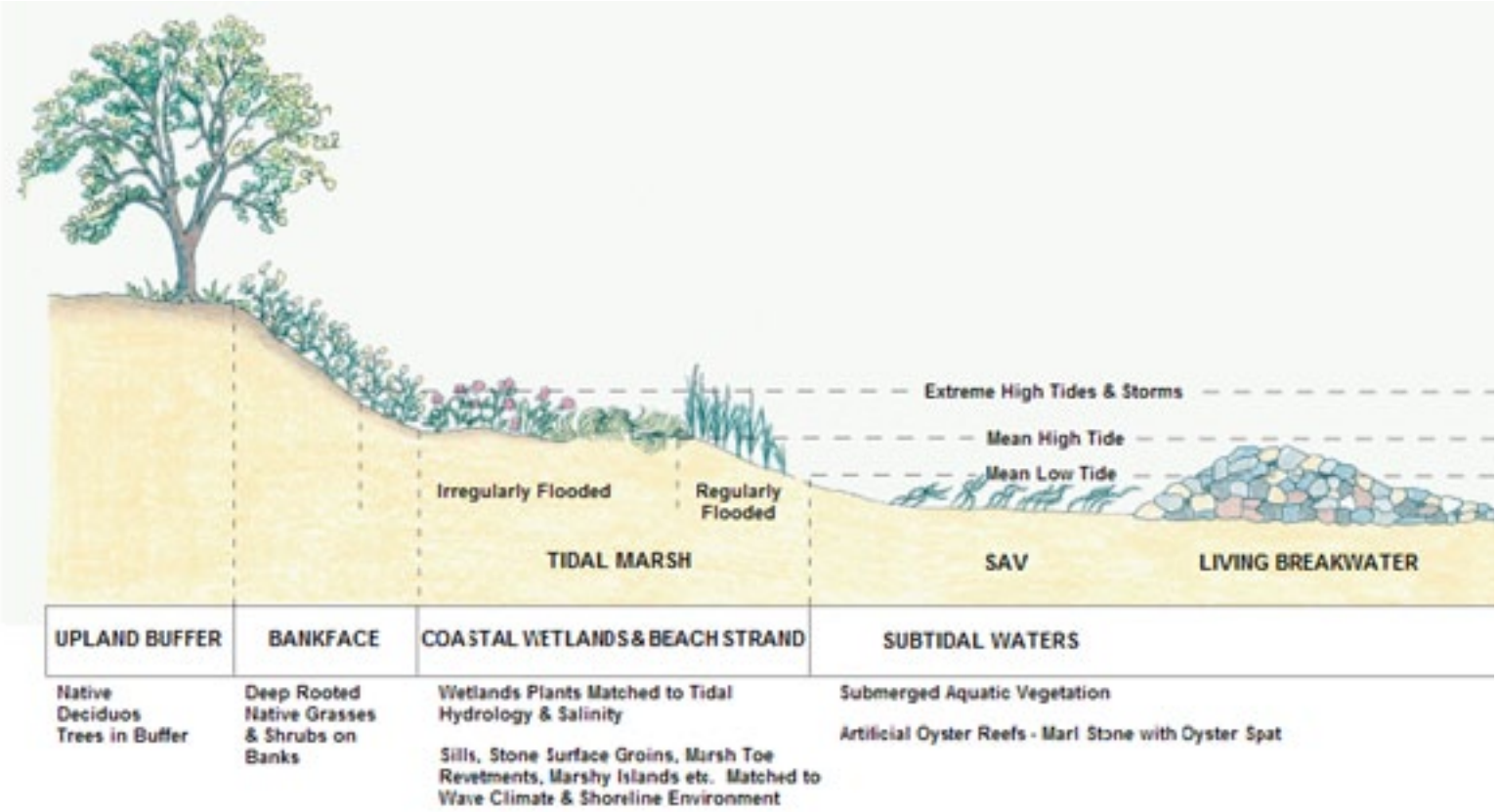
In theory, living shoreline projects comprised of low and high marsh (sand/soil fill and plants) should be able to persist and/or migrate over time in response to changes in shoreline alignments (continued natural erosion processes) and sea level rise. In practice, however, there is little empirical data to suggest that this is occurring at most of the sites completed to-date. Even if the wetland area itself was to begin the process of migrating landward in the face of sea level rise, the rock structures—purposely designed to be as minimal as possible—could be rapidly overtopped and no longer provide the structural protection desired.

Through trial and error, however, practitioners have developed criteria and techniques that can usually ensure success of a properly designed and constructed "living shorelines" project. The two most critical features that determine success of living shoreline projects are the elevations of the structures such as substrate and plants, and the ability to withstand the continuous forces over time. In sum, to ensure continued protection and environmental benefit, living shoreline projects need to be periodically evaluated for functional effectiveness, and require maintenance activities of some sort as various stages in the life of the project.

Shore Protection Alternatives in Maryland: Living Shorelines

Shore erosion and methods for its control are a major concern in estuarine and marine ecosystems. However, awareness of the negative impacts that many traditional shoreline protection methods have— including loss of wetlands and their buffering capacities—impacts on nearshore biota, and ability to withstand storm events, has grown in recent years. Nonstructural approaches, or hybrid-type projects that combine a marsh fringe with groins or breakwaters, are being considered along all shorelines except for those with large waves (from either boat traffic or a long fetch). The initial cost for these projects can be less than or greater than traditional approaches, depending on whether the wave energy is small or large; the long-run cost depends on how frequently the living shoreline must be rebuilt.

These projects typically combine marsh replanting (generally Spartina patens and Spartina alterniflora) and stabilization through sills, groins, or breakwaters. A survey of projects on the eastern and western sides of Chesapeake Bay (including Wye Island, Epping Forest near Annapolis, and the Jefferson Patterson Park and Museum on the Patuxent) found that the sill structures or breakwaters were most successful in attenuating wave energy and allowing the development of a stable marsh environment.



Sources: Jefferson Patterson Park and Museum, wetlands restoration firm Environmental Concern (www.wetland.org), Shore Erosion Control: The Natural Approach from the Maryland Department of Natural Resources; Burke et al., 2005.

Other hybrid approaches to shore protection include the following:

Sills or other marsh toe protections are low in height, often continuous structures that are emergent at low tide, but partially or completely submerged at high tides. Larger projects also often employ gaps or "windows" in the design to allow water and organisms to access the protected tidal marsh habitat behind the structure. Typically, these structures protect an existing fringe marsh area or fill and plants are placed and planted to restore a former marsh site.

Breakwaters are usually stone structures used in higher energy areas that can be either attached to the shore or placed offshore, generally parallel to the shoreline (Figure 4-6a). Unlike the lower sill counterparts, breakwaters are higher in elevation and mitigate shore erosion by preventing large waves from striking the shore. Segmented breakwaters, with natural beach situated between them, often slow the transport of sand. They can even serve as depositional areas, creating a mix of habitat types, which allows natural sand and non-vegetated beach for human or wildlife use.

Groins are hard structures perpendicular to the shore extending from the beach into the water, usually made of large boulders, wood, or concrete (Figure 4-6a.). Their primary effect is to diminish forces that transport sand perpendicular to the shore, or what is typically called longshore transport. Since they trap sediment that would be dynamically moving otherwise, their protective effect is often increased erosion farther down along the shore. They are most useful where an area requiring protection is updrift from an area where shore erosion is more acceptable. At a larger scale, jetties are similar structures intended to guard a harbor entrance, often resulting in large erosion on one side of the inlet and accretion on the other side.

Dynamic revetments (also known as cobble beaches) are a hybrid of beach nourishment and hard structures, in which an eroding mud or sand beach in an area with a light wave climate is converted to a cobble or pebble beach (Figure 4-6d). The cobbles are heavy enough to resist erosion, yet small enough to create a beach environment (Allan et al., 2005; Komar, 2007; USACE 1998).

Retreat

The primary alternative to "shore protection" is ***retreat*** (or relocation). As discussed in the previous section, shore protection generally involves coastal engineering to manage the forces of nature and environmental engineering to manage environmental consequences. By contrast, retreat often emphasizes the management of human expectations to discourage investments that would eventually lead people to attempt shore protection; it also allows the land to revert back to a natural state.

Retreat is the most common—albeit generally unnoticed—response to sea level rise in undeveloped areas. Retreat along developed estuaries is very rare, because the cost of shore protection is much less than the value of the land protected. As a result, most experience with retreat in developed areas is associated with shores along oceans and other bodies of water with powerful waves, where shore protection costs are higher. In developed areas, a retreat can either occur as an unplanned response in the aftermath of a severe storm or as a planned response to avoid the costs or other adverse effects of shore protection. Investments in buildings, infrastructure, businesses and communities can have useful lifetimes of many decades or longer. Therefore, planning, regulatory, and legal mechanisms usually play a more important role in facilitating a planned retreat than they do for shore protection, which for most projects can be undertaken in a matter of months or years. Some retreat measures are designed to ensure that a retreat occurs in areas where shores would otherwise be protected; other measures are designed to decrease the costs of a retreat but not necessarily change the likelihood of a retreat occurring. In Great Britain, an ongoing planned retreat known as "managed realignment" involves erecting new shore protection structures landward of the existing shore protection, and partly dismantling the old seaward structures to permit shallow water ecosystems to form (Midgley and McGlashan, 2004; Rupp-Armstrong and Nicholls, 2007).

Retreat is the most common—albeit generally unnoticed—response to sea level rise in undeveloped areas.

Retreat can also be considered for ecological reasons, particularly in estuarine environments. A recent assessment created sea level rise planning maps (Risingsea.net 2010) that distinguish the areas where shore protection is likely from areas where retreat would be likely assuming a continuation of existing policies (Titus and Hudgens, 2010). The authors concluded that almost 60% of the land vulnerable to sea level rise along the U.S. Atlantic Coast is likely to be developed and protected from the rising sea, while less than 10% of the area is likely to be part of conservation land available for the inland migration of ecosystem (Titus et al., 2009a). The remaining 30% are mostly farms and forests in rural areas from Georgia to Delaware Bay, where development would be allowed but is not imminent—yet. To ensure that estuaries continue to have a sufficient area of coastal wetlands as sea level rises, the authors suggested that the Corps of Engineers re-examine existing policies that favor shoreline armoring, and that policy makers at all levels reconsider the wisdom of continuing to develop low-lying coastal lands.

For a comprehensive review, see Shoreline Management Technical Assistance Toolbox (NOAA, 2006). The most widely assessed and implemented measures are discussed below.

Relocating structures is possibly the most engineering-related activity involved in a retreat. Perhaps the most ambitious relocation project in the United States has been the landward relocation of the Cape Hatteras Lighthouse (Figure 4-7a). More commonplace are

the routine "structural moving" activities involved in relocating a house back several tens of meters within a given shorefront lot, and the removal of structures threatened by shore erosion (Figure 4-8b).

Figure 4-7 Relocating Structures Along the Outer Banks (a) Cape Hatteras Lighthouse after relocation at the Cape Hatteras National Seashore, Buxton, North Carolina [June 2002]. The original lighthouse location is outlined in the foreground, and; (b) A home threatened by shore erosion in Kitty Hawk, North Carolina [June 2002]. The geotextile sand bags are used to protect the septic system. Copyright Risingsea.net (2009). Used by permission.

Conservation easements are created when certain interests, or rights of uses of the land, are purchased or donated that allow the owners of the easements to control what uses are allowed within the easement area. Land conservation organizations have purchased non-development easements along coastal bays, including the Chesapeake Bay in Maryland (MALPF, 2003). In most cases, the original motivation for these purchases is the creation of a buffer zone to protect the intertidal ecology (MDCBP, 1999). These vacant lands also leave room for landward migration of wetlands and beaches. Organizations can also purchase and create buffers specifically for the purpose of accommodating rising sea level. Blackwater Wildlife Refuge in Maryland and Gateway National Recreation Area in New York both own considerable amounts of land along the water onto which wetlands and beaches could migrate inland. Agricultural preservation programs sometimes purchase shorefront land in Maryland (Nuckols et al., 2010), Delaware (Hudgens and Neumann, 2010), and New Jersey (Craghan, 2010).

Acquisition programs involve efforts by government or a conservation entity to obtain title to the land closest to the sea. Titles may be obtained by voluntary transactions, eminent domain, or dedication of flood-prone lands as part of a permitting process. In Barnegat Light, New Jersey (Craghan et al., 2010) and Virginia Beach, Virginia (Titus et al., 2010), for example, governments own substantial land along the shore between the Atlantic Ocean and the oceanside development.

Setbacks are the regulatory equivalent to conservation easements and purchase programs. The most common type of setback used to prepare for sea level rise is the erosion-based setback, which prohibits development on land that is expected to erode within a given period of time. North Carolina requires new structures to be set back from the primary dune based on the current erosion rate multiplied by 30 years for easily moveable homes, or by 60 years for large immoveable structures (Feldman, 2009). Maine's setback rule assumes a 60-centimeter (cm) rise in sea level during the next 100 years (06-096 Code of Maine Rules §355(5)(C), (2007).

Flood hazard regulations sometimes prohibit development based on elevation, rather than proximity to the shore. Aside from preventing flood damages, these elevation-based setbacks can ensure that there is room for wetlands or other intertidal habitat to migrate inland as sea level rises in areas that are vulnerable to inundation rather than wave-generated erosion. Two counties in Delaware prohibit development in the 100-year floodplain along the Delaware River and Delaware Bay (Hudgens and Neumann 2010; Titus et al., 2009a).

Rolling easements are regulatory mechanisms or interests in land that prohibit engineered shore protection, allowing wetlands or beaches to naturally migrate inland as sea level rises (Titus 1998; 2011). Rolling easements transfer some of the risk of sea level rise from the environment or the public to the property owner (Titus, 1998). When implemented as a regulation, they are an alternative to prohibiting all development in the area at risk, which may be politically infeasible, inequitable, or a violation of the "takings clause" of the U.S. Constitution (Caldwell and Segall, 2007; Titus, 2011). When implemented as an interest in land, they are an alternative to outright purchases or conservation easements (Titus, 1998).

Rolling easements align the property owner's expectations with the dynamic nature of the shore; over the long term, they also allow the area to return to a natural state (Titus, 1991). If retreat is the eventual objective, property owners can more efficiently prepare if they expect it than if it takes them by surprise (Yohe and Neumann, 1997; Yohe et al., 1996). Preventing development in the area at risk through setbacks, conservation easements, and land purchases can also be effective, but such restrictions can be costly if applied to thousands of square kilometers of valuable coastal lands (Titus, 1991). Because rolling easements allow development but preclude shore protection, they are most appropriate for areas where preventing development is not feasible and engineered shore protection is unsustainable.

In Texas, common law recognized rolling easements along portions of the Texas Gulf Coast (Feinman v. State; Matcha v. Mattox) and the Texas Open Beaches Act (TEX. NAT. RES. CODE ANN. §§ 61.001-.178 (West 1978 & Supp. 1998) codified the public right to traverse the shore (Titus, 2011). Massachusetts and Rhode Island prohibit shoreline armoring along some estuarine shores so that ecosystems can migrate inland; several other states limit armoring along ocean shores (Titus, 2009). When implemented as a regulation, the rolling easement assumes that property owners do not have a compensable right to hold back the sea (Titus, 2011). Property owners occasionally attack rolling easement policies (e.g., Severance v. Patterson) as an unconstitutional taking of private property. To avoid that risk, governments and conservancies can obtain rolling easements that are a type of conservation easement, with the easement donated, purchased from willing sellers, or exacted as part of a planning review process (Titus, 2011). But so far, all rolling easement policies have been implemented through regulation (Titus, 2011).

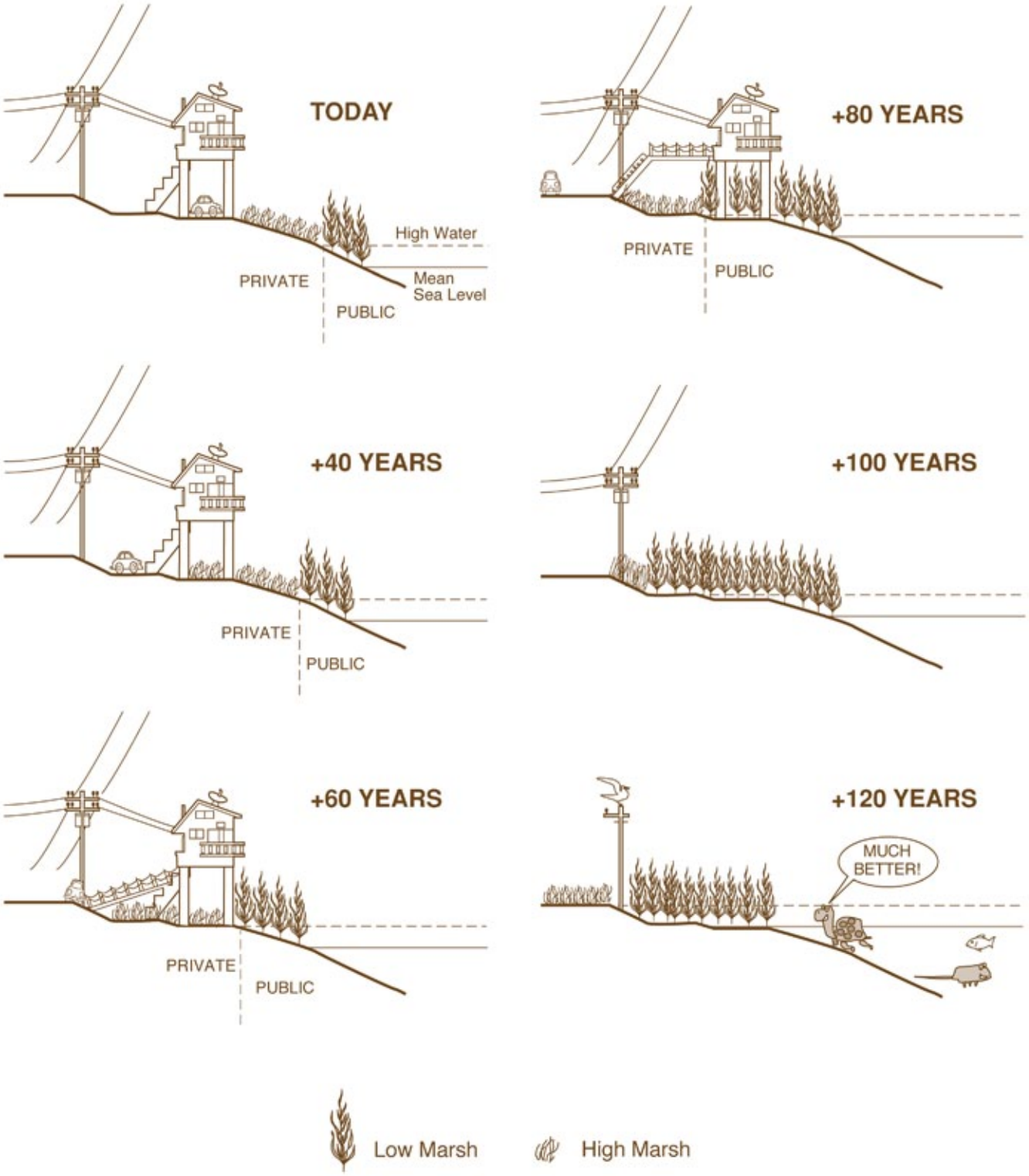


Figure 4-8 The landward migration of wetlands onto property subject to a rolling easement. A rolling easement allows construction near the shore, but requires the property owner to recognize nature's right-of-way to advance inland as sea level rises. In the case depicted, the high marsh reaches the footprint of the house 40 years later. Because the house is on pilings, it can still be occupied (assuming that it is connected to a sewage treatment plant. A flooded septic system would probably fail, because the drain field must be a minimum distance above the water table). After 60 years, the marsh has advanced enough to require the owner to park their car along the street and construct a catwalk across the front yard. After 80 years, the marsh has taken over the entire yard; moreover, the footprint of the house is now seaward of mean high water and hence, on public property. At this point, additional reinvestment in the property is unlikely. Twenty years later, the particular house has been removed, although other houses on the same street may still be occupied. Eventually, the entire area returns to nature. A home with a rolling easement would depreciate in value rather than appreciate like other coastal real estate. But if the loss is expected to occur 100 years from today, it would only offset the current property value by 1%-5%, which could be compensated or offset by other permit considerations. Source: Titus (1998).

Because the dry beach and intertidal land continues to exist, the rolling easement also preserves the public's lateral access right to walk along the shore (Matcha v. Mattox, 1986). Figure 4-8 shows how a rolling easement might work over time in an area already developed when rolling easements are obtained.

Density restrictions allow limited development near the shore. In most cases, the primary motivation is to reduce pollution runoff into estuaries, but they also can facilitate a retreat by decreasing the number of structures potentially lost if shores retreat. Maryland limits development to one home per 8.1 hectares (20 acres) within 305 meters (1000 feet) of the shore in most coastal areas (Titus et al., 2009b). In areas without public sewer systems, zoning regulations often restrict densities (Accomack County, 2008).

Size limitations allow development but limit the intensity of the development placed at risk. Small structures are also relocated more easily than a large structure. North Carolina limits the size of new commercial or multi-family residential buildings to 464 square meters (sq m) (5000 square feet [sq ft]) in the area that would be subject to shore erosion during the next 60 years given the current rate of shore erosion, or within 36 m (120 ft) of the shore, whichever is farther inland (15A NCAC 07H. 0305-0306). Maine's Sand Dune Rules prohibit structures taller than 10.7 m (35 ft) or with a "footprint" greater than 232 sq m (2500 sq ft) in all areas that are potentially vulnerable to a 60 cm rise in sea level (06-096 Code of Maine Rules §355 (5) (D). (2007).

Accommodate

Accommodation is a compromise between shore protection and retreat, applicable only to developed areas. As with shore protection, people continue to occupy a particular area, but as with retreat, no shore protection is constructed. Thus, people take measures to accommodate the rising sea. In theory, accommodation could be sustained indefinitely, but a more practical use of the accommodation option is an interim approach until a community is ready to either retreat or engage in shore protection. (In the permanent accommodation pathway, roads would be replaced with docks and houses would either become piers or be replaced with boats.) Given the compromise between protection and retreat, accommodation requires a combination of structural and nonstructural measures.

From the standpoint of restoration (and assuming that accommodation is an interim approach), nonstructural measures might include:

- Rolling Easements. In an accommodation scenario, a rolling easement allows wetlands to migrate inland but does not require the property owner to actually abandon the land (Titus 2011; see also the first 4 boxes of Figure 4-8).
- A process for deciding whether to retreat or engage in shore protection. Scenario planning at the community level can help to set priorities, based on both the natural resource value and economic resource value of the area.

Structural measures might include:

- Elevating homes (but not land surfaces), enabling a natural transition between habitats.
- New or modified ditches, swails, culverts and tide gates to mitigate flooding and/or improve the flushing of tidal wetlands.
- Replacing driveways with on-street parking, and sidewalks with catwalks so that driveways and sidewalks can convert to marsh.

Reduce Other Stressors

We have a good understanding of the ecological stresses coastal and estuarine habitats face. Key stressors include, among others, invasive species, nutrient loading (particularly nitrogen runoff), habitat loss and fragmentation, change in water quantity, change in sediment delivery to the coast, and overfishing (Nellemann et al., 2008). Coastal experts expect climate change to increase the magnitude of all but overfishing, as described below. Climate change may increase other stressors as well, such as disease and metal toxicity. Increased precipitation, for example, is expected to lead to greater flushing of contaminants such as metals; the associated increased temperatures are expected to result in higher levels of mortality in metal-exposed ectothermic aquatic species (Sokolova et al., 2008).

A prudent adaptation strategy is to incorporate the impact of climate change while attempting to reduce these stressors, or, in the words of Heller and Zavaleta (2009),"solve for both current and future conditions simultaneously." Impacts at both the landscape scale and local scale should be considered. Experts providing input to the U.S. Climate Change Science Program rated reducing other stressors with a high level of confidence in its ability to promote resilience. This was the only strategy among seven proposed to receive such a rating (CCSP, 2008).

Invasive species: Given temperature increases resulting from climate change, many U.S. coastal areas will experience an influx of species from the south. Historically, adjacent species have been considered less of a problem than invasive species from regions that are not directly adjacent. Certain areas, however, such as the Southern New England region, may be impacted from both directions. A recent paper by Greene et al. (2008) documents movement of Pacific boreal plankton into the North Atlantic region due to opening of the Bering Strait and enhanced freshwater pulses of the Labrador current. Areas with heavy ship traffic have the added burden of invasive species entering via ballast water.

Nitrogen runoff: Excessive nitrogen is one of the key problems estuaries face today (Bricker et al., 1999). Over two-thirds of U.S. estuaries have moderate to high levels of eutrophication caused by excess nutrients (Boesch, 2002). Climate change will likely increase nitrogen runoff. Increased precipitation, for example, is expected to generate additional runoff in areas that already receive nitrogen from stormwater runoff (Peterson et al., 2008). An additional 32%-34% increase in total runoff is projected for the U.S. Atlantic and Gulf coasts by 2100 (Scavia et al., 2002). The loss of brackish and tidal freshwater marshes due to sea level rise will cause reduced denitrification, also leading to increased nitrogen levels in estuarine systems (Craft et al., 2009).

Habitat loss and fragmentation: More than 50% of the U.S. population lives along the 17% of land considered coastal. In addition to an expected 25% increase in the coastal population over the next 25 years, coastal and estuarine habitat loss is likely to increase for a variety of reasons, including the human response to sea level rise (such as political pressures to build hard structures), and transgression of marine habitats onto built environments. The relationship between low and high marsh may also change, given differing rates of migration.

Change in water quantity: Hydrological changes have already been demonstrated in the U.S., particularly in the West. Climate change is only likely to exacerbate this stress, raising its level of importance. Hydrological changes will also impact sediment supply, which is critical as wetlands attempt to cope with rising sea level via vertical accretion.

Restoration to help coasts adapt to climate change stressors

Restoration can also help reduce the multiple stressors of climate change impacts. In addition to sea level rise, discussed previously, these stressors include temperature and salinity changes, changes in frequency or intensity of precipitation events, diseases, increases in invasive species, ocean acidification, increases in UV due to depletion of the ozone layer, and synergistic, nonlinear interactions. There are some practical adaptation techniques restoration practitioners can take right away, as shown in Table 4-2 (Rogers et al., 2000; Grubin et al., 2009).

Table 4-2 Adaptation techniques

IMPACT	SOLUTION
Temperature increases	Remove hard structures Increase freshwater flow through dam releases Dredge breachways to ensure mixing Model to identify critical thermal windows for key species Reduce groundwater and stream withdrawals with water consumption policies Consider relocation of diadromous species to colder streams
Salinity intrusion	Minimize by removing dams where possible
Species impacts	Manage species directly, prioritizing those most important for ecosystem function, and those likely to be impacted the most due to physiological and/or behavioral vulnerabilities
Synergistic impacts	Improve stormwater policies, especially at a watershed level Support and increase the extent of riparian buffers along streams and wetlands to at least 100 ft.

Findings and Recommendations

For restoration to succeed, we must do a better job linking humans, ecosystem services, and estuaries. Coastal communities need to be made more aware of the benefits natural habitats and species provide, and how costly it will be for them to replace the ecosystem services they provide with artificial substitutes. This requires better documentation of the economic benefits obtained at a local level from coastal resources, and it also requires outreach and education. Coastal communities also need opportunities to be directly and intimately involved with resilience and restoration efforts, to take part in visualization scenarios for their future, and to take part in the management of their coastal resources.

Recommendations

The recommendations below are intended to provide explicit, practical actions that managers and conservation scientists can undertake now, both at specific sites and at a landscape scale. In general, coastal planners need to ensure the maintenance of key processes as well as representative geophysical habitats, with corridors available between them.

Model estimates of resilience for different coastal habitats.

Coastal experts need to better understand resilience tolerance for different coastal habitats, from wetlands to beaches. Peterson et al. (2008) has proposed that ecotonal habitats, such as wetlands, have

less resilience than other habitats. Where possible, experts should test and validate models by either using a model fitted to current data to reproduce the past or using data from one region to ground-truth a model from another region (Botkin et al., 2007).

Regionally prioritize restoration sites, considering threats, likelihood of success, and connectivity.

In general, the most effective use of conservation efforts and dollars will be to regionally prioritize restoration efforts. This guidance is one of the overarching recommendations found in a review of biodiversity management in the face of climate change (Heller and Zavaleta, 2009).

Given the uncertainties in the amount of sea level rise expected in a given region over time, identify and restore those sites likely to survive the upper range of sea level rise projected for the year 2100: 1.4 to 2 meters (Rahmstorf, 2007; Pfeffer et al., 2008)

Threats need to include existing threats, as well as projected climate-influenced changes in nutrients, salinity, precipitation and runoff.

Integrate restoration efforts in time and space.

Given the synergistic impacts of climate change, integrate restoration efforts at certain sites to ensure success. Lotze et al. (2006) highlight the significant synergistic impact of multiple threats to estuaries and suggest that a synergistic approach maximizes conservation and restoration effectiveness. As an example, consider the integration of shellfish and eelgrass restoration; modeling studies show the benefits of integration (Newell et al., 2004). Shellfish filtration can improve water quality by removing up to 20% of the total nitrogen in the system. Their dead shells increase bottom structure for a variety of species and contribute to increased animal diversity and complexity. The improved water clarity can enhance eelgrass growth. Eelgrass provides structure for numerous species of juvenile fish and food for migratory waterfowl; it traps sediments, benefits crustaceans, dampens wave energies, and buffers against erosion. Addressing water flow or water quality at the same time can provide additional benefits to both groups. Coastal planners can take this type of approach in areas where they expect climate change to have multiple impacts.

Improve stormwater policies within coastal watersheds.

Increase riparian and wetland buffer protection to 100 feet to increase the amount of nitrogen taken up by the landscape before it reaches streams and, eventually, the estuaries.

Develop a triage for invasive species.

Focus on policies and actions that reduce the invasion of non-adjacent species; identify those areas likely to receive invasions from multiple sources.

Pursue the restoration of disease-tolerant native shellfish species.

As temperatures increase, diseases such as Dermo or MSX are expected to increase. Restore shellfish using native disease-tolerant or, ideally, native resistant species to enhance resilience.

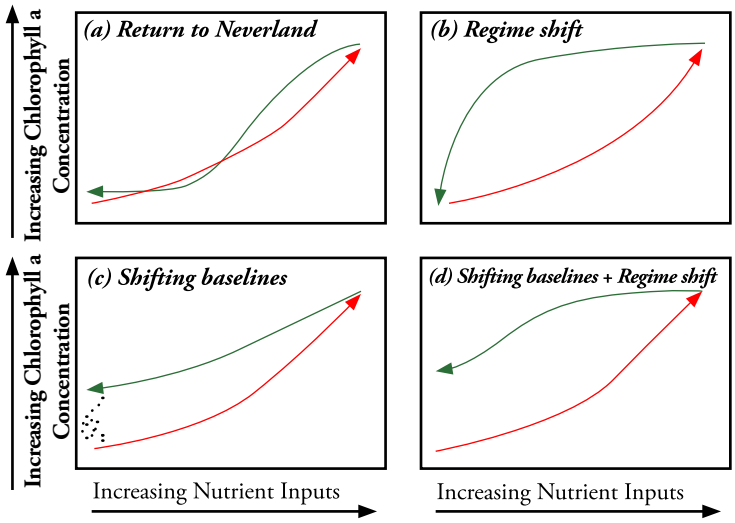


Figure 4-9. Schematic of chlorophyll response to nutrient increases and decreases: (a) return to Neverland implies that reducing nutrient will lead to an equivalent reduction in productivity. (b) regime shift results in a time lag, or hysteresis in response to nutrient reduction. (c) shifting baselines reflects other threats changing the ecosystem, preventing the ecosystem from returning to its original state;(d) comprises both shifting baselines and regime shift. A study of four estuaries where both eutrophication (nutrient increase) and oligotrophication (nutrient decrease) shows that all four approximated the pattern observed in d: shifting baselines plus regime shift. (Source: Duarte et al., 2009, with permission).

Identify and set priorities for those areas likely to benefit most from nitrogen reduction.

Bricker et al. (2003) provide a method for determining whether estuaries are likely to improve from nitrogen efforts, based on flushing potential, dilution potential, and future nutrient pressures. Areas suffering from multiple threats are poorer candidates for nitrogen reduction due to hysteresis, which means that the pollutants that caused eutrophication to occur do not have similar impacts when they are removed (Figure 4-9).

Set priorities for the protection and restoration of areas threatened by coastal development.

Coastal development limits the movement of either species or habitats resulting from climate change. To enable plants and animals to move across the landscape, we need to ensure that connectivity among geophysical processes and gradients is maintained. If patches of coastal/estuarine habitat are within a region connected through marine dispersal, then the system is more likely to survive.

It is important to consider actual, not theoretical, dispersal scales based on water currents alone (Jones et al., 2007). Numerous species have smaller dispersal scales due to behavioral restrictions in settlement. Tagging, genetic studies, and invasion dispersal suggest that, on average, a 100 km scale is appropriate for most inshore fish and crustacean species (Gillanders , 2003 and Kinlan et al., 2003). Wetland connectivity has been highly correlated with catch per unit effort in Australia; Meynecke et al. (2008) argue that "high connectivity scenarios should receive most attention

when establishing habitat protection zones." However, connectivity may have to extend at least 80 km farther. A recent global review modeling fish movement of nearly 1100 species as a response to temperature change due to climate change alone showed that the mean shift in range is expected to be approximately 80 km, measured from the center of distribution (Cheung et al., 2009).

Figure 4-10. Given increasing stressors due to climate change, ecosystem engineers may become more important for maintaining ecosystem function. Examples of ecosystem engineers include oysters (which can create oyster reefs) and beavers (which change the hydrology of an area and whose actions can aid in denitrification).

Restore animal/plant ecosystem engineers.

Ecosystem engineers, such as oysters creating oyster reefs (Figure 4-10), or skates and horseshoe crabs disturbing sediment, significantly alter habitats or change the flow of resources with their presence or activity, affecting community and ecosystem processes (Jenkins et al., 2008). As environmental stress increases, Crain and Bertness (2006) argue that the importance of ecosystem engineers increases. When stresses are low, biotic interactions drive community structure, and the main role of ecosystem engineers is to improve and stabilize ecosystem function. However, as stresses increase, the ecosystem engineer becomes essential in maintaining ecosystem function, and providing refuge from limiting physical conditions. The most important ecosystem engineers will be those that modify the limiting or constraining resources in the system. For example, an oyster reef can extend suitable habitat for a suite of other species, while at the same time mitigate sea level rise impacts to coastal communities. As Crain and Bertness state, "These positive engineering outcomes make ecosystem engineers particularly useful conservation targets, since through managing a single species, we can influence entire communities."

Mitigate the adverse consequences of shoreline armoring.

Structural options include replacement of bulkheaded shores with marshes, beaches, and other habitat. Increased flexibility is needed to allow property owners to restore lost wetlands and beaches in front of bulkheads, except possibly for the rare case where significant SAV is in front of the bulkhead. The environmental impacts of new hard shore protection structures should be mitigated by removing shore protection structures elsewhere or by setting aside additional lands that will be off-limits to shore protection. Land use measures for limiting hard shore protection include density restrictions, living shoreline protection regulations, shoreline migration conservation easements, and rolling easement zoning. Access along the shore can be preserved if permits for shoreline armoring require access along the shore inland of new or rebuilt shore protection structures.

Test different approaches to adaptation.

While a number of theoretical papers and conferences have addressed approaches to adaptation, what is lacking are real on-the-ground results for comparison (Heller and Zavaleta, 2009). Demonstration sites testing different adaptive management approaches need to be tried throughout U.S. coastal regions. We also need policy and institutional mechanisms in place that reward adaptive management and encourage experimentation.

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Chapter 5: Mitigating Greenhouse Gases Through Coastal Habitat Restoration

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Chapter citation: Needelman, B.A., and J.E. Hawkes. 2012. Mitigating greenhouse gases through coastal habitat restoration. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore-Adapt-Mitigate: Responding to Climate Change Through Coastal Habitat Restoration. Restore America's Estuaries, Washington, DC, pp. 49-57.

Climate change is caused by increasing concentrations of greenhouse gases in the earth's atmosphere. Coastal habitats, like all of the earth's ecosystems, both release and remove greenhouse gases from the atmosphere. The role of coastal habitats and oceans in carbon sequestration has received increased attention since the recent publications of "Blue Carbon: A Rapid Response Assessment" by the United Nations Environment Programme (Nellemann, 2009) and "The Management of Natural Coastal Carbon Sinks" by the International Union for Conservation of Nature (Laffoley and Grimsditch, 2009). Habitat restoration projects will have a net positive or negative effect on greenhouse gases in the atmosphere depending on how they affect the release and removal of greenhouse gases. State, regional, and national greenhouse gas mitigation programs may use restoration projects that cause a net reduction in greenhouse gas concentrations. Restoration projects may also be eligible for funding through carbon credit or carbon offset programs. If a project leads to a net increase in greenhouse gases, however, this effect should be considered against other benefits of restoration.

Background on Greenhouse Gases

The earth's atmosphere provides a critical service of heat retention, acting as a blanket for the earth—without it the world would freeze. Sunlight warms the earth; the earth in turn radiates heat outward. Certain gases in the atmosphere trap most of this radiated heat—this is known as the greenhouse effect. The significant greenhouse gases, in order of decreasing impact, are water vapor, carbon dioxide, methane, ozone, nitrous oxide, and chlorofluorocarbons (CFCs). Human activities have increased the atmospheric concentration of many greenhouse gases, particularly carbon dioxide, methane, ozone, nitrous oxide, and chlorofluorocarbons.

Carbon dioxide (CO_2)

The carbon dioxide concentration in the atmosphere has risen from about 280 ppm (parts per million) prior to the industrial revolution to a current level above 390 ppm, an increase due largely to emissions from the burning of fossil fuels and from deforestation. The Intergovernmental Panel on Climate Change (IPCC) has estimated that the concentration of carbon dioxide will rise to between 450 and 1000 ppm over the next century (IPCC, 2007).

In a process called the carbon cycle, there is a constant exchange of carbon atoms present within carbon dioxide (CO_2) and carbon atoms in the inorganic and organic matter on the earth's surface. The quantity of carbon dioxide in the atmosphere represents a tiny percentage of the total carbon on earth; it is highly sensitive to changes in the larger, earth-bound carbon pools.

Most of the earth's carbon resides in limestone and other carbon-rich rocks, and is generally immobile until the rocks weather and release carbon into the atmosphere. In coastal habitat areas with exposed carbon-rich rocks any changes that may increase weathering of these rocks may cause carbon emissions.

The next largest carbon pool on earth is in seawater, where carbon occurs in dissolved, mineral, and organic forms. The amount of carbon in seawater is affected by chemical and physical characteristics such as pH, temperature, and ocean currents and layering. Aquatic organisms also take up carbon dioxide through photosynthesis and release it through decomposition.

After seawater, soils and terrestrial organisms (mainly plants) are the next largest pools in the carbon cycle. Living and dead plant tissue, such as a forest or peat soils, can hold carbon for thousands of years.

Methane (CH_4)

Among the greenhouse gases whose concentrations have risen most significantly over the past centuries, methane is second only to carbon dioxide. Methane is 21 times more potent than carbon dioxide as a greenhouse gas (EPA, 2011). Before the industrial revolution methane concentrations were at about 715 ppb (parts per billion). Current concentrations exceed 1700 ppb, with most of this rise occurring over the past 50 years (IPCC, 2007). The increase in methane concentrations primarily results from agricultural activities (rice agriculture and ruminant livestock production), fossil fuel use (mining and burning), and landfills. Freshwater wetlands are the largest natural sources of methane, although brackish wetlands also produce methane (Poffenbarger et al., 2011).

Nitrous oxide (N_2O)

Of the other gases that contribute to the greenhouse effect, only nitrous oxide emissions are significant from natural systems. The nitrogen cycling processes of nitrification and denitrification create nitrous oxides. Natural sources of nitrous oxides are primarily tropical soils (mainly wet forest soils) and oceans. Nitric oxide (NO), nitrogen dioxide (NO_2) and ammonia have short life spans in the atmosphere, but do have indirect effects. Nitrous oxide has a global warming potential 310 times greater than that of carbon dioxide (EPA, 2011). The concentration of nitrous oxide has risen in the atmosphere from 270 ppb in pre-industrial times to 319 ppb in 2005 (IPCC, 2007). The chief human-related sources of nitrous oxide are agricultural soil and waste management, combustion processes, and wastewater treatment. Nitrogen contamination of rivers and estuaries is also a significant source of human-induced nitrous oxide emissions (Kroeze et al., 2005).

Greenhouse Gases and Coastal Habitats

Greenhouse gases enter and exit coastal habitats through biological, chemical, and physical processes. In order to understand greenhouse gas movement, it is also important to be aware of the movement of carbon and nitrogen in other forms such as carbon dissolved in seawater and nitrogen in a polluted river. Carbon, the main constituent of both carbon dioxide and methane (CH_4), enters and exits ecosystems primarily through photosynthesis and decomposition.

Photosynthesis, decomposition and carbon sequestration

Photosynthesis in plants and other organisms uses energy from sunlight to convert carbon dioxide from the air into simple sugars. The photosynthesizing organisms use the sugars as building blocks for larger organic molecules and as a fuel for life processes. When the organisms and plants use the sugars for energy, a process called respiration, carbon dioxide is released back into the atmosphere. This also happens in humans and other non-photosynthesizing organisms—when we breathe, we are releasing carbon dioxide. The decomposition of organic matter also releases carbon dioxide into the atmosphere. The net balance of photosynthesis and respiration/decomposition is the carbon balance of an ecosystem; when there is a net increase in an ecosystem's stored carbon it is called carbon sequestration.

Ecosystems vary widely in their carbon sequestration rates. The highest rates are found within ecosystems in which photosynthesis is high (converting atmospheric carbon dioxide to organic matter) and carbon storage is high (preventing carbon from being respired back into the atmosphere). Rapidly growing plants, such as marsh vegetation and some forests, have the greatest rates of photosynthesis. Plants store carbon in their biomass or transfer it to soil organic matter (e.g., through decomposing leaf litter or roots). In coastal habitats, trees and wetland soils have the largest capacities for carbon storage. Trees are able to store carbon in plant biomass, as long as they are alive. Wetland soils store carbon well because the lack of oxygen in saturated soils slows decomposition.

Carbon sequestration in coastal habitats

Estuarine wetlands have among the highest carbon sequestration rates of any ecosystem due to their high rates of photosynthesis and low decomposition rates (Figure 5.1). Moreover, the volume of many wetland soils is actually increasing as they accrete with sea level rise, further allowing for high carbon sequestration rates. Freshwater marshes tend to have higher carbon sequestration rates than brackish and salt marshes because salinity is a stress even to salt-tolerant plants, although methane emissions are a concern in freshwater marshes. In some coastal restoration projects there is a lag of several years before the vegetation is well-established and a subsequent delay in higher rates of carbon sequestration (Crooks et al., 2009).

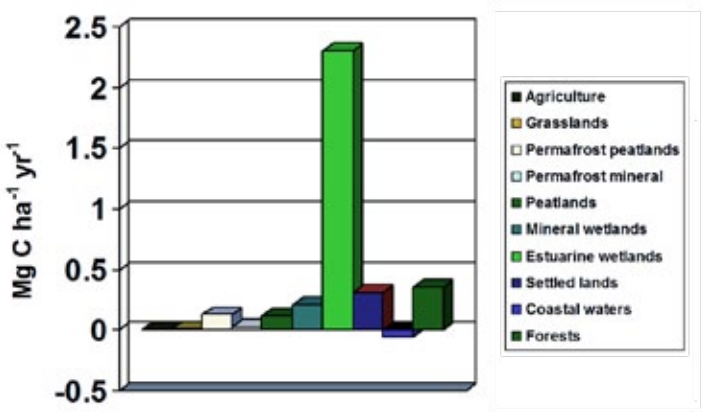

Figure 5.1. Current carbon sequestration rates per hectare per year in North American ecosystems (derived from data from CCSP, 2007).

In a review of data from over 150 salt marsh and mangrove sites, it was estimated that coastal wetlands have a mean carbon sequestration rate of about 2000 lbs C per acre per year (2.1 Mg C per hectare per year) (Chmura et al., 2001). In terms of carbon dioxide, this is about 7000 lbs per acre per year. This average rate did not differ substantially by climatic zones or between marshes and mangroves. However, there was a wide range of sequestration rates: one site had a carbon sequestration rate of 200 pounds C per acre per year; another sequestered 55,000 pounds C per acre per year.

Seagrass beds may have significant carbon sequestration because of their relatively high rates of photosynthesis (Laffoley and Grimsditch, 2009), but it is difficult to quantify their carbon sequestration rates due to the movement of carbon in aquatic systems and the variability among seagrass species. Most seagrass species do not develop the levels of organic matter sediment concentrations that are found in emergent wetlands, suggesting that much of the carbon photosynthesized by seagrasses is either lost through decomposition or exits the system. It would be necessary to quantify the fate of this lost carbon in order to properly measure carbon sequestration rates in these systems. Also, much of the carbon accumulated in seagrass beds is derived from outside sources such as eroded upland sediments and falling plankton, further complicating carbon sequestration estimates in these systems (Gacia et al., 2002).

Methane emissions are highly variable in freshwater wetlands—they are nearly zero in some freshwater coastal wetlands and quite high in others.

Scientists do not think that coral reefs sequester carbon because their carbon outputs tend to outweigh their inputs (Ware et al., 1991; Laffoley et al., 2009). Corals do take up carbon when they precipitate calcium carbonate using calcium (Ca^{2+}) and bicarbonate (HCO^{3-}) from seawater. However, this process results in the release of carbon dioxide (CO_2) gas due to a shift in pH. One group of researchers determined that the carbon outputs of coral reefs tend to outweigh their inputs such that corals are actually a net source of 0.02 to 0.08 Gt (billions of tons) of carbon to the atmosphere per year (Ware et al., 1991). Less work has been done on shellfish carbon sequestration, but the basic calcium carbon precipitation process is similar suggesting that they are probably not net sinks for carbon.

Significant chemical and biological carbon sequestration occurs in the ocean and is influenced by coastal habitats directly and indirectly. Marsh-influenced estuaries export dissolved inorganic carbon (as the ions carbonate or bicarbonate) into coastal waters. Oceans release some of this dissolved inorganic carbon back into the atmosphere as carbon dioxide, but some of this coastally generated carbon remains in the ocean long-term (Wang and Cai, 2004). An indirect biological influence occurs when estuaries export nutrients to oceans that increase growth rates of phytoplankton (small photosynthesizing marine organisms). As these phytoplankton die, the carbon contained in their bodies sinks deep in the ocean and can be stored (Subramaniam et al., 2008).

Methane (CH_4) emissions

Methane, a greenhouse gas with 21 times the potency of carbon dioxide (EPA, 2011), is a common by-product of decomposition of organic matter under the highly anaerobic conditions found in some coastal wetlands. Carbon sequestration in some coastal habitats may be partially or fully offset by methane emissions (Poffenbarger et al., 2011).

Sulfate, an ion that is present as a salt in seawater, inhibits methane generation such that saline wetlands tend to generate less methane than freshwater wetlands. When sulfate concentrations are sufficiently high, sulfate-reducing bacteria are able to outcompete the methane-generating bacteria (methanogens), reducing overall methane emission from the system. In salt marshes (>18 ppt salinity), methane generation is nearly zero and can be safely disregarded. However, in brackish wetlands (0.5-18 ppt) methane emissions may be significant (Poffenbarger et al., 2011).

Methane emissions are highly variable in freshwater wetlands—they are nearly zero in some freshwater coastal wetlands and quite high in others. On a greenhouse gas basis, methane emissions in freshwater wetlands may cancel out these systems' carbon sequestration. In fact, some of these wetlands are net emitters of greenhouse gases. However, other freshwater coastal wetlands, particularly those with low or fluctuating water tables, may not develop sufficiently anaerobic conditions near the soil surface to emit significant quantities of methane. Water level management can significantly reduce methane emissions from managed wetland restoration projects (Crooks et al., 2009).

Nitrous oxide emissions

The total global emissions of nitrous oxide equal approximately 18 million metric tons (Mt) N per year (40 billion pounds). Estuaries contribute about 0.25 Mt N per year (Kroeze et al., 2005). Coastal upwelling contributes about 0.2 Mt N per year. Nitrogen pollution of estuaries and coasts causes these emissions. Although it is difficult to quantify, any conservation or restoration project that reduces nitrogen inputs to these ecosystems will likely reduce nitrous oxide emissions. Restoration projects that integrate wastewater treatment or other nutrient-rich input waters should consider and account for the release of nitrous oxides to the atmosphere (or the prevention of this release). However, since the nitrogen pollution usually originates outside the restoration or conservation project site and the nitrous oxide would likely have been emitted regardless of the presence of the project, it may be reasonable to exclude nitrous oxide emissions from the project's overall greenhouse gas accounting (Crooks et al., 2009).

Funding Projects and Achieving Greenhouse Gas Emission Mitigation Goals Through Coastal Habitat Restoration

Greenhouse gas mitigation through coastal habitat restoration, primarily through carbon sequestration, may provide funding opportunities for restoration projects and be a mechanism for states and regions to achieve greenhouse gas mitigation goals. Funding secured for carbon sequestration would generally be in the form of offset credits, which are payments provided by carbon emitters so that they can exceed their voluntary or mandatory emissions limit. Offset credits are available through voluntary and mandatory programs in which people or organizations that emit greenhouse gases are seeking a means to counter their greenhouse gas emissions. In this section, the policy and science challenges associated with bringing coastal habitats into carbon markets are discussed.

Carbon markets

Despite their name, carbon markets do not actually trade existing carbon. Rather, carbon markets trade the reduction of future carbon dioxide and other greenhouse gas emissions into the atmosphere. These are standardized as carbon dioxide equivalents (abbreviated as CO_{2e}). Carbon markets can be either voluntary or mandatory. In a voluntary carbon market, a given entity (company, individual, community, or other greenhouse gas "emitter") voluntarily offsets its carbon emissions by purchasing carbon allowances and/or offsets from another party (an offset developer or broker). This other party then uses its carbon offset revenue to support projects that reduce carbon in the atmosphere. These projects might include methane destruction (via anaerobic digesters); planting trees or avoiding deforestation to sequester carbon; paying to implement energy efficiency measures to reduce fossil fuel use; or developing new renewable energy capacity where the new renewable source displaces fossil fuel-generated energy thereby reducing greenhouse gas emissions.

The Maryland Commission on Climate Change's Greenhouse Gas Reduction Strategy

The state of Maryland established a Commission on Climate Change in 2007 to develop a climate action plan. The Commission recommended that the state use emissions cuts and offsets to reduce greenhouse gas emissions by 25 to 50% below 2006 levels by 2020 and by 90% by 2050. Energy efficiency options were deemed the quickest and most effective approaches. Within the recommended offset options, the commission included wetland restoration and coastal wetland protection. The commission emphasized that early actions are key; that greenhouse gas reductions will benefit the state economy; and that local reductions will have local benefits.

See http://www.mdclimatechange.us/ for more information.

In the U.S., there are voluntary carbon markets and a few regional compliance markets for certain industries. If a federal compliance market evolves, there may be increased demand for greenhouse gas emission reductions and a corresponding rise in prices for those reductions.

Compliance or mandatory carbon markets operate under a regulated limit to carbon emissions (a "cap"), where each large-scale emitter or company will have a limit on the amount of greenhouse gases that it can emit. Each emitter receives allowances or emissions permits for every ton of carbon dioxide equivalent it releases into the atmosphere. These permits set an enforceable cap on the amount of greenhouse gas pollution that the company is allowed to emit. Over time, the limits become stricter, allowing less and less pollution, until the ultimate reduction goal is met.

Those regulated greenhouse gas sources (emitters) that can reduce the amount of carbon dioxide they emit below their required limit may trade (sell) their unused permits to other greenhouse gas sources that are emitting beyond their allowable limit and cannot easily or cost-effectively reduce their emissions. This "cap and trade" is intended to create a system that guarantees a set level of overall greenhouse gas reductions, while rewarding the most efficient companies and ensuring that the cap can be met at the lowest possible cost to the economy.

Greenhouse gas emission reduction goals

From local to regional to national levels, Americans are working to reduce greenhouse gas emissions by setting emission reduction targets and goals. The Environmental Protection Agency is responsible for reporting annual inventories of anthropogenic greenhouse gas emissions (see **http://www.epa.gov/climatechange/emissions/**).

Under the Regional Greenhouse Gas Initiative, ten northeastern states have committed to reduce their power sector carbon dioxide emissions to 10% below 1990 levels by the year 2018. At a state level, the California Global Warming Solutions Act of 2006 (AB

32) caps California's greenhouse gas emissions at 1990 levels by 2020. New Jersey's Global Warming Response Act (S 2114) from 2007 reduces greenhouse gas emissions to 1990 levels by 2020, which is approximately a 20% reduction, followed by a further reduction of emissions to 80% below 2006 levels by 2050. Maryland's Greenhouse gas reduction act of 2009 requires a 25% reduction in state greenhouse gas emissions from 2006 levels by 2020 (See box). The California Air Resources Board recently adopted cap-and-trade regulation that includes provisions for offset crediting.

Potential to reduce greenhouse gases through restoration and conservation

The restoration and conservation of some coastal habitats can reduce greenhouse gases. However, the land areas involved in individual restoration and conservation projects tend to be too small to substantially reduce atmospheric greenhouse gas concentrations. The U.S. Climate Change Science Program estimated that the total carbon sequestration rate of the existing 25,000 km^2 of estuarine wetlands in the United States is 5.4 Mt C per year and that the historical loss of sequestration capacity since about 1950 is about 0.5 Mt C per year (Bridgham et al., 2007a). These numbers are relatively small compared to the current carbon imbalance in the United States, which was estimated at 1093 Mt C per year. While a portfolio of approaches will be needed to dramatically lessen this imbalance, only very large coastal habitat restoration and conservation programs would contribute to national scale emission reduction goals. More realistically, multiple coastal habitat conservation and restoration projects may contribute to state and regional-level greenhouse gas reduction goals if aggregated.

Science Challenges Associated with Carbon Sequestration Crediting

Coastal restoration project managers must have accurate measures of carbon sequestration and other greenhouse gas fluxes if their restoration projects are to be eligible for carbon offset credits and related funding. Direct measurement is expensive and time-consuming, though it may be necessary to meet trading program verification requirements. Scientists are working on models for the estimation of carbon sequestration and methane emissions.

Measuring carbon sequestration rates

The primary change in carbon quantity of coastal and estuarine habitats is in soil carbon because above-ground vegetative biomass does not change substantially over long time periods (except in some forested systems). Direct measurement is the most straightforward means to estimate soil carbon sequestration rates in coastal habitats. In general, it is better to measure the net change of carbon in a given system than to measure input and outputs, which can vary tremendously over time. If the total carbon content of a system is increasing over time, this increase can be used as a measure of carbon sequestration. There are, however, several challenges. Some of the carbon in a system may have been deposited there from outside of the project area, such as eroded sediments that are rich in carbon—this is known as allochthonous carbon. Project managers should only count allochthonous carbon toward a project's carbon budget if the carbon would have been returned to the atmosphere in the absence of the project.

Soil sampling depth poses another challenge when estimating coastal habitat carbon. The density and volume of many coastal habitat soils are constantly changing. Researchers cannot simply sample to a specified depth at the beginning of a project and then sample to the same depth again in later years. If the soil has expanded between samples, the original sample depth would not reach deeply enough to include the same carbon that had been present in the initial sample. Conversely, if the soils have compacted over time, the original sample depth would capture soil not included in the initial sample. The accretion of materials at the soil surface further complicates the issue of sampling depth. A solution is to sample to some reference plane within the soil profile, such as a mineral layer or an installed benchmark that is stable at a given horizontal plane in the soil. If samples are always collected to this reference plane, researchers can be confident that any carbon gains or losses above that reference plane are real, regardless of varying sampling depth.

Interventions that prevent habitat loss could receive carbon credits through the mechanism of avoided losses both for the loss of future carbon sequestration and the loss of the existing carbon pool back to the atmosphere.

Measuring methane emissions

Methane emissions may pose a problem to sequestration projects wherever organic matter is decomposing under anaerobic conditions in low to moderate salinity coastal habitats. While precise methane emission quantification is expensive and may be beyond the scope of many habitat restoration projects, it may be practical to assess whether methane emissions are occurring and if these emissions may be significant. Such monitoring should generally be performed under peak methane emission conditions—warm temperatures, high water table levels, and low salinity. Methane emissions are also being included in models being developed for carbon crediting.

Avoided losses

Coastal habitat loss has occurred rapidly over recent decades. It has been estimated that 1150 square miles (3000 km^2) of coastal wetlands have been lost since the 1950s in the continental United States (Bridgham et al., 2007b). Scientists project increased coastal habitat loss over the next century. As these coastal habitats disappear, their carbon sequestration capacity is lost. A potentially more significant loss is that some of the carbon contained within these systems in soils and vegetation will be lost to the atmosphere (Murray et al., 2011). It is a key research need to be able to predict the fate of this existing carbon following habitat loss. Interventions

that prevent habitat loss could receive carbon credits through the mechanism of avoided losses both for the loss of future carbon sequestration and the loss of the existing carbon pool back to the atmosphere. It is a challenge to predict future losses across various climate scenarios and there are many non-climate related factors that affect habitat loss. Nevertheless, protecting existing habitat is typically less costly and more ecologically sound than re-creating or restoring degraded or lost habitats. Valuation of the ecosystem services provided by conserved coastal habitats would help policymakers weigh the benefits of investment in protection now against an investment in restoration later.

Emissions during restoration

Some activities associated with restoration may directly cause greenhouse gas emissions. For example, the fuel combustion for dredged material transport emits carbon dioxide. Only those emissions that are increased due to the restoration practice need to be accounted for in carbon crediting. For example, if the dredge material would have been transported an equal distance regardless, these emissions do not need to be quantified.

Policy Challenges Associated with Carbon Sequestration Crediting

There are a number of policy-related challenges associated with the use of coastal habitat restoration to generate carbon credits. In this section, some policy challenges are reviewed. Policymakers need to balance the needs of prioritizing and encouraging coastal habitat restoration with other priorities in greenhouse gas policy.

Additionality and portfolio funding

Most carbon offset programs require that the carbon sequestration credited to a project be additional to any carbon that would have been sequestered even in the absence of the project or the carbon-related funding. This rule prevents emitters from buying carbon credits that are not genuinely offsetting their greenhouse gas emissions. There are two general types of additionality: financial additionality and regulatory additionality.

To demonstrate financial additionality, a project must show that its carbon would not have been sequestered without the funding from the sale of carbon credits. Proving financial additionality is straightforward when a project is voluntary (e.g., not required by law) and completely funded through carbon credits. However, many restoration projects have a portfolio of funding sources that blend public and private funds to support the multiple ecosystem services provided by coastal habitats. In publicly-funded projects, the financial additionality requirement prevents a reduction of public expenditures when private credit funds increase. In portfolio-funded cases ("stacked credits"), a project can prove additionality in two ways. The entire project can claim additionality if project managers can show that the project would not have happened without the extra carbon offset funds. Alternatively, projects may be eligible if it is demonstrated that they exceed the average ("business-as-usual" or "common practice") rates of restoration and conservation within given regions and habitat types (Crooks et al., 2009).

Regulatory additionality requires that no government mandates the project under any type of regulatory program. For example, if a developer must create new wetlands to compensate for damaging or destroying other wetlands, the new wetlands would not be eligible for carbon offset funding. However, if the developer performs the restoration in a different way as a result of the carbon offset funding, then it may be possible to consider the project's sequestered carbon as additional. For example, a developer with a regulatory mitigation requirement to restore a freshwater wetland could instead restore a salt marsh with lower methane emission rates, if regulators approved. There is some uncertainty as to whether restoration projects under some federal mandates would qualify as regulatory additionality if the government is not currently enforcing or funding those programs but carbon offsets would allow new projects.

The challenge of proving additionality—particularly financial additionality—may pose a significant barrier to restoration projects through carbon offsets. Policymakers should be cautious when applying financial additionality rules to coastal habitat restoration projects. We do not want to develop a system where projects that create few, if any, ecological benefits other than carbon sequestration (e.g., geological sequestration) can qualify for financial additionality, while restoration projects that create significant ancillary benefits beyond sequestration are not eligible for funding.

Defining "restoration"

A significant issue in carbon crediting and accounting is defining what constitutes a restoration activity. Intensive restoration projects such as wetland re-creation may be clearly eligible for carbon credits, but these are also the most expensive strategies. Lower cost strategies, such as plugging drainage ditches or applying dredge materials to existing marshes to keep elevations ahead of sea level rise may be more efficient restoration practices, but their eligibility for credits is less clear.

Land ownership and tenure

In order to engage in a carbon transaction, there must be clear title or ownership of the carbon rights. No transaction can proceed without clear legal ownership. For terrestrial carbon projects, the landowner or a land lessee with specific greenhouse gas rights owns the carbon. Landowners can sell or donate a conservation easement on the land that includes greenhouse gas rights; or they can sell or donate the greenhouse gas rights with contractual assurances that the land use will be consistent and compatible with the carbon sequestration project's requirements concerning time horizons, risk management, monitoring, and other considerations.

As some carbon credit standards evolve, there is a decreasing emphasis on requiring easements on the land for the life of the carbon sequestration project, especially since many landowners are reluctant to place their lands under long-term easement. Any registry, market, or exchange requires documentation of legal ownership of the greenhouse gas rights so they can demonstrate that the asset is real and is only accounted for once, and they can guarantee, through independent verification, that the carbon/greenhouse gas emission reduction or avoidance is occurring or did occur.

Beyond proving ownership, carbon projects need to comply with all applicable environmental, planning or regulatory requirements, particularly in terrestrial-based projects that involve some form of land use change. Project implementers must identify any local, state, or national regulatory requirements and the greenhouse gas agreements must designate the party responsible for compliance.

Case study on carbon sequestration at the Blackwater National Wildlife Refuge

The U.S. Fish and Wildlife Service (USFWS) and the U.S. Army Corps of Engineers has considered a long-term project to use clean dredged material from the Chesapeake Bay shipping channel to restore up to 20,000 acres of tidal marsh at the Blackwater National Wildlife Refuge and surrounding state and private lands. Barges would carry the dredged material to a coastal storage location where it would be slurried and pumped inland to the refuge. Estimates for restoration sequestration rates range from 3.7 to 8.5 metric tons of carbon dioxide per acre per year; the total project could sequester from 75,000 to 170,000 metric tons of carbon dioxide per year. Target salinities of the restored marshes have not been established, but methane emissions have been documented from brackish marshes in this region, so a portion of this sequestration would be offset by methane. At a carbon price of $20 per metric ton, the sequestration alone could draw annual revenues from $1,500,000 to $3,400,000. While these revenues seem substantial, they would only contribute a percentage of total project cost.

Risk assessment and insurance

Projects seeking carbon credits from mandatory programs need to determine the risk associated with errors in greenhouse gas estimates. Greenhouse gas fluxes are highly variable, making precise estimates difficult and statistical uncertainty high. In general, the longer the study period, the lower the overall variability.

Carbon crediting projects usually need to carry insurance to guard against losses. For example, insurance would protect against a forest fire that diminishes or eliminates the carbon sequestered by the trees. Presently, it is unclear what type of insurance would be necessary for coastal habitat restoration projects.

Funding potential of various restoration strategies

The potential to fund a coastal habitat restoration project with carbon credits depends on project scale, carbon sequestration rate, restoration cost, and the offset value of carbon dioxide sequestered. The cost of estimating and verifying greenhouse gas sequestration in small projects would likely be higher than the value of the offsets themselves. If restoration practitioners can aggregate the sequestration of many small projects that are similar, it may become cost effective.

The price of carbon is difficult to project into the future. In general, voluntary markets place a lower price on carbon offsets than mandatory compliance markets. The average price for a ton of carbon dioxide equivalent in voluntary markets in 2009 was $6.50 (Hamilton et al., 2010). In 2009 the mandatory European Union program was selling at from $12 to $20 per ton of carbon dioxide; in 2008 their prices went as high as $42 per ton. The demand for carbon sequestration may increase as more governments move to regulate greenhouse gas emissions. Intensive high cost mitigation technologies such as carbon capture and storage (CCS), in which coal plants capture their carbon dioxide emissions and inject the carbon dioxide deep into the earth for storage, may drive up carbon prices, increasing the attractiveness of other carbon offset methods such as coastal habitat restoration for sequestration.

Findings and Recommendations

Coastal habitats both emit and remove greenhouse gases from the atmosphere. Tidal marshes are the coastal habitat most appealing for greenhouse gas reduction goals due to their high rates of carbon sequestration (averaging 2000 lbs C per acre per year). Some freshwater and brackish marshes emit methane, negating some or all of the carbon sequestration benefits of restoration in these systems unless project managers can control the methane emissions (e.g., through water management). The net greenhouse gas benefits of even large coastal restoration and conservation programs are likely to be relatively small when compared to national-scale emission reduction goals. Coastal habitat restoration and conservation programs may contribute significantly to state and regional-level greenhouse gas reduction goals, especially when aggregated. Carbon credits may provide a substantial funding source for coastal habitat restoration projects, particularly if restoration managers can blend carbon credit funds with revenue for other ecosystem services (e.g., portfolio

funding or stacked credits), and if the value of carbon credits climbs higher.

Carbon sequestration is one of the many benefits of coastal habitat restoration. As the nation moves toward reducing greenhouse gas emissions and pursues adaptation strategies to reduce the negative effects of global warming, governments should consider the valuable contributions that coastal habitat restoration can make toward these goals.

Recommendations

Develop cost-effective, reliable methods to estimate carbon sequestration and methane emission rates in coastal habitats, in coordination with limited direct sampling.

The cost of statistically defensible direct sampling of carbon sequestration and greenhouse gas fluxes in complex natural systems may be too great for application within carbon crediting programs. A more tractable approach is the use of modeling or other indirect estimation methods, possibly corroborated with limited field data.

Develop the capacity to predict the rate of return of carbon pools to the atmosphere following habitat loss so that avoided losses through conservation can be eligible for carbon crediting.

The avoided loss of coastal habitats would preserve their carbon sequestration potential and possibly prevent their existing carbon pools from being emitted back into the atmosphere. The quantification of avoided losses will require sound scientific estimation methods given the uncertainty of climate change and other land perturbation scenarios.

Develop mechanisms to aggregate small and moderately sized restoration projects to allow access to carbon credit funding.

The labor and costs associated with documenting carbon sequestration may be too great for individual small and moderately sized restoration projects; however, if similar projects can be aggregated, they should be able to access funding through carbon markets.

Make carbon credits available to restoration programs that range from conservation of existing habitats to habitat creation.

Habitat restoration spans a suite of tools from conservation of existing habitats to creations of new ones, usually with corresponding increases in effort and cost. However, it is easiest to estimate carbon sequestration within creation projects and more complicated for less intensive restoration practices. Methods need to be developed such that less-intensive and more cost-efficient restoration and conservation strategies are not excluded from carbon markets.

Determine the current rate of restoration in regions so that restoration practitioners can demonstrate "additionality" when they increase the pace of restoration projects using carbon credit funding.

The demonstration of additionality may be a significant barrier in bringing coastal habitat restoration into carbon markets. The development of "business-as-usual" or "common practice" rates of restoration and conservation within given regions and habitat types may allow for any projects that exceed these rates to be considered additional. This will help avoid a situation where restoration projects are excluded from carbon markets while projects without ancillary environmental benefits are included.

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Appendix A
Glossary of Terms

Accretion – Gradual gain of land elevation, as in the addition of sand to a beach by wind or ocean currents.

Acquisition program – Efforts by government and/or nongovernmental entities to obtain title to conservation land.

Additionality – Requirement for greenhouse gas offsets to ensure that any greenhouse gas reductions from a project are in addition to what would have happened anyway, or in the business-as-usual scenario, that actually "offset" emissions from other sources.

Allochthonous carbon – Entry of carbon from external sources in streams or other flowing water.

Beach nourishment – Artificial placement of sediment to a beach.

Beachfill – Shoreline protection measure that involves the purposeful addition of native beach material (from an offshore or inland source) to a beach to make that beach higher and wider, which provides a buffer against wave action and flooding (also known as beach nourishment or sand replenishment).

Breakwater – Shoreline protection structures typically constructed of large rocks and placed off shore to reduce shore erosion caused by storm waves. Breakwaters can either be attached to the shore or located offshore, generally parallel to the shoreline.

Bulkhead – Shoreline protection measure that uses vertical walls designed to prevent wave erosion or the land from slumping toward the water.

Coastal habitat – Marine or estuarine area or natural environment in which an organism or population normally lives. A habitat is made up of physical and biological factors necessary to sustain life.

Conservation easement – Purchased interest in land that allows the owner of the easement to prevent the owner of the land from developing it.

Coral bleaching – The whitening of corals due to the expulsion or loss of color of symbiotic algae.

Density restriction – Limiting the amount of development that can occur within a given land area.

Dike – Shoreline armoring measure that uses high, impermeable earthen walls designed to keep the area behind them dry. Generally requires a means of removing rainwater and seepage, such as tide gates or a pumping system.

Dredge and fill – A largely obsolete approach to shoreline protection in which navigable channels are dredged through a marsh and the dredge material is used to elevate the remaining marsh to create dry land. The technique is rarely used because of the resulting loss of tidal wetlands.

Dynamic revetment – A shore protection measure that is a hybrid of beach nourishment and hard structures, in which a cobble beach or berm is constructed to protect an eroding shore.

Ecosystem service – Any service provided by an ecosystem that is given economic, ecological, or cultural value by humans.

Elevation capital – The elevation of a coastal landscape within the tidal range.

Enhanced wetland accretion – Equivalent of a beachfill operation for wetlands, in which a thin-spray of fine sediment is used to imitate the natural process of wetland accretion through sedimentation.

Erosion – Losses of surface or edge of land materials are greater than deposition causing a decrease in elevation or a lateral loss of land.

Estuary – Semi-enclosed body of water where freshwater inflow mixes with marine water.

Eustatic sea-level rise – Increase in volume of the world oceans.

Eutrophication – Excessive increase of nutrients to a water body resulting in increased primary production in an ecosystem.

Groin – Shore protection measures that use hard structures perpendicular to the shore extending from the beach into the water, usually made of large rocks, wood, or concrete.

Hypoxia – Dissolved oxygen in a water body is not sufficient to support aquatic life, often results from eutrophication.

Interaction – When the sum of two forces is not equal to the sum of its parts.

Inundation – To cover an area with water, especially floodwaters.

Isostatic rebound – Long-term process in which large regions of land are rising or lowering following the retreat of glaciers.

Jetty – An engineering structure built at the mouth of a river or tidal inlet to help stabilize a channel for navigation; designed to prevent shoaling of a channel by littoral materials and to direct and confine the stream or tidal flow.

Living shoreline – Subset of nonstructural shore protection that relies primarily on plants or shellfish. Examples include regrading sand or mudflats to marsh elevation and planting marsh grasses, mangrove restoration, coral restoration, oyster reefs, and mussel reefs.

Mitigation – A general term meaning to lessen or make less severe; in the context of climate change it general means any action that lessens climate change, for example by decreasing the quantity of greenhouse gases in the atmosphere.

Nonstructural shore protection – Shoreline protection options that generally include the use of vegetation and allows for natural coastal processes to remain through the strategic placement of plants, stone, sand fill, and other structural and organic materials.

Offset credit – Funding available through voluntary or mandatory programs in which greenhouse gas emitters buy carbon credits (often in dollars per ton carbon dioxide equivalent) to agencies responsible for carbon sequestration or other greenhouse gas mitigation projects.

Oscillation – Shifts in ocean current and atmospheric circulation patterns.

Photosynthesis – Process that converts carbon dioxide into organic compounds, especially sugars, using the energy from sunlight.

Relative sea-level rise – Rise in sea level relative to changes in the elevation of a land surface.

Resilient – Ability of a system to adapt to and recover from disturbance.

Restoration – Manipulation of the physical, chemical, or biological characteristics of a site with the goal of enhancing, creating, or returning self-sustaining natural or historic structure and functions to coastal habitats.

Revetment – Shoreline armoring measure whose sea side follows a slope that is more effective at dissipating the energy of storm waves than bulkheads and seawalls.

Rolling easement – Regulatory mechanisms or interests in land that prohibit engineered shore protection, allowing wetlands or beaches to naturally migrate inland as sea level rises. In Texas, the rolling easement also requires removal of structures (e.g., buildings) that impede automobile traffic along the beach once the vegetation line is landward of the structure.

Salt wedge – A sharp boundary in estuaries that separates an upper less salty layer from an intruding wedge-shaped salty bottom layer. The mouths of the Mississippi, Columbia and Hudson rivers are examples of salt wedge estuaries.

Seawall – Vertical walls (shoreline armoring) that use impermeable barriers designed to withstand the strongest storm waves and to prevent overtopping during a storm.

Sequestration – Uptake and storage of a material, such as carbon.

Setbacks – Regulations that prohibit development within a specified zone along the shore. The regulatory equivalent to conservation easements and purchase programs.

Self-organization – Process where a structure or pattern appears in a system without a central authority or external element forcing it to occur.

Shore protection – Generally refers to a class of coastal engineering activities that reduces the risk of flooding, erosion, or inundation of land or structures.

Shoreline armoring – Shoreline protection measure that uses engineered structures to keep the shoreline in a fixed position or to prevent flooding when water levels are higher than the land elevation.

Sill – Hybrid shore protection measure that uses low rock or sandbag structures that are emergent at low tide, but often partially or completely submerged at high tides.

Size limitation – Allows development near the shore, but limits the size or density of the development placed at risk.

Soft shore protection (also called nonstructural shore protection) – A method of shore protection that prevents shore erosion through the use of materials similar to those already found in a given location, such as adding sand to an eroding beach or planting vegetation whose roots will retain soils along the shore.

Subsidence – Lowering of land elevation.

Sustainable – Being maintained at a constant state without exhausting natural resources or causing severe ecological damage.

Sustainable landscape – An area that, over a cycle of disturbance events, maintains its characteristic diversity of composition, structure, and function.

Threshold – Level of an ecosystem variable at which dramatic, and often irreversible, change occurs.

Tidal range – Distance between high and low tides.

Tide gates – Type of shoreline armoring that uses barriers across small creeks or drainage ditches; the barriers open during low tides to allow water to escape downstream, but close during high tides to prevent water from flowing upstream.

Transgress – Migration of coastal habitats inland.

Wrack – Plant materials mixed with other debris deposited on a beach by high tides or storms.

Appendix B
List of Organizations and Publications

American Littoral Society **http://www.littoralsociety.org**

Association of State Wetland Managers **http://aswm.org**

Chesapeake Bay Foundation **http://www.cbf.org**

Coalition to Restore Coastal Louisiana **http://www.crcl.org**

Coastal and Estuarine Research Federation **http://www.erf.org**

Coastal States Organization **http://www.coastalstates.org**

The Role of Coastal Zone Management Programs in Adaptation to Climate Change. **http://www.coastalstates.org/documents/CSO%20Climate%20Change%20Final%20Report.pdf**

Conservation Law Foundation **http://www.clf.org**

The Environmental Law Institute **http://www.eli.org**

New Frameworks for Managing Dynamic Coasts: Legal and Policy Tools for Adapting U.S. Coastal Zone Management to Climate Change (Written by Sandra S. Nichols & Carl Bruch of the Environmental Law Institute and published in the Sea Grant Law & Policy Journal. p. 19-42, 2008.

Galveston Bay Foundation **http://www.galvbay.org**

Intergovernmental Panel on Climate Change **http://www.ipcc.ch**

Fourth Assessment Report: Climate Change 2007 Synthesis Report **http://www.ipcc.ch/ipccreports/ar4-syr.htm**

Climate Change 2007: The Physical Science Basis **http://www.ipcc.ch/ipccreports/ar4-wg1.htm**

Climate Change 2007: Impacts Adaptation and Vulnerability **http://www.ipcc.ch/ipccreports/ar4-wg2.htm**

Climate Change 2007: Mitigation of Climate Change **http://www.ipcc.ch/ipccreports/ar4-wg3.htm**

Special Report on Land Use, Land-use Change and Forestry **http://www.grida.no/climate/ipcc/land_use/index.htm**

International Union for Conservation of Nature **http://www.iucn.org**

The Management of Natural Coastal Carbon Sinks **http://www.iucn.org/knowledge/publications_doc/publications/?4229/The-Management-of-Natural-Coastal-Carbon-Sinks**

National Wildlife Federation **http://www.nwf.org**

The Nature Conservancy **http://www.nature.org**

NOAA Coastal Services Center **http://www.csc.noaa.gov**

NOAA Fisheries Restoration Center **http://www.nmfs.noaa.gov/habitat/restoration**

Salt Marsh Restoration and Monitoring Guidelines **http://www.nmfs.noaa.gov/habitat/restoration/publications/saltmarsh1.pdf**

NOAA National Estuarine Research Reserve System **http://www.nerrs.noaa.gov**

NOAA Ocean and Coastal Resource Management Program **http://www.coastalmanagement.noaa.gov/programs/coast_div.html**

Adapting to Climate Change: A Planning Guide for State Coastal Managers **http://coastalmanagement.noaa.gov/climate/docs/adaptationguide.pdf**

Adapting to Climate Change: A Planning Guide for State Coastal Managers–A Great Lakes Supplement **http://coastalmanagement.noaa.gov/climate/docs/adaptationgreatlakes.pdf**

North Carolina Coastal Federation **http://www.nccoast.org**

NY Department of State Division of Coastal Resources **http://www.nyswaterfronts.com/**

Protecting and Restoring Habitats **http://www.nyswaterfronts.com/waterfront_natural_resources.asp**

Oregon Department of Fish and Wildlife **http://www.dfw.state.or.us**

Habitat Conservation Summaries for Strategy Habitats: Estuaries **http://www.dfw.state.or.us/conservationstrategy/document_pdf/b-habitat_4.pdf**

The Oregon Conservation Strategy **http://www.dfw.state.or.us/conservationstrategy/contents.asp**

People for Puget Sound **http://www.pugetsound.org**

Restore America's Estuaries **http://www.estuaries.org**

Hope for Coastal Habitats: People, Partnerships & projects Making a Difference **http://www.estuaries.org/images/stories/docs/Hope%20for%20Habitats%202010.pdf**

Jobs & Dollars: Big Returns from coastal Habitat Restoration **http://www.estuaries.org/images/81103-RAE_17_FINAL_web.pdf**

The Economic and Market Value of Coasts and Estuaries: What's at Stake? **http://www.estuaries.org/images/stories/docs/policy-legislation/final-econ-with-cover-5-20-2008.pdf**

Rhode Island Habitat Restoration Portal **http://www.edc.uri.edu/restoration**

Report on Habitat Monitoring Protocols **http://www.edc.uri.edu/restoration/html/tech_sci/habsalt.htm**

Save San Francisco Bay Association **http://www.savesfbay.org**

Save the Bay-Narragansett Bay **http://www.savebay.org**

Society for Ecological Restoration International
http://www.ser.org

Society of Wetland Scientists **http://www.sws.org**

South Bay Salt Pond Restoration Project
http://www.southbayrestoration.org

Report on Climate Change and Sea Level Rise
http://www.southbayrestoration.org/climate

Tampa Bay Watch **http://www.tampabaywatch.org**

United States Agency for International Development (USAID)
http://www.usaid.gov

Adapting to Coastal Climate Change: A Guidebook for Development Planners

http://www.usaid.gov/our_work/cross-cutting_programs/water/docs/coastal_adaptation/adapting_to_coastal_climate_change.pdf

http://www.usaid.gov/our_work/cross-cutting_programs/water/news_announcements/coastal_climate_change_report.html

U.S. Army Corps of Engineers - Engineer Research and Development Center - Environmental Laboratory
http://www.erdc.usace.army.mil

U.S. Climate Change Science Program
http://www.climatescience.gov

The Effects of Climate Change on Agriculture, Land Resources, Water Resources and Biodiversity
http://www.climatescience.gov/Library/sap/sap4-3/default.php

The State of the Carbon Cycle Report (SOCCR)
http://www.climatescience.gov/Library/sap/sap2-2/default.php

http://cdiac.ornl.gov/SOCCR/index.html

http://www.nsf.gov/news/news_summ.jsp?cntn_id=110769

Weather and Climate Extremes in a Changing Climate
http://www.climatescience.gov/Library/sap/sap3-3/default.php

Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region
http://www.climatescience.gov/Library/sap/sap4-1/default.php

Adaptation Options for Climate-Sensitive Ecosystems and Resources
http://www.climatescience.gov/Library/sap/sap4-4/default.php

U.S. Environmental Protection Agency Climate Change
http://www.epa.gov/climatechange/index.html

Coastal Zones and Sea Level Rise
http://www.epa.gov/climatechange/effects/coastal/index.html

U.S. Environmental Protection Agency Climate Ready Estuaries Program **http://www.epa.gov/cre**

Rolling Easement Primer
http://www.epa.gov/cre/downloads/rollingeasementsprimer.pdf

Adaptation Planning for the National Estuary Program
http://www.epa.gov/cre/downloads/CREAdaptationPlanning-Final.pdf

U.S. Environmental Protection Agency Wetlands Program
http://www.epa.gov/wetlands

U.S. Fish and Wildlife Service **http://www.fws.gov**

Rising to the Challenge: Strategic Plan for Responding to Accelerating Climate Change **http://www.fws.gov/home/climatechange/pdf/CCDraftStratPlan92209.pdf**

Five Year Action Plan for Implementing the Climate Change Strategic Plan **http://www.fws.gov/home/climatechange/pdf/CCDraftActionPlan92209.pdf**

U.S. Geological Survey Patuxent Wildlife Research Center
http://www.pwrc.usgs.gov

Regional Standards to Identify and Evaluate Tidal Wetland Restoration in the Gulf of Maine
http://www.pwrc.usgs.gov/resshow/neckles/gpac.htm

Guide on Installing and Using Surface Elevation Tables (SETs)
http://www.pwrc.usgs.gov/se

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