CHAPTER

2

Coastal Ecosystems

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Introduction: Coastal Communities at the Land-Sea Interface

The fringing ribbons of habitats that make up the land-sea interface maintain marine diversity and play critical roles for both nearshore and offshore plants and animals. The Northwest Atlantic coastline is particularly well known for its hundreds of productive estuaries that provide juvenile nursery and spawning grounds for fish, mollusks, seabirds, and crabs. This report focuses specifically on the contributions that coastal ecosystems make to marine diversity.

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The edge of earth that meets the sea – what we call coastline – is the ultimate ecotone, a critical ecological transition, as dramatic and obvious a natural boundary as one can find on Earth. While well defined, coastlines are very dynamic over geologic time. Over millennia, estuarine and ocean shorelines have advanced and retreated thousands of kilometers inland and seaward, and back again in cycles. The zone where ocean meets earth includes diverse landforms that are cut and shaped by waves and tides and by the continuous flow of new sediments carried by freshwater in coastal watersheds. The adjacent shallow, well-lit, and productive coastal waters give rise to habitats like the salt marshes, oyster reefs, and seagrass meadows discussed in this chapter, critical habitats that directly and indirectly support many of the species mentioned throughout this report.

The coasts and estuaries in this region are also of great importance to humans. Tremendous material, aesthetic, and spiritual resources associated with shorelines have attracted and sustained humans for thousands of years. Our coasts and estuaries are where we live, recreate, work, and gather. They help support the economy and sustain us in many ways, including providing places to live, opportunities for tourism, shipping and transportation routes, commercial fishing, and seafood processing. Conversely, the malfunctioning of these systems in the form of pollution, habitat destruction, hypoxia, harmful algal blooms, fishery collapses, and increased coastal erosion can have devastating social and financial impacts for coastal communities.

Coasts and estuaries and their component organisms and habitats provide ecosystem services at multiple scales. For example, at the scale of meters, estuarine bivalves such as the Eastern oyster convert pelagic primary production into food and habitat for benthic organisms and clear water for submerged vascular plants. At the kilometer scale, tidal wetland vegetation cycles nutrients, sequesters carbon, and serves as a marine nursery. At the coast-wide scale, each estuary supports a wide array of coastal migratory fishes, and at the global scale the network of estuaries in this region produces the food that fuels shorebirds flying to Alaska and tuna swimming to the Mediterranean Sea.

Recognizing the heterogeneity and ever-changing nature of the coastline, this section of the assessment reviews the history of coastal systems in the region, provides an overview of coastal habitats such as salt marshes, seagrass beds, and oyster reefs, examines some of the threats and human interactions with these systems, provides an in-depth look at sea level rise and reviews potential strategies for enhancing resilience of coastal systems.

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Selection of Target Coastal Habitats

For coastal habitats, the team chose to focus on a limited number of targets. These are most simply summarized in three categories; the various types of habitats that make up the land-sea interface (e.g., salt marsh, beach), seagrass meadows (beds of submerged marine rooted vascular plants), and nearshore shellfish assemblages.

The land-sea targets discussed in this section are consistent with the initial charge to the group, which was to reexamine conservation targets already identified in TNC's adjacent terrestrial North Atlantic Coast (NAC) and Northern Appalachian (NAP) ecoregional plans from a marine perspective. Within the nearshore shellfish assemblage category, specific targets were selected based on general criteria of 1) need for specific conservation action, 2) wide historical distribution and significant abundance within the region, 3) relative importance of ecosystem services provided, and 4) cultural and economic value. The resulting list focuses on species located in closer proximity to human settlements, those for which there are economic markets, and bounded estuarine embayments that enhance ecological services. Other economically important shellfish species that occur in some nearshore areas but are more typically offshore were excluded as not currently overfished and likely having less coastal habitat value (ASMFC 2007).

The following targets were selected for this assessment:

- Land-sea interface
- Vegetated tidal wetlands (salt and brackish emergent marshes)
- Sandy beaches
- Cobble shores
- Non-vegetated sheltered coasts, including sand and mud flats
- Rocky headlands
- Coastal salt ponds
- Seagrass beds
- Nearshore shellfish assemblages
- Eastern oyster
- Hard clam
- Softshell clam
- Bay scallop
- Blue mussel
- Ribbed mussel

Population Status and the Importance of the Northwest Atlantic Region: A Historical Review of Key Coastal Habitats and Species

The purpose of this section is to help provide a historical context for conservation and restoration and a call to action for setting thoughtful and ambitious goals going forward. Restoration and conservation goals need to consider quantitative knowledge about the past and the environmental constraints of the present. They also need to be ambitious enough to make a difference – to affect the trajectory of ecosystem state conditions in ways that benefit nature and people. This section is not intended to be a comprehensive inventory of loss and damage to Northwest Atlantic coastal ecosystems. It is rather a sampling of available datasets that collectively can provide context for the assessment of current condition provided in the rest of this chapter.

Although quantitative data on historical conditions are relatively scarce, in recent years a large amount of qualitative and anecdotal historical data has become more readily available through internet sources. Some of the old stories ring true, and some may contain exaggeration or outright fiction. However, in total, these stories, frequently verified through comparisons with empirical data, strongly evoke the shifting baselines phenomenon (Pauly 1995). The condition of present day coastal ecosystems may be correctly perceived as being somewhat degraded in comparison to conditions a few generations ago, without full appreciation of the magnitude of damage and loss in comparison to conditions a few hundred years ago. Perhaps an inkling of baseline conditions from around the time of European settlement is revealed in this report from 1629, transcribed from Massachusetts Bay Colony reports in 1846.

> *The abundance of sea-fish are almost beyond believing; and sure I should scarce have believed it except I had seen it with mine own eyes. I saw great store of whales, and grampuses, and such abundance of mackerels that it would astonish one to*

behold; likewise codfish, abundance on the coast, and in their season are plentifully taken. There is a fish called a bass, a most sweet and wholesome fish as ever I did eat; it is altogether as good as our fresh salmon; and the season of their coming was begun when we came first to New-England in June, and so continued about three months' space. Of this fish our fishers take many hundreds together, which I have seen lying on the shore, to my admiration. Yea, their nets ordinarily take more than they are able to haul to land, and for want of boats and men they are constrained to let a many go after they have taken them; and yet sometimes they fill two boats at a time with them. And besides bass, we take plenty of scate and thornback, and abun dance of lobsters, and the least boy in the Plantation may both catch and eat what he will of them. For my own part, I was soon cloyed with them, they were so great, and fat, and luscious. I have seen some myself that have weighed sixteen pound; but others have had divers times so great lobsters as have weighed twenty-five pound, as they assured me. (Young 1846).

Even a cursory review of the historical and current conditions of Northwest Atlantic coastal ecosystems reveals that tremendous changes, including significant resource depletion, have taken place since European settlement. At least four marine species in the Northwest Atlantic became extinct in historic times – Atlantic gray whale (early 1700s), sea mink (1880), great auk (1884), and in 1929 the eelgrass limpet was lost during the eelgrass wasting disease pandemic (Geerat 1993; Carlton et al. 1999). While total range-wide extinctions in marine ecosystems appear to be relatively uncommon or go unnoticed, local extirpations and sharp population reductions with associated loss of ecosystem services are quite evident.

Prior to 1900, thousands of rivers and streams were dammed, and as a result, many thousands of kilometers of spawning habitat for diadromous fish were lost. Intensive logging cleared entire watersheds, leading to erosion and delivery of excessive sediment to estuaries, dramatically changing bathymetry and impacting a variety of habitats and species. Silt and enormous quantities of sawdust and wood debris from mills were dumped in estuaries, smothering shellfish, eelgrass, and benthic communities. Meanwhile, urban centers like Boston and New York grew rapidly into their adjacent estuaries, filling coastal wetlands and hardening natural shorelines. Unregulated effluents from textile mills, tanneries, and other industries combined with untreated sewage to poison and degrade benthic and pelagic habitats (Jackson 1944; Buschbaum et al. 2005). Against this backdrop of estuarine habitat destruction, largely unregulated harvesting of marine resources proceeded with the illusory idea that the ocean's bounty was limitless (Huxley 1884). However, by the mid to late 1800s many authors began to describe the damage that had begun to accrue and some of their observations are excerpted below. Modern scientists are revisiting the same questions, equipped with better scientific understanding while also at a great disadvantage due to the long passage of time. To provide an historical context for several of the conservation targets, the following sections highlight changes in salt marshes, eelgrass, and oysters.

Salt Marshes

Salt marshes are intertidal wetlands typically located in low energy environments such as estuaries. They exist both as expansive meadow marshes and as narrow fringing marshes along shorelines. Considered one of the most productive ecosystems in the world, salt marshes provide numerous ecological functions, including shoreline stabilization, wildlife habitat, and nutrient cycling. Their critical role in providing breeding, refuge, nursery, and forage habitats for diverse marine fauna is well known. Salt marsh dependent species facilitate the export of nutrients and carbon from coastal to offshore food webs. The emerging field of valuing nature (calculating ecosystem services in economic terms) is sometimes controversial, but by any measure salt marsh is one of the most valuable habitat types on Earth. Bromberg Gedan et al. (2009) cautiously estimate that the ecosystem services of one hectare of salt marsh exceed a value of $14,000 per year (Table 2-1).

In the past few centuries, a large portion of the Northwest Atlantic's salt marsh habitat has been altered or destroyed. Soon after European settlement, salt marshes were ditched and drained to facilitate hay production, and subsequently to control mosquitoes. Over decades, various forms of coastal development (urban expansion, roadways,

Table 12-1 Valuation of salt marsh ecosystem services. Reprinted with permission from Bromberg Gedan et al. (2009).

Ecosystem Service	Examples of Human Benefits	Average Value (Adj. 2007 $[a] ha^{-1} year^{-1})
Disturbance regulation	Storm protectio and shoreline protection	$2824
Waste Treatment	Nutrient removal and transformation	$9565
Habitat/refugia	Fish and shrimp nurseries	$280
Food Production	Fishing, hunting, gathering, aquaculture	$421
Raw materials	Fur trapping	$136
Recreation	Hunting, fishing, birdwatching	$1171
TOTAL		**$14,397**

residential development, and industry) have altered and reduced the extent of marshes through diking, dredging, filling, and armoring.

A comprehensive estimate of salt marsh loss along the eastern seaboard has not yet been produced and is beyond the scope of this project. However, GIS methods are increasingly being used to examine historical maps to produce local and regional spatially explicit estimates. It has been estimated that Rhode Island salt marsh area has been reduced by 53% since 1832 and that, since 1777, 40% of Massachusetts salt marsh has been lost, with over 80% lost in the heavily filled Boston area estuary (Bromberg Gedan and Bertness 2005). At Great Bay, New Hampshire a comprehensive review of historical data identified likely locations of salt marsh loss (Figure 2-1). Results indicate that the current extent of salt marsh in the Great Bay estuary is about 400 hectares and the identified restoration opportunities total about 200 hectares (GBERC 2006).

Eelgrass

Eelgrass *(Zostera marina)* is the major seagrass in the western North Atlantic, a marine flowering plant that grows in subtidal and intertidal regions of coastal waters in both protected and exposed systems. In addition to providing food and critical spawning and refuge habitat for fish and invertebrates (Wyda et al. 2002; Heck et al. 2003), the complex networks of leaves, roots, and rhizomes serve to trap nutrients and sediments, protect shorelines from erosion, and filter pollution. In northern latitudes eelgrass typically exhibits a seasonal change in abundance, with low biomass in winter months followed by rapid increases in the spring and early summer (Short et al. 2007).

Oysters and other shellfish benefit from associations with eelgrass in several ways. Eelgrass meadows trap and sequester suspended sediments that might otherwise smother juvenile shellfish and reduce habitat quality for adults. The beds also create eddies in currents that can affect larval retention and settlement, and the plants provide potential attachment sites for planktonic stages of some shellfish, notably bay scallops *(Argopecten irradians)* (Newell and Koch 2004).

Figure 2-1. Estimated salt marsh loss at Great Bay, New Hampshire. This image shows the detail of a map from the Great Bay Estuarine Restoration Compendium (2006). Dark orange indicates areas of probable loss identified using comparison of maps from 1918 with modern survey data showing current salt marsh distribution (beige areas).

In the North Atlantic, a wasting disease first noted in the 1930s caused a rapid coastwide decline in the extent of eelgrass. The link between the disease and the marine slime mold *Labrynthula zosterae* is now well established (Den Hartog 1989; Muehlstein et al. 1991). It is thought that higher than average salinity and human impacts on seagrass systems facilitated the disease.

Despite the widespread loss of the great majority of the eelgrass along the Northwest Atlantic coast, many eelgrass beds recovered over the subsequent few decades. However, this recovery coincided with rapidly increasing nutrient and sediment loads to coastal ecosystems, minimizing recovery in some areas and leading to the eventual loss of thousands of hectares of eelgrass beds that had briefly returned following the disease outbreak (Orth et al. 2006; Wazniak et al. 2007). Because of its functional role

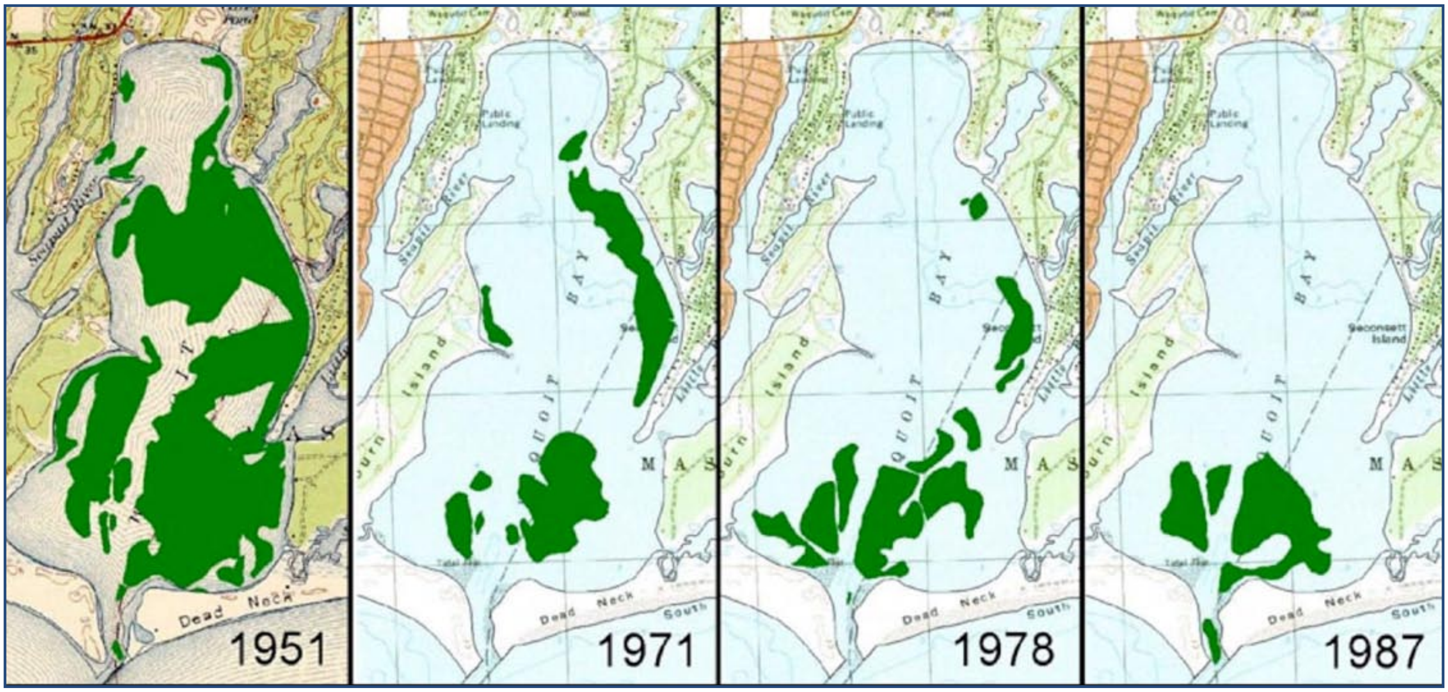

Figure 2-2. Eelgrass (Zostera marina) loss at Waquoit Bay, Massachusetts. This image shows post-disease re-growth followed by loss due to eutrophication (Costa et al. 1992). Nitrogen oncentrations in this embayment doubled between 1938 and 1990 (Bowen and Valiela 2001).

within coastal ecosystems, the loss of eelgrass has secondary impact on dependant fauna, from waterfowl such as brant *(Branta bernicla)* to bay scallops, and myriad other fish and invertebrate species (Bowen and Valiela 2001; Deegan et al. 2002; Kennish et al. 2007).

A comprehensive estimate of eelgrass loss and restoration opportunities for the project area has not yet been completed. However, estimates for some locations (Figure 2-2 and 2-3), have been produced through comparison of aerial photography with old maps and the use of habitat models (Orth and Moore 1983; Orth and Moore 1984; GBERC 2006). The greatest amount of eelgrass loss in the Northwest Atlantic has occurred within Chesapeake Bay, where more than half the area historically covered by eelgrass was lost by the 1970s (Robert Orth, personal communication).

Eelgrass restoration efforts are picking up steam throughout the region, including at locations in Great Bay, New Hampshire, in Long Island Sound, and the seaside lagoons of the eastern shore of Virginia. As an example, the Conservancy is working with the Virginia Institute of Marine Science, Virginia's Coastal Zone Management Program, and NOAA to expand the world's largest successful seagrass restoration project. This landscape scale restoration project is being monitored to evaluate benefits for diverse eelgrass community fauna and includes re-introduction of eelgrass dependant bay-scallops and oyster settlement substrate.

Oysters

Eastern oysters *(Crassostrea virginica)* are found in shallow subtidal and intertidal areas throughout the Northwest Atlantic, providing substantial ecosystem services including water filtration, provision of fish habitat, and erosion control (Coen et al. 2007).

Much attention and resources have been brought to bear on protecting and conserving coral reef systems around the world. In temperate waters, reefs formed by oysters and other shellfish provide similar critical habitat and

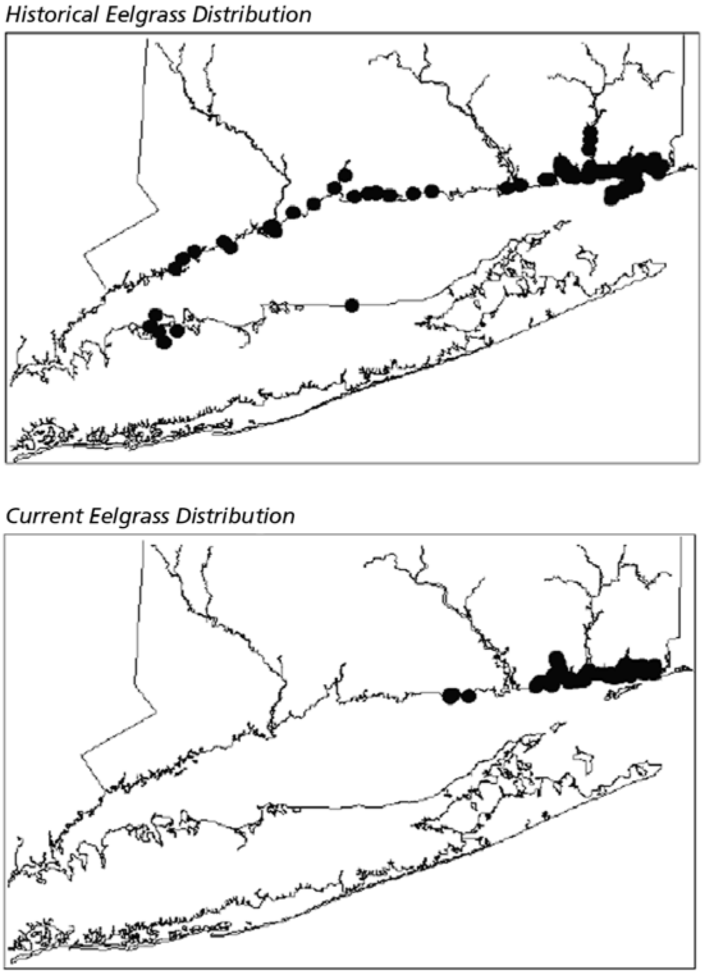

Figure 2-3. Long Island Sound Eelgrass Distribution. Comparison of historic and 2003 eelgrass (Zostera marina) bed locations (from LISHRI 2003).

ecosystem benefits as their tropical reef brethren. Globally, native shellfish are not just highly threatened, they are *functionally extinct* in most bays (Beck et al. in review). It is difficult to identify intact oyster reefs or shellfish beds anywhere in the northern hemisphere, including the major estuaries, tidal rivers, coastal bays, and lagoons of the Northwest Atlantic.

Many oyster shell middens along the Atlantic coast's estuaries and tidal rivers have been located and studied. These data-rich shell piles are monuments to the persistence of both abundant shellfish resources and human harvesters for thousands of years before European settlers stepped ashore.

Drake (1875) made many observations regarding the condition of oysters and other natural resources along the New England coast in the late 1800s. In reference to the famous thirty foot high oyster shell middens along the shores of the Damariscotta River in southern Maine and the abundance and large size of oysters in Massachusetts, he wrote:

> *The shell heaps are of common occurrence all along the coast. The reader knows them for the feeding-places of the hordes preceding European civilization. Here they regaled themselves on a delicacy that disappeared when they vanished from the land. The Indians not only satisfied present hunger, but dried the oyster for winter consumption...Josselyn mentions the long-shelled oysters peculiar to these deposits. He notes them of nine inches in length from the joint to the toe, that were to be cut in three pieces before they could be eaten. ... The problem of the oyster's disappearance is yet to be solved.*

Ingersoll (1881) published a comprehensive review of oyster distribution and associated industry for the United States Bureau of Fisheries. Substantial oyster reefs, consisting of much larger oysters than are typically found today, were noted in nearly every estuary and tidal river in the region. His 1881 review stated:

> *In 1634 William Wood, in his New England's Prospect, speaks of "a great oyster bank" in Charles river, and another in the "Misticke", each of which obstructed the navigation of its river. Ships of small burden, he says, were able to go up as far as Watertown and Newton, "but the Oyster-bankes do barre out the bigger Ships."... "Ships without either Ballast or loading, may floate downe this River; otherwise the Oyster-banke would hinder them which crosseth the Channell."*
>
> *"The Oysters," adds Wood, "be great ones in form of a Shoehorne; some be a foot long; these breed on certain banks that are bare every spring tide. This fish without shell is so big, that it must admit of a division before you can well get it into your mouth."*

This bank appears to have been a very well-known and prominent feature in those days, though no popular tradition of it remains. For example, Winthrop's History of New England, edited by the Rev. John Savage, p. 106, contains under date of August 6, 1633, the following statement: "Two men servants to one Moodye, of Roxbury, returning in a boat from the windmill, struck upon the oyster-bank. They went out to gather 'oysters, and, not making fast their boat, when the flood came, it floated away, and they were both drowned, although they might have waded out on either side; but it was an evident judgment of God upon them, for they were wicked persons.

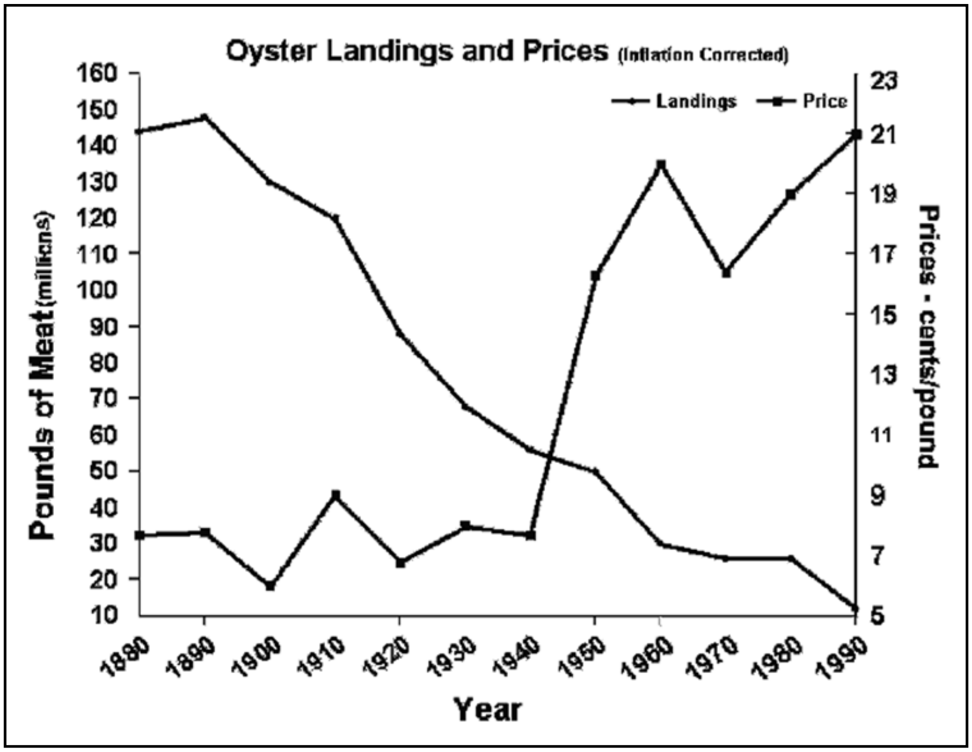

Figure 2-4. East Coast oyster landings and prices (inflation-corrected) of oysters, 1880 to 1990. Reprinted with permission from Mackenzie (2007).

The loss of oyster populations throughout the Northwest Atlantic is chronicled in many of the annual reports of the United States Bureau of Fisheries (USCF 1916). There is a wealth of credible historic information and maps indicating that oysters were formerly much more abundant than in modern times. East coast annual oyster harvests peaked at nearly 27 million bushels during the 1890s, declined to about 12 million bushels by 1940, and have been well below 0.5 million bushels in recent years (Figure 2- 4). Intense market demand and increasingly effective fishing methods fueled oyster fishery growth during the 1800s even though oyster populations had already been sharply reduced during the 17th and 18th centuries due to pollution and sedimentation from mills and logging.

Chesapeake Bay, the nation's largest estuary, has historically produced the highest oyster landings in the Northwest Atlantic. Ingersoll (1881) reports that in 1880 total Chesapeake Bay oyster production exceeded 17 million bushels. In Maryland and Virginia, the oyster industry employed at least 32,000 people in harvesting, processing, and marketing operations. Additional Chesapeake Bay production included millions of seed oysters sold and transported to help augment diminished oyster resources at many locations from Delaware to Maine. However, even during these times of extraordinary abundance, there were warning signs that these harvest levels were unsustainable (Ingersoll 1881; USBCF 1893).

Comprehensive and detailed estimates of oyster loss and current restoration opportunities for the project area have not been produced. However, loss and restoration potential have been estimated for some locations using both historic maps and habitat models. At Great Bay, New Hampshire the extent of oysters before significant losses occurred between the 1700s and about 1970 remains unknown. However, GIS analysis of available map data (Figure 2-5) indicates that oysters covered at least 365 hectares, and perhaps as much as 525 hectares, compared to the current extent of live oyster bottom of 20 to 40 hectares. It should be noted that although disease has taken a heavy toll on oysters within the Great Bay

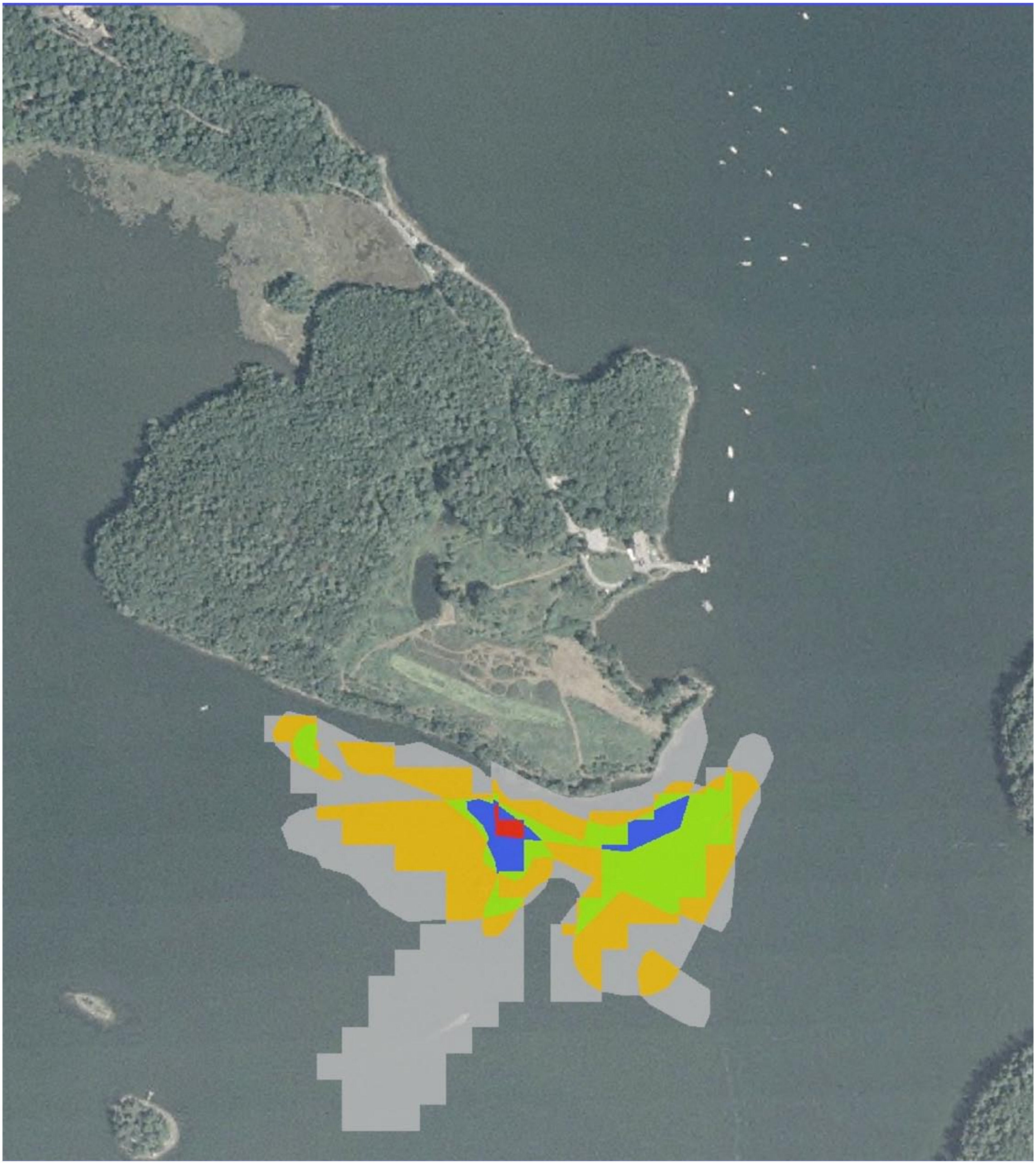

Figure 2-5. Overlay of seven oyster distribution maps from Great Bay, New Hampshire. Colors indicate number of coincident survey footprints (gray = 1, yellow = 2, green = 3, blue = 4, and red = 5). This analysis was used in preparation of the Great Bay Estuarine Restoration Compendium to inform confidence levels regarding the validity of historic maps.

estuary, oysters in an area closed to harvest due to pollution concerns are thriving and forming a three-dimensional reef structure.

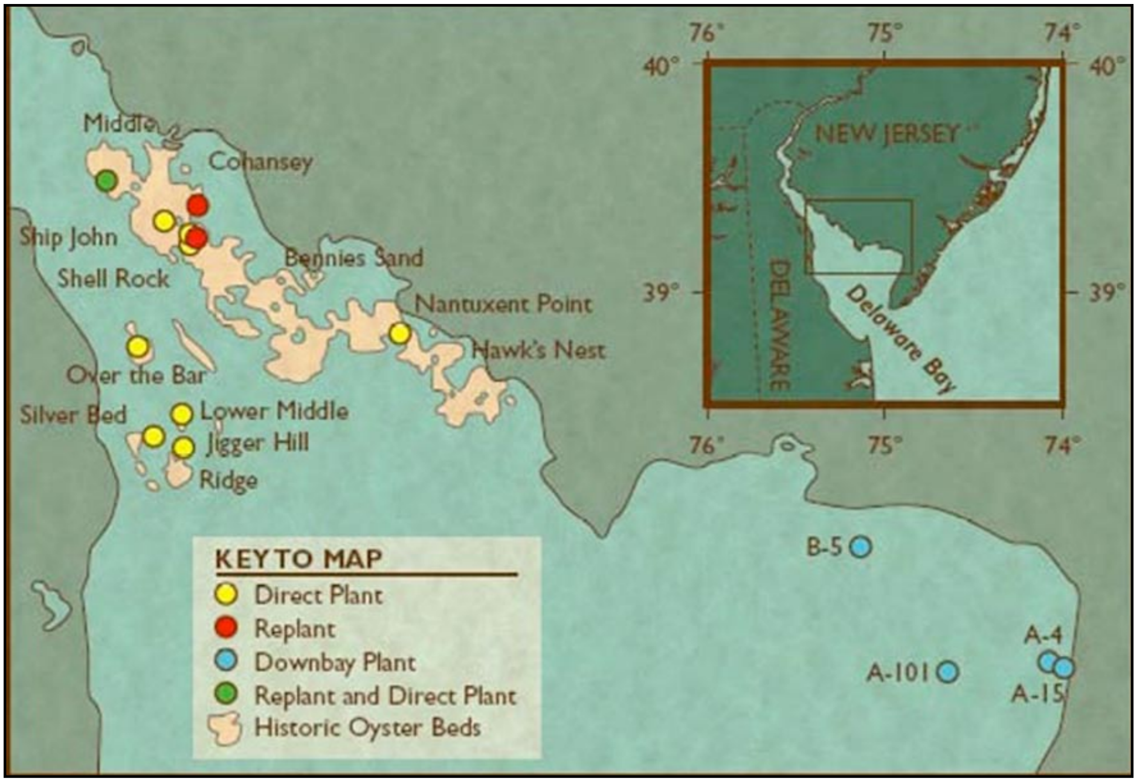

Figure 2-6. Delaware Bay's historic oyster reefs and restoration sites. This map image is reprinted courtesy of the Delaware Bay Oyster Restoration Task Force.

Since 2005, the Delaware Bay Oyster Restoration Task Force has strategically planted millions of bushels of shell material onto historic reef sites in Delaware Bay (Figure 2-6), attaining initial goals of equilibrium conditions for settlement habitat. Recent observations suggest that restoration efforts are leading to a substantial increase in juvenile oyster survival (DBOP 2009).

These are only two examples; additional oyster restoration projects are proceeding or being initiated in many states of the Northwest Atlantic region (MDNR 2009; NJB 2009; VIMS 2009).

Throughout the Northwest Atlantic, a combination of factors continues to limit prospects for effective oyster restoration. These factors include continued recreational and commercial oyster harvest pressure, two oyster diseases (MSX and Dermo), excess sediments, reduced freshwater flows, and dredging for navigation. The relative importance and nature of these stresses varies substantially geographically. However, the long-held notion that oyster diseases present an insurmountable barrier to effective restoration is yielding to increasing evidence that, with appropriate investment and protection of sufficient numbers of oysters within sanctuaries, native oyster restoration can be very successful (Powers et al. in press).

Lessons Learned

The historical anecdotes and data summarized above provide evidence that the condition and geographic extent of coastal habitats and populations of key species are greatly diminished compared to past times. At the same time, the outdated notion that undisturbed nature represents an ideal state has given way to a more realistic view - that ecosystems are dynamic, with multiple potential stable states and ever-changing mosaics of diverse habitats. It is not realistic to set restoration goals that attempt to recreate the exact conditions of the past.

With that caveat in mind, we also recognize that human activities have unintentionally altered many ecological processes necessary for the long term persistence of estuarine habitats and the species that depend on them (Lotze et al. 2006; UNEP 2006). Left unchecked, these alterations can drive ecosystems into alternate and relatively stable states that are clearly undesirable, possibly including hypoxic or anoxic "dead zones," food webs simplified by the loss of formerly dominant species, and a loss of natural resources and ecological services desired and required by human communities (Leslie and Kinzig 2009). These undesirable states are now being observed in coastal ecosystems around the world.

Our challenge is to set ambitious and achievable conservation and restoration goals, in clear recognition of all the threats that degrade coastal ecosystems. At many locations, habitat and species-focused restoration will not be successful without prior substantial and successful work to conserve land within coastal watersheds and to abate point and non-point pollution impacts. Policy-focused strategies to reduce water pollution, habitat loss and harvest of threatened species, as well as place-based projects to plant eelgrass and oysters, to restore salt marshes, and to improve fish passage are urgently needed. An invigorated whole-ecosystem approach offers much promise for increasing ecological resilience - the ability of an ecosystem to rebound from disturbances (Leslie and Kinzig 2009). We have an opportunity now to learn from history and move forward with coordinated science and policy to avoid and reverse undesirable ecosystem state conditions so that our coastal habitats continue to support life and produce the material and aesthetic goods and services that people want and need.

> *Human impacts have pushed estuarine and coastal ecosystems far from their historical baseline of rich, diverse, and productive ecosystems. The severity and synchrony of degradation trends and the commonality of causes and consequences of change provide reference points and quantitative targets for ecosystem based management and restoration. Overexploitation and habitat destruction have been responsible for the large majority of historical changes, and their reduction should be a major management priority. Eutrophication, although severe in the last phase of estuarine history, largely followed rather than drove observed declines in diversity, structure, and functioning. Despite some extinctions, most species and functional groups persist, albeit in greatly reduced numbers. Thus, the potential for recovery remains, and where human efforts have focused on protection and restoration, recovery has occurred, although often with significant lag times.* (Lotze et al. 2006)

Ecosystem Interactions and Ecological Dependencies

Natural Shorelines

Vegetated Tidal Wetlands – Salt, Brackish, and Freshwater Emergent Marshes

Among the most biologically productive ecosystems on earth (Teal 1962; Odum 1970; Valiela et al. 1976; Nixon 1980), salt marshes perform many ecosystem services that are highly valued by society. Salt marshes protect estuarine water quality by acting as a sink for land-derived nutrients and contaminants (Valiela et al. 2004; O'Connor and Terry 1972; Teal and Howes 2000). They are also an important component of the estuarine food web: there is a strong positive relationship between the productivity of salt marshes and the productivity of coastal fisheries (Peterson et al. 2000). During high tide, salt marshes and the network of tidal creeks and pools within them provide food and important nursery grounds for shellfish and finfish, including many commercially harvested species (Teal 1962; Weisburg and Lotrich 1982; Dionne et al. 1999; Able et al. 2000; Cicchetti and Diaz 2000). Juvenile menhaden, for example, derive much of their energy from marsh plant detritus rather than from a phytoplankton–based food web (Pernell and Peters 1984). Able et al. (2000) found that the guts of striped bass *(Morone saxatilis)* caught in marsh creeks were full of killifish *(Fundulus heteroclitus),* a common marsh resident. During low tide, salt marshes provide foraging opportunities for terrestrial species, including songbirds and shorebirds. Salt marshes also provide valuable wildlife habitat and nesting areas for osprey, the sharp-tailed sparrow and the clapper rail.

Typical northeastern salt marshes are described by Niering and Warren (1980), Edinger et al. (2002), Bertness (2006), and others. The low marsh zone, which is flooded on a daily basis by the tides, is dominated by the cordgrass, *Spartina alterniflora*. Low marsh grades into high salt marsh habitat. At slightly higher elevations, these are flooded periodically by spring and flood tides (Edinger et al. 2002). High salt marsh habitat occurs in a band from the mean high tide level to the landward limit of the highest spring tides. The dominant plant species in the high salt marsh community is the salt-meadow grass or marsh hay *(Spartina patens)*. Spikegrass *(Distichlis spicata)*, black-grass (*Juncus gerardii*), and glassworts *(Salicornia* spp.) are also common in the high marsh. Characteristic invertebrates of the salt marsh include ribbed mussels *(Geukensia demissa)* and fiddler crabs *(Uca* spp.), both of which boost productivity of marsh plants.

As sea level has very gradually risen since the last glaciations period, salt marshes have grown both horizontally and vertically (Redfield 1965 and 1972). Horizontal growth occurs via migration into adjacent upland areas and vertical growth occurs through the accumulation of

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mineral and biologic sedimentary materials that form the peat substrate (Bertness 2006). Each year's new growth builds on these two types of sediments that form the marsh peat. Historically, this type of accretion has more or less kept pace with changing relative sea level in most parts of our region. However, human alterations such as shoreline hardening and development can impede this growth.

In regions where rivers bring large quantities of freshwater, salt water tidal marshes may grade to brackish and even completely fresh. Long bands of freshwater tidal marsh occur along the shores of the Hudson, Connecticut, and Kennebec River estuaries, for instance. Here, the graminoid (grass and grass-like) species shift from cordgrass to cattails, rushes, wild rice, and numerous forbs, many of which are restricted to this habitat and thus rare in the region. Brackish and freshwater tidal marshes are important for migrating waterfowl and anadromous fishes and, like salt marshes, contribute considerable carbon to the estuaries of which they are part. In some parts of the region, these wetlands have been heavily impacted by industrial development of major ports or by dams which have shifted the tidal flooding and salinity regimes. Rising sea level will be a particularly important factor in determining future trends in tidal marsh health and distribution.

A very small percentage of the overall shoreline in this region is classified by National Oceanic and Atmospheric Administration (NOAA) Environmental Sensitivity Index (ESI) as "swamp," mostly in the Southern New England and Mid-Atlantic subregions. According to ESI, freshwater tidal swamps are forested or shrub-dominated tidal wetlands, a classification used in the United States Fish and Wildlife Service (USFWS) National Wetlands Inventory (NWI), that occur along freshwater tidal portions of large river systems characterized by gentle slope gradients coupled with tidal influence over considerable distances. The swamp substrate is always wet and is subject to semidiurnal flooding by fresh tidal water (salinity less than 0.5 ppt). The characteristic trees are ash *(Fraxinus)* and tupelo *(Nyssa* and *Taxodium* species) (Reschke 1990).

Sandy Beach and Dune systems

There are three primary types of sandy beach systems found within the region: barrier island and barrier beaches, primarily found in the south, and pocket beaches, generally found in the north at the head of small bays.

Sandy ocean beaches especially in the southern half of the region are often associated with barrier island systems. In their natural state, sand-derived barrier islands and barrier beaches attached to the mainland are highly dynamic systems, constantly shaped and reshaped by winds, storms and ocean currents. Generally speaking, prevailing winds and nearshore currents cause North Atlantic barrier islands to migrate slowly southward (westward on Long Island), with sand lost from the north (east) end often transported to build new beaches and dunes at the south (west) end. Hurricanes and nor'easters episodically move tremendous quantities of sand, both onshore and offshore, as well as along the main axis of the islands. Barrier beaches typically protect tidal lagoons, coastal salt ponds, or salt marshes behind them. Breaches or blowouts of the beach/dune systems can occur during major storms, creating new channels for flow between the ocean and back bays, and flood plain deltas which eventually submerge to create sand flats, or become vegetated to create wetlands.

In the more northern part of the region sandy beaches tend to be pocket beaches at the head of small bays or fringing beaches at the base of bluffs. These are much smaller than barrier beaches but cumulatively still figure in the overall sediment budget and habitat dynamics of estuaries.

All types of sandy beaches in this region are breeding grounds for endangered and threatened species such as the piping plover, least terns, Arctic terns, roseate terns as well as several species of sea turtles (see Chapter 11 and 12 for more information). They also provide critical roost sites for migrant shorebirds. The sand of an open beach may appear relatively devoid of marine life, but a variety of species live in the sand as infauna, often serving as important food sources (Bertness 2006). The value of sandy beaches to marine species is enhanced by their functional relationship to the habitats behind them (e.g. dune systems) and to the productive sand and mud flats (see below) often associated with them.

Sandy ocean beaches have been long been valued for their recreation and tourism value and billions of dollars are spent to maintain these resources. This maintenance can include artificial stabilization to minimize erosion. However, in some cases the very techniques designed to secure the beach for human uses, such as groins, beach walls, and beach fill, actually interfere with the dynamics necessary for sandy shorelines and barrier islands to persist. This is particularly relevant in the face of rising sea level and storm surges. Thus, these shoreline armoring measures are actually detrimental to the ecological communities that rely on the beaches and adjacent habitats (Pilkey and Dixon 1996).

Cobble Shores

Cobble shores range from the mid to high energy cobble-filled nooks among the rocky headlands to stretches of cobble-lined shoreline adjacent to sandy beaches. More common in the northern half of the region, they support a different suite of species than the rocky headlands, as the cobble provides a less stable substrate for attachment. Cobble stones roll about in the surf, and are shoved into piles during one storm event and spread out again in another. Species associated with the cobble shore tend to be small, mobile, and short-lived (Tyrrell 2005), commonly including Irish moss, barnacles, periwinkles, and other invertebrates and the shorebird species that feed on them. The large algae species of the rocky headlands are mostly absent here but may be present on larger boulders.

Sand and Mud Flats

Non-vegetated sheltered coasts, usually sand and mud flats, have received less attention by resource managers than sandy ocean beaches or vegetated tidal wetlands, and therefore their importance to wildlife and humans has often been overlooked. Recently, however, the focus on the relationship between endangered shorebirds and sheltered beach-nesting horseshoe crabs has brought to light the ecological importance of these often under-protected coastlines. Intertidal sand and mud flats of the sheltered coasts can be fringing or expansive, depending on bathymetry and tidal amplitude.

Sediment size, sediment chemistry, inundation cycle, salinity, frequency of disturbance, and latitude are all determinants of the biotic community within flats. These flats are habitat for shellfish such as blue mussel *(Mytilus edulis),* Eastern oyster *(Crassostrea virginica),* hard clam (*Mercenaria mercenaria*) and soft shell clam *(Mya arenaria).* In addition to the typical resident invertebrate communities of annelids, crustaceans, and bivalves, tidal flats are foraging grounds for marine organisms such as eels, crabs, fish, snails, and shrimp at high tide and terrestrial organisms, particularly shorebirds, at low tide.

A variety of algal species often grow or float among the shells, rocks, and other structures present in the intertidal areas. The algae and bacteria that grow here provide additional food for fish, shellfish, and other animals using this habitat. However, in some areas of anthropogenic eutrophication excessive growth of certain green algae species can actually suffocate the infauna of the mudflats below.

Rocky Headlands

The organisms of the stable bedrock and boulder seacoast include those capable of attaching to rock and withstanding intense wave impact and periodic desiccation. These include attached macroalgae such as rockweeds *(Ascophyllum nodosum, Fucus spp.)*, kelp *(Laminaria spp.)*, *Enteromorpha* spp., and *Rhizoclonium* spp., and invertebrates such as blue mussel *(Mytilus edulis)*, rock barnacle *(Balanus balanoides)*, sea star *(Asterias spp.)*, and sea urchin *(Arbacia punctulata)*. As the environment is high energy, rocky shore communities may be less vulnerable to human caused degradation, although eutrophication, sedimentation, overexploitation, and trampling can still pose problems (Menge and Branch 2001). Like large intertidal cobble and boulders, rocky headlands also provide habitat for juvenile lobsters (Cowan 1999) and fishes. Island occurrences of rocky headlands provide haul out areas for seals and nesting areas for seabirds.

Coastal Salt Ponds

Coastal salt ponds, found mostly in southern New England (according to the NWI), are marine shoreline lakes or ponds formed when sandspits or barrier beaches close off a lagoon or bay from the surrounding estuarine or oceanic waters. These ponds can be permanent, transient, or periodic. The salt pond water is often less saline that the surrounding embayment and its volume is dependent upon the rates of freshwater input, evaporation, and the frequency of breaching or flooding. Some ponds have been modified to have permanent inlets, and some are managed by opening and closing inlets. Salt pond species are usually the same as those found in adjacent sheltered brackish embayments; however, unique community assemblages can arise within ponds that are only periodically breached. Species which can tolerate salinity and temperature changes such as the killifish *(Fundulus heteroclitus)*, Eastern oyster *(Crassostrea virginica)*, and American eel *(Anguilla rostrata)* can thrive in salt ponds. Isolation within a salt pond can protect species, at least temporarily, from migratory marine predators. In winter, coastal salt ponds provide migratory refuge for a broad variety of waterfowl including canvasback duck *(Aythya valisneria)*, pintail *(Anas acuta)*, scaup *(Aythya affinis)*, and common loon *(Gavia immer)*.

Seagrass Beds

Seagrasses are marine, subtidal, rooted vascular plants found in shallow coastal waters in various types of sediment substrate from sand to mud. Eelgrass *(Zostera marina)*, the major seagrass species in the region, grows in perennial beds that form highly diverse and productive

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ecosystems providing a wide range of services. Widgeon grass *(Ruppia maritima)* is an annual seagrass species that also grows in the region but tends not to form extensive bed structures. Eelgrass beds serve as shelter and nursery grounds for hundreds of species from all phyla, including juvenile and adult fishes, shellfish, and invertebrates.

The plants can contribute significantly to the overall primary productivity of an estuary; energy present in seagrass enters the estuarine food web as detritus. In addition, numerous animals feed directly on seagrasses, including fishes, geese, swans, sea turtles, and crabs. Seagrass provides structure for benthic (seabed) communities and can slow down currents, thereby increasing sediment trapping. The seabed is stabilized by seagrass roots and rhizomes. Seagrass provides oxygen to the water column and shallow benthos, and takes up nutrients (e.g. nitrogen and phosphorus) during its growing season (spring to fall), re-releasing the nutrients through organic decay.

Seagrasses support a diverse epiphyte (plants that grow on the surface of another plant) community, including benthic diatoms and other algae, and free-floating macro and microalgae. Other organisms living on blades of eelgrass include protozoans (ciliates, flagellates, and foraminifera), nematodes, and copepods (Perry 1985). Sessile (attached) animals living on the blades and at the base of eelgrass shoots include bay scallops, crustaceans, sponges, anemones, bryozoans, tube worms, polychaetes, barnacles, and other arthropods and tunicates (Perry 1985).

Seagrass beds can occur in association with a variety of natural shoreline types. Ecological factors contributing to the distribution and continued health of seagrasses include water quality, depth, substrate type, light and nutrient regime, existing meadow size, germination and growth, water temperature, pore water chemistry, salinity, sediment dynamics, and wave energy. Many of these attributes are site specific. Although in many parts of the region seagrass beds have significantly declined, computer models (Short and Burdick 2005) have recently become available to help determine the most suitable places for eelgrass within some estuaries.

Nearshore Shellfish Assemblages

Dense beds of oysters, clams, scallops, and mussels once populated the bays and estuaries of the Atlantic coast, providing a wide array of ecological services. For instance, oysters develop vertical reef structures that provide fish habitat, filter the water and modify patterns of estuarine circulation, sediment transport, and wave energy. The viability of nearshore shellfish populations is highly dependent on sustainable harvest levels and presence of high quality settlement substrate, as well as estuarine water quality and salinity regimes. Although many shellfish species are found in abundance in the region, populations of some formerly dominant bivalve species are dwindling.

Prominence as a food source often overshadows the critical roles that shellfish assemblages play in ecosystem function (Grabowski and Peterson 2007). Bivalves are suspension feeders that, in abundant colonies, have the capacity to filter volumes of water equivalent to entire bays in a matter of days (Newell 2004). Filter feeders exert controls on harmful algal blooms and may facilitate eelgrass productivity (Peterson and Heck 1999; Wall et al. 2008). Reefs formed by oysters and blue mussels provide refuge and structure for many marine plants, animals, and invertebrates (ASMFC 2007), including economically valuable fish (Peterson et al. 2003). Once established, shellfish form dense colonies that provide many services, especially water filtration that directly benefits other species and habitats like eelgrass. In intertidal areas, shellfish beds trap sediments and stabilize shorelines against wave and storm erosion (Piazza et al. 2005; Meyer et al. 1997). The loss of shellfish habitat therefore has wide-ranging and serious implications for human and marine communities alike.

Larval forms of bivalves are preyed upon by many fish and marine invertebrates. As juveniles and adults, bivalves are major forage for all forms of fish, invertebrates (especially crabs, whelks, and starfish), shorebirds, seabirds, and even mammals.

Eastern Oyster *(Crassostrea virginica)*

Also known as the American oyster, this species is arguably the most historically dominant and commercially valuable shellfish species found throughout the region. Reefs occur in both subtidal and intertidal locations, with commercial activities focused on subtidal beds. Oysters are widely recognized as “ecosystem engineers” that create essential fish habitat, augment water quality, and provide services fundamental to the ecological health of estuaries and nearshore areas. The Eastern oyster occurs naturally from the Gulf of St. Lawrence (Canada) to the Gulf of Mexico. In the region, most remaining oysters are located from Delaware Bay south. Oysters form reefs in subtidal areas to depths of 10 m and intertidal areas (primarily south of Long Island), tolerating a wide range of temperatures and salinity levels. Spawning is temperature dependent, and larvae are planktonic. Larvae require hard substrate and prefer biogenic surfaces (e.g. shell bottom) for successful recruitment.

Hard Clam *(Mercenaria mercenaria)*

Hard clams, also known as quahogs or littlenecks, are widely-distributed in subtidal areas of the Northwest Atlantic. A commercially valued species, dense beds of hard clams create benthic habitat and contribute to improved water quality. The hard clam is found from the Gulf of St. Lawrence (Canada) to Texas, although they are most abundant from Massachusetts to Virginia. Hard clams aggregate in intertidal and subtidal areas to depths of 15 m, and typically occur in locations with salinity levels >19 ppt. Spawning is temperature dependent. Larvae are planktonic and settle in a variety of substrate types, including sand, sandy mud, and gravel.

Softshell Clam *(Mya arenaria)*

Softshell clams, also known as steamers, are a dominant filter-feeder in intertidal areas and mudflats of coastal embayments, from the Bay of Fundy to the mid-Atlantic coast, but are most abundant from New England to the Chesapeake Bay. An important commercial species, especially in New England, this species also stabilizes soft sediments and is capable of considerable water filtration. Softshell clams populate intertidal and subtidal areas to depths of 200 m, with preferred salinity levels > 20 ppt in northern areas and 4-15 ppt in southern areas. Spawning is temperature dependent. Larvae are planktonic and settle in a range of substrate types, including sand, sandy mud, mud, clay, and gravel, but not in cobble or rocky ledges.

Bay Scallops *(Argopecten irradians)*

Bay scallops, unlike deeper-water sea scallops, are primarily estuarine bivalves that congregate in subtidal low energy areas such as seagrass meadows. Bay scallops are historically an important commercial species, and existing populations help maintain water quality by filtering algae and phytoplankton. Distributed from New England to Texas, they are most abundant from Cape Cod (Massachusetts) to Virginia. The species occurs in low-energy, shallow subtidal areas to depths of 18 m. Bay scallops do not tolerate low annual salinity levels (< 10 ppt). Spawning is temperature dependent, and the planktonic larvae may attach to eelgrass shoots before settling to the bottom.

Blue Mussel *(Mytilus edulis)*

Blue mussels are found extensively in subtidal and intertidal areas throughout the Northwest Atlantic region, Europe, and other temperate waters. Beds are common from Labrador (Canada) to South Carolina, and typically found in littoral zones to depths of 100 m (maximum depth 500 m). Considered of lesser commercial value than other shellfish, mussels have become dominant shellfish species in northern regions, forming large reefs and filtering extensive reaches of coastal water bodies. Blue mussels are preyed upon by many aquatic species, especially waterfowl and macro-invertebrates. This species tolerates a wide range of salinity levels and temperatures. Spawning is temperature and food-dependent and may occur more than once a year. The planktonic larvae settle first on algae and seaweed before attaching to hard shell or rock substrates.

Ribbed Mussel *(Geukensia demissa)*

Ribbed mussels inhabit salt marshes throughout the region and oyster reefs in southern parts of the region. Where present, these mussels can form colonies as dense as 100 m^{-2} that provide sediment stabilization, water quality controls, and food sources for many crustacean and avian species. Ribbed mussels occur from the Gulf of St. Lawrence (Canada) to Texas. The species prefers intertidal areas of salt marsh and oyster reef habitat, and tolerates a wide range of salinity levels and temperatures. Spawning is temperature and food dependent. Larvae are planktonic and must attach to filamentous or reef-type structures.

Northwest Atlantic Distribution and Characterization

Methods

Overview

Previous terrestrially-focused ecoregional assessments by TNC delineated specific beach and dune systems and tidal wetlands of regional importance based on their size, natural condition, and presence of rare nesting birds, plants or exemplary terrestrial natural communities. Unlike these earlier efforts, this assessment is the first to focus on the coast from a marine perspective. To facilitate characterization of the entire coastline and potential values of various subsets of the coast for marine processes, the coast was divided into 62 discrete stretches of shoreline and nearshore habitat (Coastal Shoreline Units, hereafter CSUs). These were stratified by subregions (Gulf of Maine, Southern New England, and the Mid-Atlantic Bight), and by estuary type. Each unit in the United States portion fits into one of four Coastal Marine Ecological Classification Standard (CMECS) types (Madden et al. 2005) assigned by the Environmental Protection Agency (EPA) (Figure 2-7). The CMECS types of coastal areas are 1) river dominated, 2) lagoon, 3) coastal embayment, and 4) fjord. In addition, the relatively uniform Canadian coastline within this region was characterized as the Bay of Fundy type. The CSUs of the region sorted into the following categories:

- Lagoons (7 examples)
- Embayments (10 examples)
- River-dominated (20 examples)
- Fjords (18 examples)
- Bay of Fundy (7 examples)

Each discrete CSU delineates a segment of coast line typically encompassing a large estuary or a set of small interconnected estuaries or a barrier beach and lagoon system. Each was characterized by summarizing a variety of natural features that have presumed relevance to how the coastline contributes to marine productivity and biodiversity. These included:

- Amount of tidal marshes (both salt and brackish emergent marsh)
- Amount of eelgrass beds
- Types of shellfish beds
- Amount of beaches and dunes
- Amount of rocky shores and cliffs
- Number of salt ponds
- Diversity of natural shoreline habitats
- Importance to estuarine-dependent fish species
- Importance to diadromous fish species
- Importance to coastal breeding or wintering birds

In addition, the condition of each CSU was summarized with respect to the amount of development, man-made shoreline, and land use. It should be noted that the underlying data and methods for these characterizations could be applied to any geography, estuarine site classification, or state for purposes of comparison.

CMECS Classification

The CMECS classification focuses on the importance of estuary size, shape, and flushing in dictating processes within an estuary and the adjacent coastal area. The classification variables are considered to be “natural” characteristics of the estuary, in both material and energetic terms, meaning those which influence estuarine processing to varying degrees and are not generally controllable or influenced by either stressor or response variables. The types recognized in the CMECS classification are so distinct in geomorphology and hydrology that they not only look very different from each other, but also process nutrients in very different ways based on their exchange with the ocean, fresh water inflow, and residence time. Although other coastal and estuarine classifications exist in the region (Engle et al. 2007; Bricker et al. 2007), the CMECS classification brings together many local classifications via a standard format. The resultant classes provide useful descriptors for biological and response characteristics of the environment and are being used in the forthcoming EPA e-Estuary project which will provide a database and tools to support environmental decision-making for estuaries (Detenbeck 2008, personal communication).

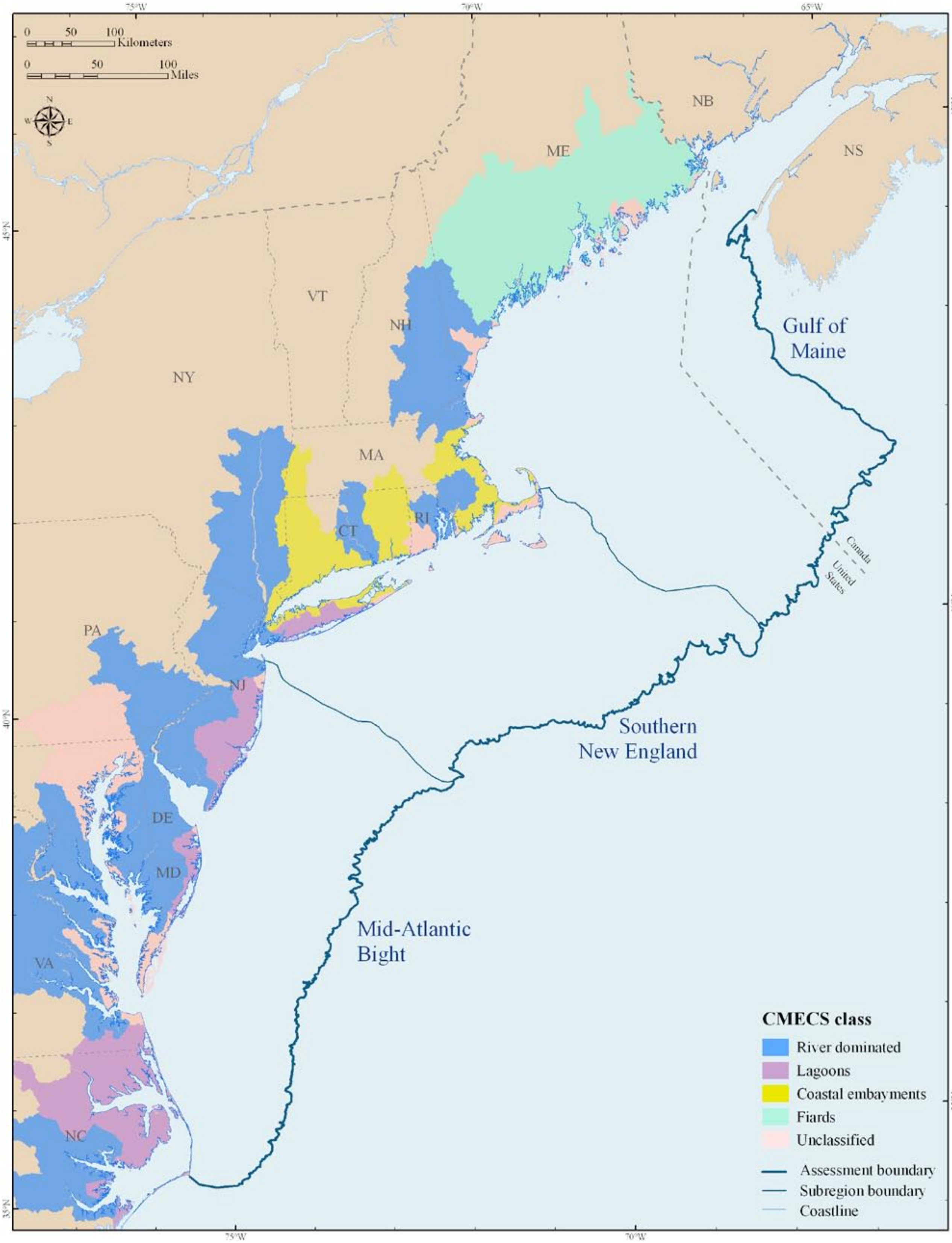

Figure 2-7. Coastal Marine Ecological Classification Standard (CMECS) types (Madden et al. 2005) as assigned by the EPA.

River Dominated areas include river channels, drowned river valleys, deltaic estuaries, salt wedge estuaries, and tidal fresh marshes. This class of estuary tends to be linear and seasonally turbid, especially in upper reaches, and can be subjected to high current speeds. These estuaries are sedimentary and depositional, and can be associated with a delta, bar, or barrier island and other depositional features. These estuaries also tend to be highly flushed, with a wide and variable salinity range, and seasonally stratified. They have moderate surface to volume ratios, high watershed to water area ratios, and can have very high wetland to water area ratios as well. These estuaries are often characterized by a V-shaped channel configuration and a salt wedge.

Coastal lagoon areas include lagoons, sloughs, barrier island estuaries, bar-built estuaries, and tidal inlets. This class of estuary tends to be shallow and highly enclosed, with reduced exchange with the ocean. They often experience high evaporation, and are quiescent in terms of wind, current, and wave energy. They tend to have a very high surface to volume ratio, low to moderate watershed to water area ratios, and can have a high wetland to water ratio. Note that the length of the outer barrier beaches that form the lagoons was included in the CSU characterizations below.

Coastal embayments include bays, sounds, and coastal bights. This class of estuary is loosely bounded by landforms, open to marine exchange, and has moderate to high salinities. They are well-flushed, often deep, and subject to potentially high energy input from tides, winds, waves and currents. These estuaries can range from very low to very high in terms of surface area to volume, watershed to water area, and wetland to water ratio.

Fjords, glacially carved embayments that are drowned by the sea, are deep, seasonally cold-water estuaries with low to moderate riverine inputs found at mid to high latitudes. This class of estuary has relatively complex, usually rocky shorelines and bottoms and is partially enclosed, sometimes by mountainous landforms. The waters of fjords are typically stratified, often due to a geologic sill formation at the seaward end formed by glacial action. However, the fjords of the Gulf of Maine (sometimes referred to as "fjards" – see Pettigrew et al. 1997) lack the topographic and benthic constrictions of true fjords and are generally well mixed.

Delineating CSU Boundaries

Four project sub-teams made CSU delineations based upon continuity of processes and natural breaks. The team collectively reviewed and approved a final set of 62 delineations, shown in Figure 2-8.

To the extent possible, areas were delineated at oceanographic discontinuities such as large-scale oceanic currents. Estuarine circulation models and tidal maps of discontinuities (i.e. where currents move in opposite directions) were consulted. These delineations were then compared with information on the biogeography of marine invertebrates (Wigley and Theroux 1981). The sub-teams attempted to avoid crossing over watersheds and consolidating areas with very different freshwater inputs. In Maine, focus area boundaries already delineated by Maine's Beginning with Habitat program were considered (BwH 2009). Generally, islands along the Maine coast were included in their most immediate nearby CSU. Riverine CSUs were separated for midsize to large tributaries by intuitive natural features. In general, strings of barrier island lagoons are presented as single CSUs. Unit boundaries were sometimes extended beyond a particular feature or estuarine unit so that the coast would be divided into a contiguous string of CSUs. (For some parts of the region where this delineation resulted in relatively large units, subunits were also delineated based on coastal ecology and locally accepted delineations for planning and management purposes.)

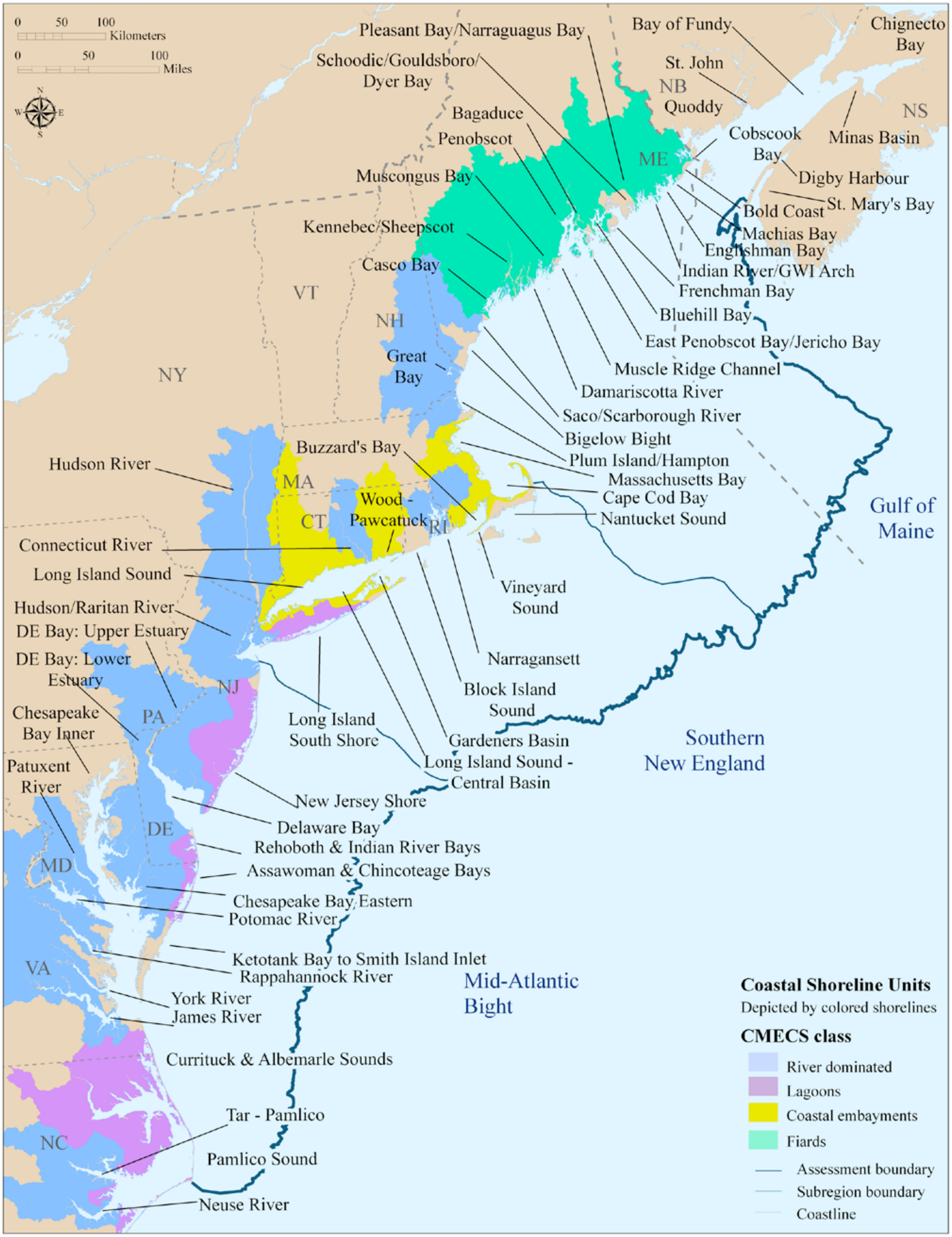

Figure 2-8. Coastal Shoreline Units (CSUs) delineations based upon continuity of processes and natural breaks.

Characterizing Coastal Shoreline Units

Each CSU was characterized with respect to size, habitat diversity, and condition in order to identify patterns by subregion and by CMECS type.

Size

Size is an important CSU parameter because many other variables are likely to correlate with it. Size of each CSU was characterized by shoreline length and hectares of intertidal habitat. In general, the lagoon and river types are much larger than the embayment or fjord CSU types, with an average shoreline length of 2,791 and 1,798 km respectively versus 690 and 483. Similarly, the average intertidal habitat area of lagoons is 10 times that of embayments. This is why subdivisions of many lagoons and rivers into tier 2 subunits were deemed helpful. However, there is a large range in size within all four classes. In particular, riverine CSUs range from 7,163 km for the eastern Chesapeake Bay CSU to only 237 km for the Saco River/Scarborough CSU in Maine. There is corresponding regional variation in size of CSUs. In general, the highly indented Gulf of Maine coast is characterized by fjords, on average the smallest of the four types, so the CSUs of the Gulf of Maine are on average one fifth the size of those of the Mid-Atlantic.

Habitat Diversity

Habitat diversity of CSUs was characterized in several ways. First, the length of each CSU shoreline was calculated by major habitat type, as per the ESI. The ESI classifies the coastline into 22 categories, which was consolidated into the following eight categories for simplification of interpretation: 1) beach, 2) flat, 3) marsh, 4) swamp, 5) rocky shore/cliff/platform, 6) non-rocky bluff/steep/platform, 7) manmade, and 8) undefined.

Second, the amount of six intertidal habitat classes was calculated (in hectares) for each CSU. Intertidal habitat types were mapped by extracting intertidal coded polygons from the NWI (US DOI FWS 2008) in the United States and by extracting coastal ecosystem polygons from the Northern Appalachian Ecoregional Planning coastal target polygon dataset (Anderson et al. 2006a) in Canada. The polygons were placed into the following six intertidal habitat categories 1) unconsolidated shore (sand, gravel, cobble), 2) unconsolidated shore (mud, organic, flat), 3) emergent marsh, 4) forested wetland, 5) rocky shore, and 6) scrub-shrub wetland.

The quantification of emergent marsh or vegetated tidal wetlands in the analyses presented here is different than the quantification of "tidal wetlands" in the North Atlantic Coast Ecoregional Assessment (Anderson et al. 2006b). Unlike the 2006 coastal assessment, which lumped unvegetated tidal wetlands and some submerged lands into tidal wetland complexes, this assessment separated out vegetated tidal wetlands (e.g., salt marsh, tidal marsh or emergent marsh) from unvegetated wetlands. The rationale for this difference in approach is the desire to distinguish "wetland loss" and "wetland conversion" as threats to these estuarine systems. With the exception of vegetated tidal wetlands that get filled and or armored, "wetland loss" attributable to other causes is often first evidenced by the loss of emergent vegetation and then submergence of land.

Third, the amount of seagrass was calculated and the number of coastal salt ponds was counted within each CSU. Unlike the NWI and ESI datasets, seagrass coverage was determined by combining many different datasets from federal, state and local data sources. These sources include Maine Department of Marine Resources, New Hampshire Department of Environmental Services, Massachusetts Department of Environmental Protection, Rhode Island Narragansett Bay Estuary Program, USFWS (for Connecticut), New York Sea Grant (for the Hudson River), Peconic Estuary Program, (for Peconic Bays, New York), NOAA Coastal Services (for Long Island's south shore estuaries), Rutgers Center for Remote Sensing and Spatial Analysis (for New Jersey), ESI (for Delaware), Virginia Institute of Marine Science (for Chesapeake Bay and the Eastern Shore of Virginia), and TNC's Carolinian Ecoregional Plan (for North Carolina). Data collection methods for seagrass coverage tend to vary by locality, as did year of data collection (1968 – 2008). For consistency at the regional scale, seagrass meadows are shown as presence or absence only, although in some geographies more fine scale delineations (such as continuous/discontinuous; thick, medium, or thin; or root or above ground biomass/unit area) are available and these attributes are preserved in the dataset. Some states have only one year of data, while others have several, collected in subsequent or consecutive years. Consequently, two different seagrass datasets were compiled: total historical seagrass coverage and the most recent available year of data. For this report, seagrass presence in the most recent year of data is presented, outlined by a 2-point line for graphical display. Coastal salt pond data was summarized from 2008 Natural Heritage Program Element Occurrences.

Finally, the diversity of benthic habitats was characterized, by depth, grain size, and seabed form, offshore to 1,000 m (see Chapter 3 for further information). Unfortunately, data were lacking for several of these parameters for the Canadian portion of the region, so the Fundy CSUs were not characterized for these attributes. The variables and the attribution method are briefly presented in a summary table (Table 2-2).

Assessment of CSU Condition

Indicators of both shoreline condition and water quality were examined within the estuaries for which there were consistent coast-wide data. For shoreline condition, the proportion of man-made vs. natural shoreline within each CSU was calculated, derived from the ESI. The number of man-made structures per unit of shoreline was determined to be another appropriate indicator, but found that the relevant NOAA dataset was inconsistent with respect to date and sometimes incomplete.

Nearshore land use is a relevant potential indicator of both shoreline condition and water quality. The amount of developed land in the nearshore zone was calculated for two areas: the area adjacent to the shoreline that was lower than 2 m elevation and for the area within 300 m horizontal distance of the shoreline. These two measures generally track each other but the former can be particularly helpful when considering potential impacts of sea level rise. Finally, the amount of developed and agricultural land and impervious surface was calculated within each CSU watershed. These watersheds do not exactly coincide with those used by NOAA in their Estuarine Eutrophication Assessments. Maps for the latter are provided for comparison and in many cases corroboration. The condition variables are briefly presented in Table 2-3.

Characterizing Nearshore Shellfish Assemblages

Despite the commercial importance of these target species (except ribbed mussel), reports of population distribution, abundance, and health status are not available consistently region-wide. To address questions of distribution and abundance, two metrics were examined for nearshore shellfish assemblages. Presence/absence of each species (where data were available) was documented for each bay to examine distribution. As a proxy for population status, NOAA's National Marine Fisheries monthly commercial landings statistics was analyzed.

Distribution

The primary source for distribution data was the 1995 National Shellfish Register of Classified Shellfish Growing Waters (NOAA 1997). The 1995 Register is the most recent, and only regional, dataset for shellfish distribution and abundance in the Northwest Atlantic. Other state and local shellfish datasets were identified, but a lack of consistent standards, spatial coverage, and availability rendered these sources unusable for this assessment. In developing the 1995 Register, NOAA worked with state shellfish resource managers to identify nearshore shellfish waterbody areas, resulting in a catalogue of about 2,900 discrete areas from Maine to North Carolina. State managers were asked to rank each waterbody, known as Classified Shellfish Areas (CSA), for the relative abundance of each shellfish species compared with all other state waterbodies.

The CSA database was found to contain many entries coded as "Not Reported," for non-managed shellfish species like blue mussel and ribbed mussel. Mussel abundance was reported for less than 1% of areas across the region.

Table 2-2. Attribute Variables for Coastal Shoreline Units (CSU).

Category	Data Source	Measure	Subtypes	Brief Method
Shoreline length by major habitat type	NOAA Environmental Sensitivity Index, 2001-2004. Scale 1:24,000 (US); Provincial Coastline Scale 1:24,000 (New Brunswick), 1:100,000 (Nova Scotia)	kilometers	beach	Each shoreline segment was assigned to a CSU to yield a total length for each CSU. For those CSUs in the US, the segment lengths were then summarized by the ESI subtype categories. For those CSUs in Canada, the only subtypes included were man-made and undefined.
Intertidal habitat area	USFWS National Wetlands Inventory, 1970-2008. Scale 1:100,000 (US) Provincial Wetland Datasets (New Brunswick and Nova Scotia), 2000. Scale 1:20,000-1:50,000.	hectares	unconsolidated shore (sand, gravel, cobble)	Each polygon was assigned to a given CSU based on nearest proximity. The total area of each of the habitat subtypes was then summed for each CSU.
			unconsolidated shore (mud, organic, flat)	
			emergent marsh (vegetated tidal wetlands)	
			forested	
			rocky shore	
			scrub-shrub	
Other Coastal Habitats	Various Seagrass Datasets, 1968 – 2008. Scale = < 1:24,000	hectares	seagrass	Each polygon was assigned to a given CSU based on nearest proximity. The total area of each in seagrass was then summed for each CSU.
	State Natural Heritage Program Element Occurrences 2008	number	coastal salt ponds	Each point was assigned to a given CSU based on nearest proximity. The total number of coastal salt ponds was then summed for each CSU.
Offshore 1000 m Buffer Benthic Habitat Diversity	TNC Ecological Marine Units (grain size, seabed form, depth) 2009	% of the 1000 m buffer zone	*Depth Zones*	Each CSU shoreline was buffered 1,000 m horizontally seaward. The Ecological Marine Units types and depth zones within the buffer were summarized for each CSU.
			0 to -1 m	
			-2 to -3 m	
			-4 to -10 m	
			-11 to -30 m	
			-31 to -100 m	
			-100 m and deeper	
			Grain Size	
			clay or silt	
			very fine sand	
			fine sand fine sand	
			% grain size medium sand	
			coarse sand	
			pebbles	
			Seabed Forms	
			Depression	
			Mid Flat	
			High Flat	
			Low Slope	
			High Slope	
			Steep/Sideslope	

Table 2-3. Condition variables for Coastal Shoreline Units (CSU).

Category	Data Source	Measure	Subtypes	Brief Method
Man-made shoreline	NNOAA Environmental Sensitivity Index, 2001-2004. Scale 1:24,000 (for US); Provincial Coastline Scale 1:24,000 (for New Brunswick), 1:100,000 (for Nova Scotia); US land cover: EPA National Land Cover Dataset, 2001; New Brunswick and Nova Scotia: DNRE. Generalized 1:10,000 forest stand data c. 1990s	% of total CSU length	beach	For the non-Maine part of the US coast, the length of "man-made" was summarized for each CSU based on source NOAA ESI line type coding. Special processing was done to assign a "man-made" class in Maine and Canada, where no man-made shoreline types had been assigned by NOAA or other sources. The processing method included overlapping the developed land cover cells with the shorelines to identify sections of the shoreline that were adjacent to developed lands, and thus likely "man-made" shorelines.
	United States land cover: EPA National Land Cover Dataset, 2001; EPA Impervious Surface Dataset, 2001	% of total land area in whole upstream watershed	% developed (residential, commercial, transportation, and quarries)	The full upstream watershed for each CSU was delineated using Basin Delineator Tool distributed with the USGS National Hydrography Plus dataset. Inputs to the tool for each CSU included all reaches with their outflow within 100 m of the CSU shoreline. The land cover types within the delineated full watershed were then summarized for each CSU.
			% agriculture (row crops and pasture)	
			% natural (including barren)	
			% impervious surface	
Eutrophication (for US only)	NOAA National Estuarine Eutrophication Assessment, 1999, 2004 update	Reporting of NOAA metrics in the primary and secondary Ecological Drainage Unit associated with each CSU	NOAA NEEA 1999 overall eutrophication	The NOAA NEEA dataset was provided at the Estuarine Drainage Area (EDA) watershed unit scale. These EDA units did not overlap one to one with our CSUs. To summarize the NEEA data by CSU, we joined each CSU component arc to the nearest EDA. The percent of the total CSU shoreline length occurring in each EDA was then calculated. The four eutrophication subtype metrics of interest were reported for the primary EDA with which each CSU was associated. For CSUs crossing more than one EDU, the four eutrophication subtype metrics of interest were also reported for the secondary EDA with which each CSU was associated.
			NOAA NEEA 1999 influencing factor on eutrophication (human influence)	
			NOAA NEEA 1999 projected changes in eutrophic conditions through 2020 based on projected population growth and susceptibility	
			NOAA NEEA 2004 update to overall eutrophication	

Lacking other spatial data sources for these species, mussels could therefore not be included in ecoregional abundance mapping.

For managed species, more than 50% of areas in the region included data for populations of Eastern oyster, hard clam, softshell clam, and bay scallop. For these species, most of the "Not Reported" areas appeared to be in states without substantial natural populations remaining. For example, oysters were under-reported in most of Maine and New Jersey; hard clams were under-reported in Maine and south of Virginia; and softshell clams and bay scallops were not reported south of New Jersey. In addition to species absence, some under-reporting was likely due to inconsistencies among states. NOAA noted that "data quality was directly related to the resources available to conduct shellfish management responsibilities." However, state managers did provide "final verification of the data content" (NOAA 1997). With a greater than 50% overall reporting rate, very good coverage of state-managed shellfish beds, and few other reporting options, the CSA database was determined to be a reasonable and adequate source for regional shellfish reporting.

In developing a map of target shellfish distribution and abundance, CSA entries with ranked abundances for the four target species under state management (oyster, hard clam, softshell clam, and bay scallop) were used. Abundance ranks could not be compared across states and further do not provide any historical context for shellfish distribution and abundance. Therefore, ranks of "High," "Medium," and "Low Abundance" for each shellfish species were converted to present and ranks of "None" or "Not Reported" to absent. In addition, each area was assigned a number from 0 to 4 depending on the number of reported target species present there in order to identify those areas of particular importance for protection of shellfish assemblages.

Population Status

As a proxy for population status, National Marine Fisheries Service (NMFS) monthly commercial landings data were analyzed for mollusk species (NOAA 2008). Eastern oyster, hard clam, softshell clam, and bay scallop landings data were queried for each state for the entire reporting period of the database (1950 to 2007). Data are from continuous records collected by joint state and federal agencies, and reported as metric tons (wet weight).

To understand the changes in historical landings for each state and species, time series of annual landings were analyzed for 1) maximum annual harvest in the series, 2) year of the maximum harvest, 3) total number of years reported (out of 58 possible reporting years from 1950 to 2007), 4) mean value for the last three years reported in the time series, and 5) last three-year average as a percentage of the maximum annual harvest. New Hampshire, as the only assessment state without commercial shellfish landings, was not included in the NMFS database. For New Hampshire, a time series of annual estimates of standing stock was analyzed for Eastern oyster and softshell clam, as surveyed by the New Hampshire Department of Fish and Game (NHEP 2006). Results are presented in Table 2-4.

Several important caveats apply to this use of commercial landings data as a proxy for abundance. First, data are not normalized for fishing effort. Peak harvest benchmarks may reflect levels of unsustainable pressure. Further, it is possible to have a sustainable fishery even if current harvest levels are very low compared to historic benchmarks. Natural variability in year-to-year recruitment can also produce wide swings in standing stock and harvest opportunity. Finally, NMFS mollusk datasets include aquaculture landings (totals not available separately) that contribute to recent landings totals and may mean that the results presented here overestimate natural bed conditions. For the four target species, maps were developed to show the last 3-yr average landings as a percent of maximum harvest by 0 - 10%, 11 - 50%, and 51 - 100% levels for each state (Figure 2-9, 2-10, 2-11, and 2-12).

Table 2-4. Monthly Commercial Landings Summary as reported by NOAA National Marine Fisheries Service (1950-2007). http://www.st.nmfs.noaa.gov/st1/commercial/landings/monthly_landings.html Note: New Hampshire values are estimated standing stock from field surveys (NHEP 2006) converted from bushels to metric tons (wet weight).

	ME	NH	MA	RI	CT	NY	NJ	DE	MD	VA	NC
Eastern Oyster											
Maximum harvest (metric tons)	158.7	2057.4*	134.1	418.3	3740.8	3985.7	3284.9	1968.6	9263.4	11568.4	735.2
Year of maximum	1990	1993	1980	1950	1993	1950	1950	1954	1973	1958	1952
Number years reported	35	12	49	46	57	58	55	48	58	57	58
Last 3 yr reported mean (metric tons)	19.8	99.9*	67.5	34.7	87	92.5	144.6	35.6	192.2	41	191.6
Last 3 yr mean (as % of maximum)	12%	5%	50%	8%	2%	2%	4%	2%	2%	0%	26%
Hard Clam											
Maximum harvest (metric tons)	258.1		985.7	2277	2330.3	3877.8	2306.4	366.6	360.4	1128.2	699.3
Year of maximum	1951		1951	1955	2004	1971	1950	1950	1969	1965	1980
Number years reported	51		49	57	56	57	46	56	39	47	58
Last 3 yr reported mean (metric tons)	1.8		197.1	361.3	1699	697.2	830.3	27.6	8.8	107.7	190.6
Last 3 yr mean (as % of maximum)	1%		20%	16%	73%	18%	36%	8%	2%	10%	27%
Softshell Clam											
Maximum harvest (metric tons)	3553.9	437.4*	932.3	227.1	1.7	178.3	204.1		3703.3	180.6	
Year of maximum	1977	1997	1982	1950	1950	2006	1950		1964	1966	
Number years reported	46	38	48	58	18	57	40		53	12	
Last 3 yr reported mean (metric tons)	840.5	57.4*	434.4	89.1	0.1	130.2	12.5		54.4	65.3	
Last 3 yr mean (as % of maximum)	24%	13%	47%	39%	6%	73%	6%		1%	36%	
Bay Scallop											
Maximum harvest (metric tons)			929.9	203.5	190.6	448.1	170.7				289.7
Year of maximum			1971	1978	1953	1962	1964				1968
Number years reported			41	29	17	58	15				54
Last 3 yr reported mean (metric tons)			53.3	1.3	5.5	3.5	11.7				5.4
Last 3 yr mean (as % of maximum)			6%	1%	3%	1%	7%				2%

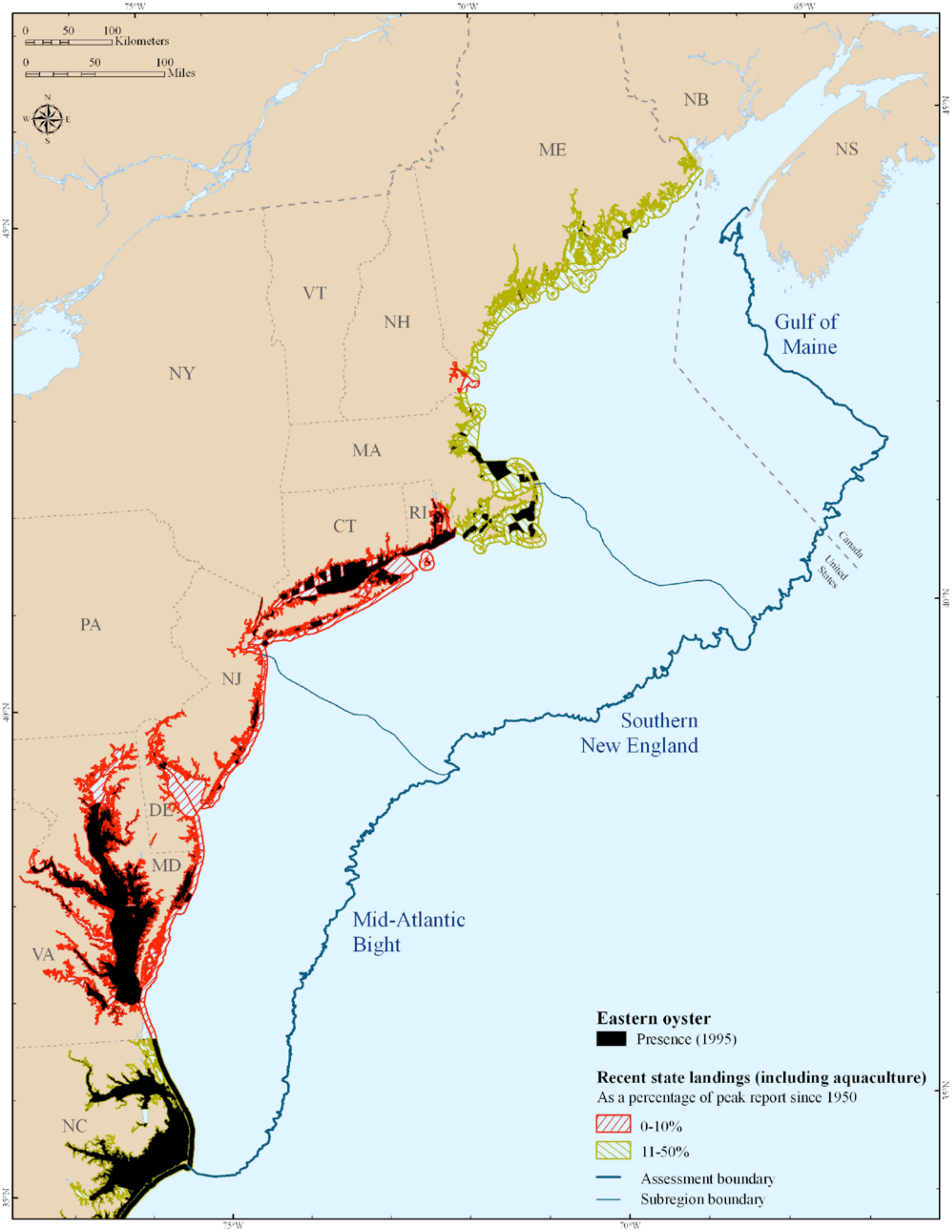

Figure 2-9. Most recent 3-yr average of Eastern oyster landings, represented as a percent of maximum harvest by 0-10%, 11-50%, and 51-100% levels for each state.

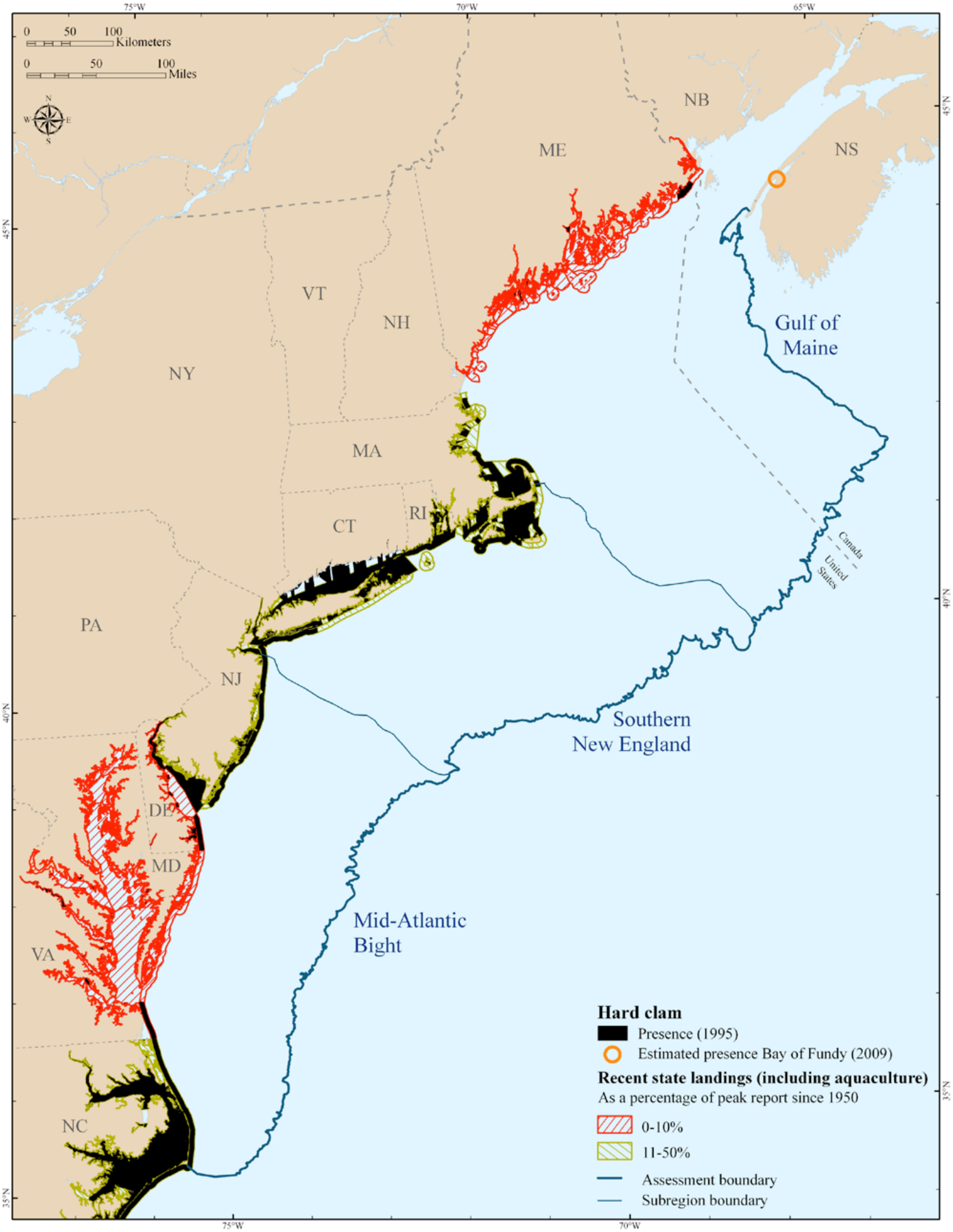

Figure 2-10. Most recent 3-yr average of hard clam landings, represented as a percent of maximum harvest by 0-10%, 11-50%, and 51-100% levels for each state.

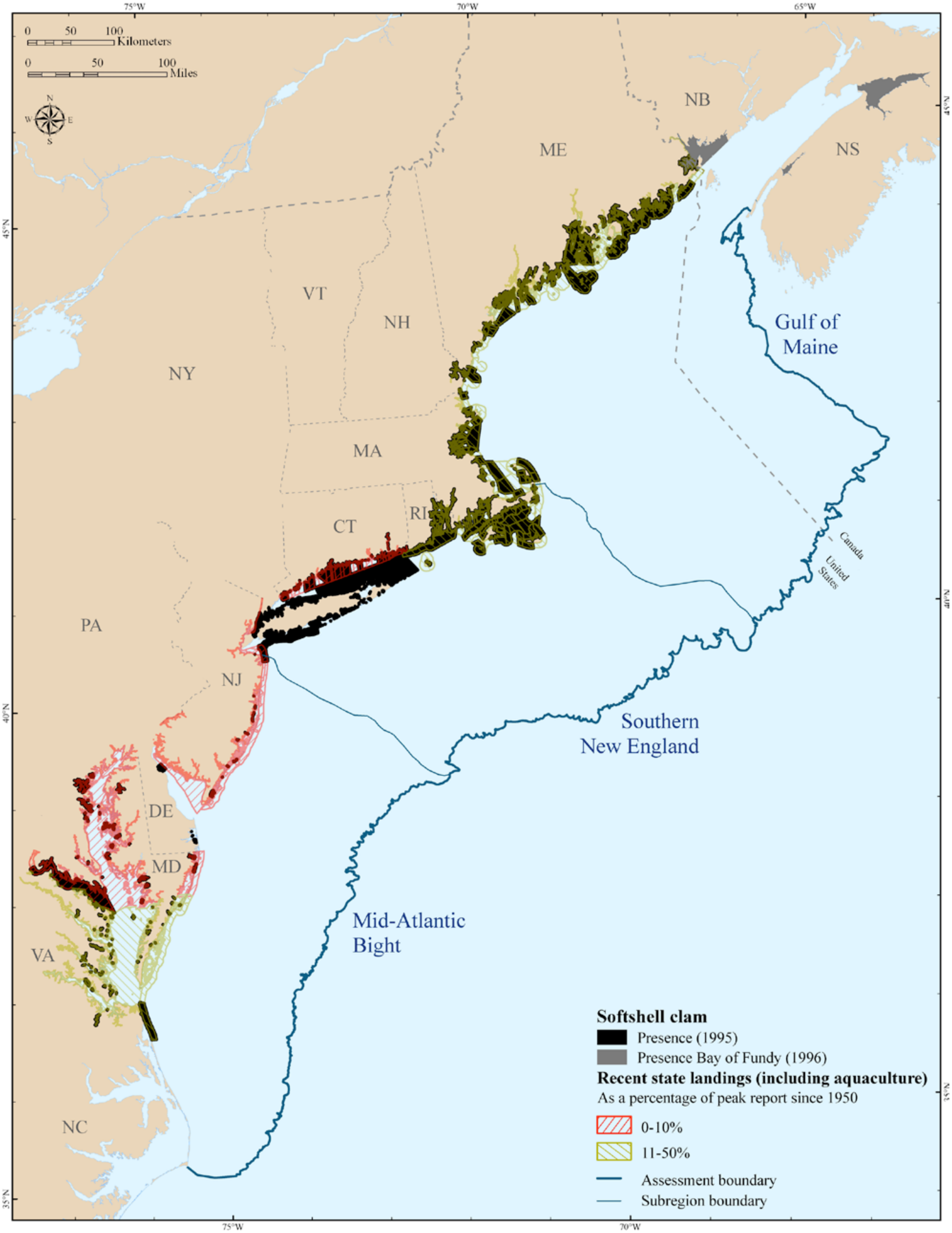

Figure 2-11. Most recent 3-yr average of soft shell clam landings, represented as a percent of maximum harvest by 0-10%, 11-50%, and 51-100% levels for each state.

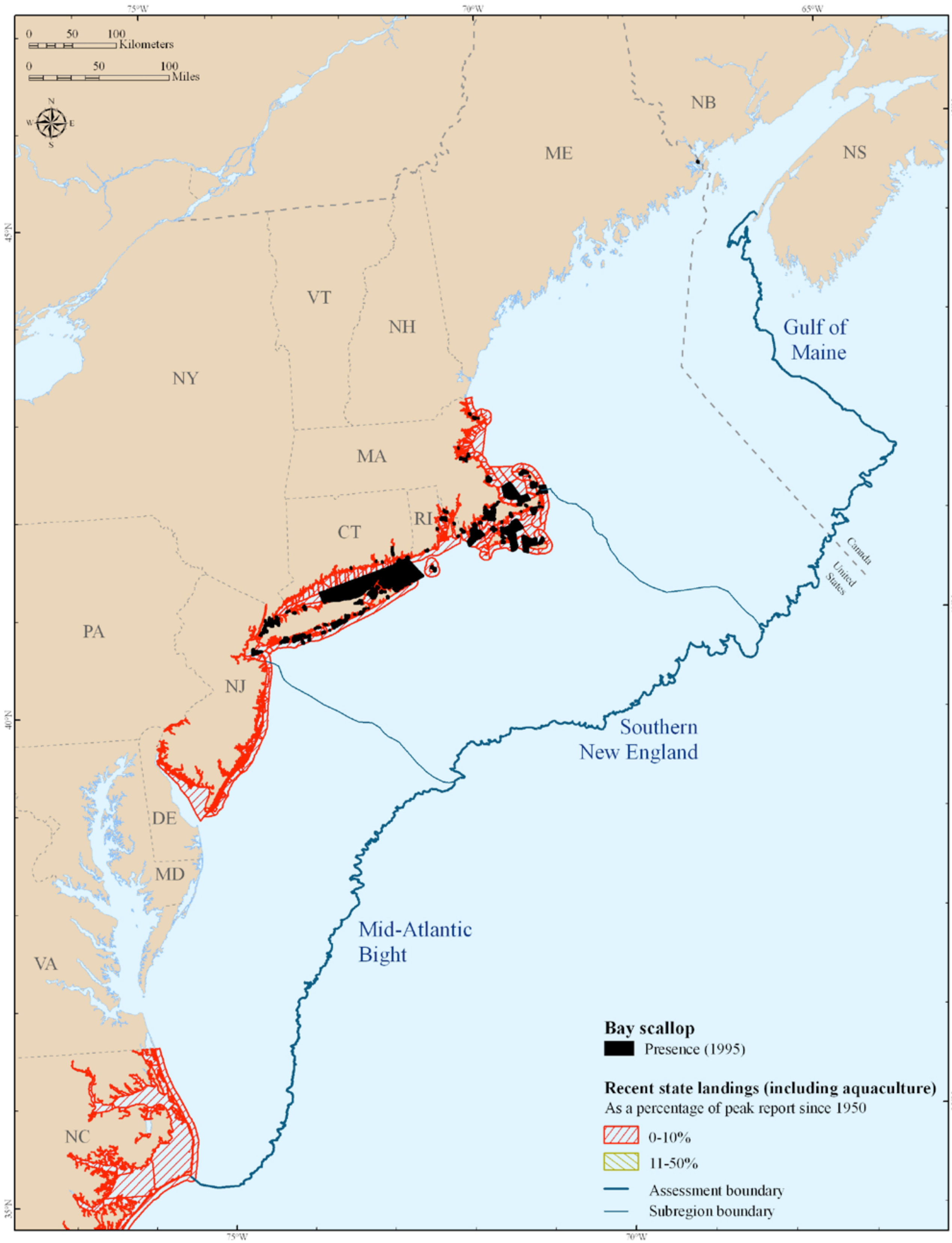

Figure 2-12. Most recent 3-yr average of bay scallop landings, represented as a percent of maximum harvest by 0-10%, 11-50%, and 51-100% levels for each state.

Data, Analysis, and Areas of Importance

Shoreline Habitat Diversity

The shoreline habitats and intertidal NWI type characterization corroborated stratification by CMECS class. For example, rocky shorelines are essentially non-existent in the lagoon and riverine types, but prominent in fjord types. Swamp shorelines are only a small percentage of any CSU shoreline, but do not occur at all in fjord or Fundy CSUs. Marshes make up the highest percentage of shoreline habitats in lagoons and riverine CSUs. Beach and flat shorelines are found in the highest percentages in embayments and fjord CSUs. However unconsolidated intertidal habitats of mud make up more than 50% of intertidal habitats in most fjords while unconsolidated shores of sand, gravel, and cobble make up over 50% of intertidal habitats in most embayments. Although these differences between CMECS classes were evident, significant differences among CSUs of the same CMECS class were also observed. For example, some embayment CSUs have > 50% beach shorelines, while others have only 10% - 15% beach shorelines. Differences were also observed among subregions (Gulf of Maine, Southern New England, and Mid-Atlantic Bight). Although the 8,000 km of beach shoreline in the region were surprisingly evenly distributed across the three subregions, beaches of fjords are most often small pocket or cove beaches whereas those of the lagoon and embayment areas are often very long, nearly continuous barrier beaches. Salt marshes are also found to occur in all subregions and CMECS estuarine types. As a percent of shoreline length, there are not such marked differences within CMECS types or subregions. However, in areal extent they make up over 70% of intertidal habitat in most lagoons and riverine types and < 35% in other groups. The total area of salt marshes in lagoon types of the Mid-Atlantic Bight is orders of magnitude greater than in the rest of the region, especially Gulf of Maine fjords (Figure 2-13, 2-14, and 2-15).

Seagrass beds occur along the entire Atlantic coast (Figure 2-16). Based on the most recent data available from each state, the largest seagrass bed coverage occurs in the Pamlico Sound CSU (36,429 hectares), although other CSUs have significant amounts of seagrass habitat (e.g., Casco Bay, 3,331 hectares; Nantucket Sound, 6,462 hectares; Long Island South Shore, 9,861 hectares; Chesapeake Bay Eastern, 24,838 hectares). By CMECS type, the vast majority of seagrass in the region occurs within CSUs of the lagoon (63,459 hectares) and riverine types (44,087 hectares). However, there is substantial variation within each CMECS class. For example, Chesapeake Bay Inner has 9,710 hectares of seagrass, whereas several other CSUs of the riverine type have only several hundred hectares. The regional seagrass dataset includes historical time series snapshots of eelgrass coverage and presents a new opportunity to evaluate loss and identify spatially explicit restoration priorities. Areas mapped as coastal salt ponds only occur in the embayment type. Among the 10 CSUs of this type, five had no coastal salt ponds and others had as many as six or eight.

Not surprisingly, these differences in characteristic habitat extend to the immediate offshore zone. At the scale of individual CSUs, calculating the percent of various benthic classes within the 1,000 m zone would not be accurate enough to fairly compare one CSU to another. However, when combined into CMECS classes, the average percentages do seem meaningful. The benthic zone just offshore from fjords includes significant areas deeper than 31 m and is characterized by steep canyon seabed forms, largely absent from the offshore zones of other CSUs. In contrast, benthic zones immediately offshore of lagoons and riverine CSUs have extensive areas within the seagrass growing depth zone of 1 to 3 m. The benthic zones offshore of lagoons are characterized by clays, silt, and fine sands and have zero mapped areas of pebble or cobble, which are abundant in the nearshore of the Gulf of Maine.

Abundance and variety of stream habitats feeding the CSUs, particularly relevant for diadromous fish, were not included because of the challenges of identifying comparable metrics across the region. Diadromous fish habitat use and distribution is addressed in a separate chapter.

Note: Further characterizations of spatial complexity, sinuosity, and functional connectivity among habitats could

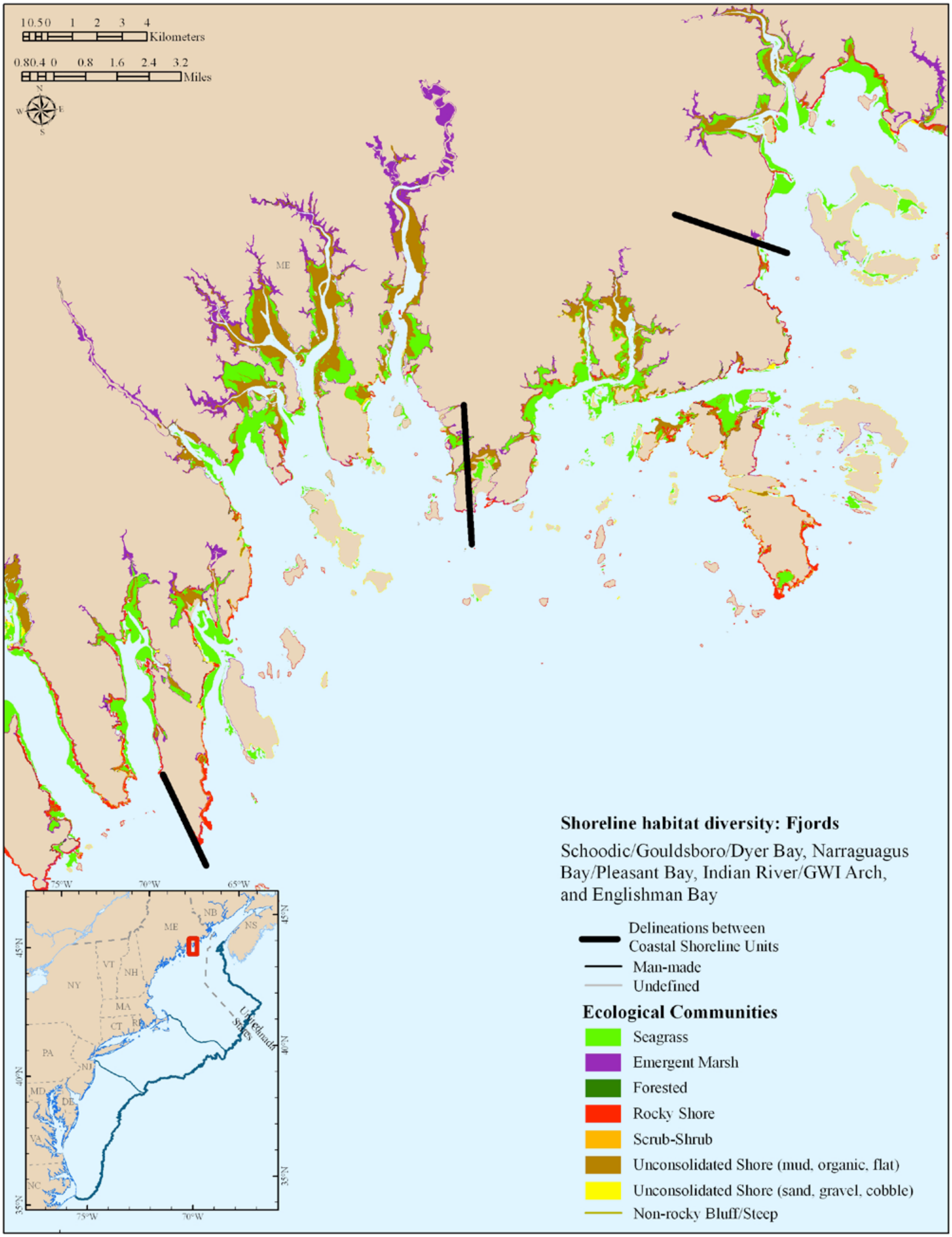

Figure 2-13. A fjord example of shoreline habitat diversity.

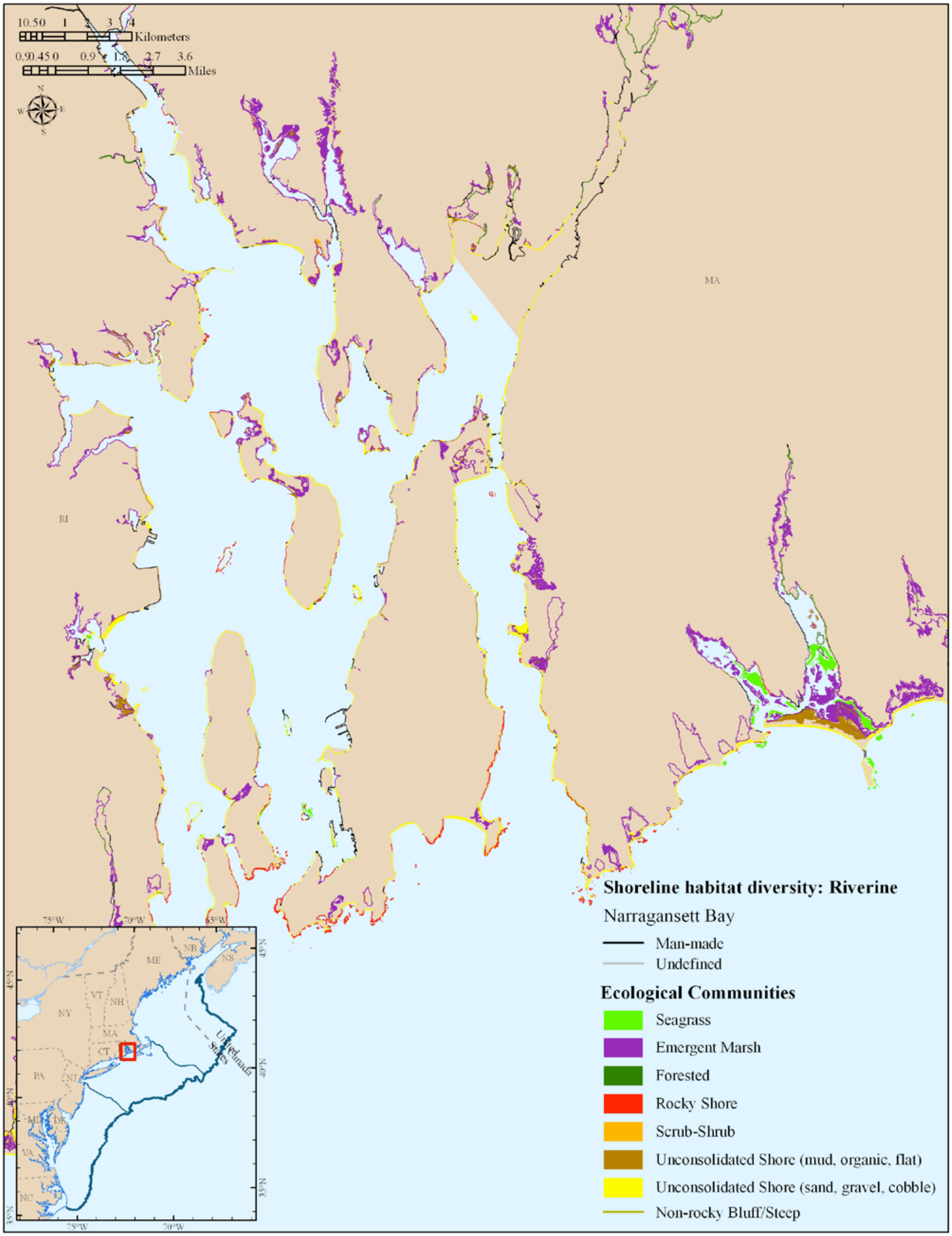

Figure 2-14. A riverine example of shoreline habitat diversity.

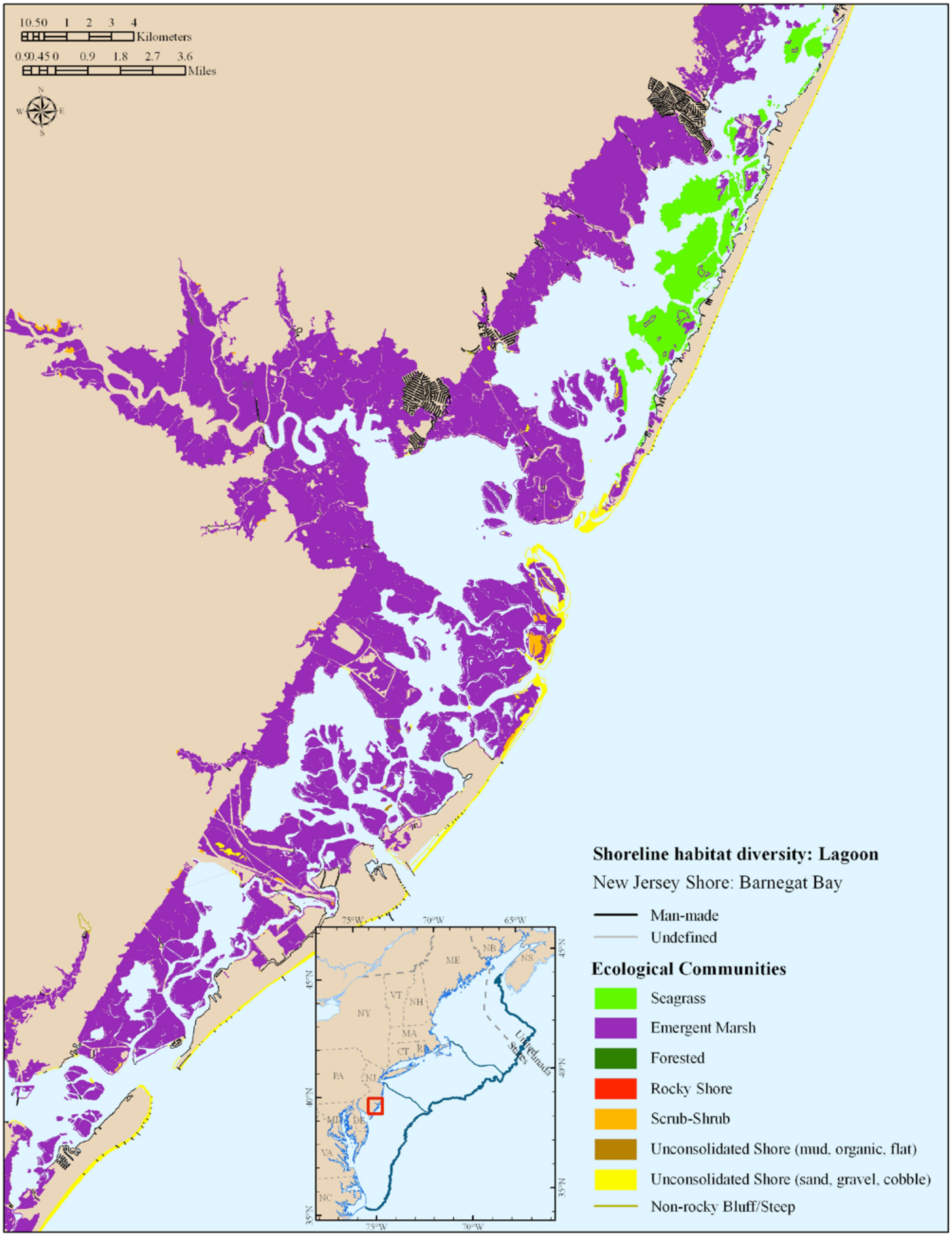

Figure 2-15. A lagoon example of shoreline habitat diversity.

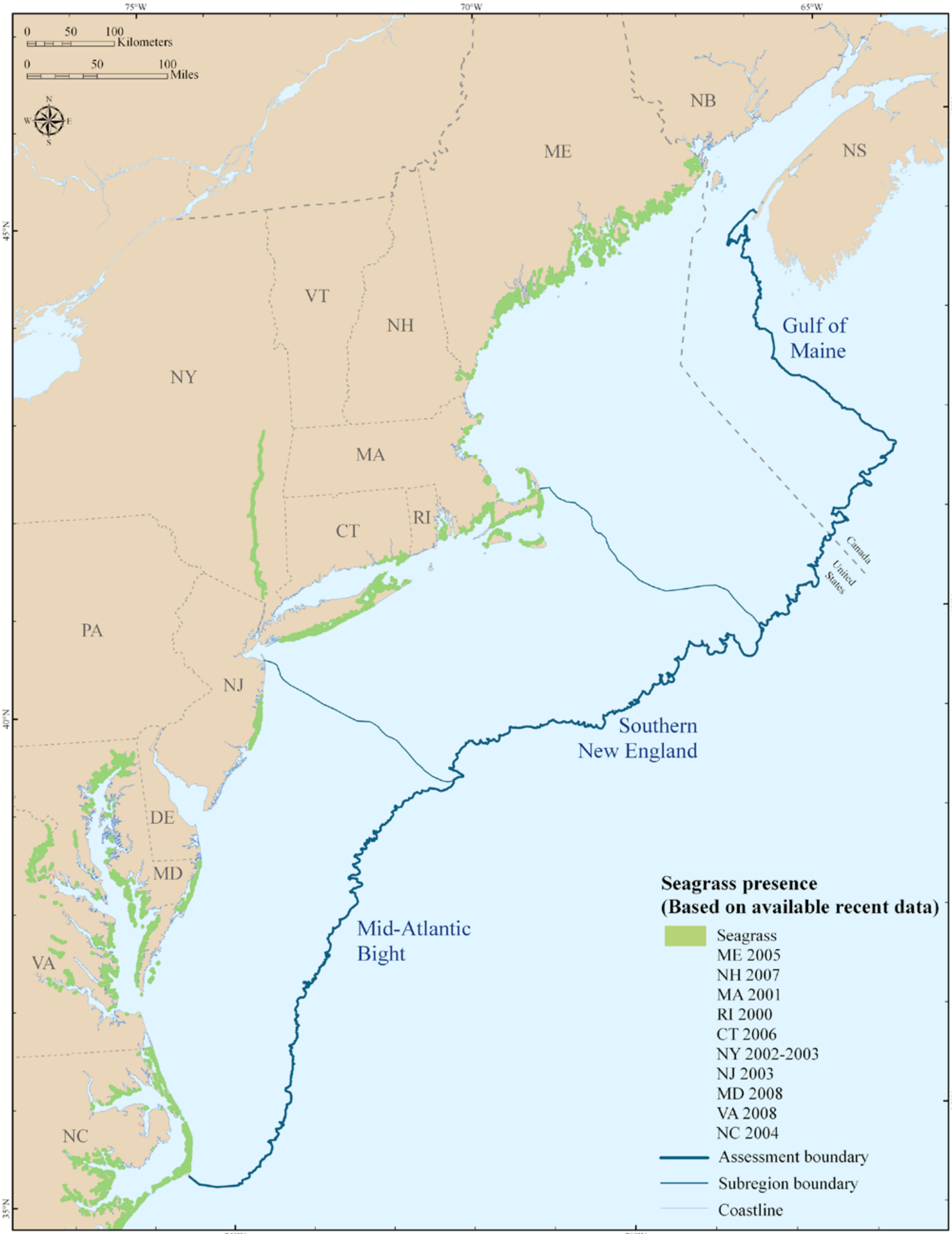

Figure 2-16. Seagrass presence (most recent year of data) in the Northwest Atlantic region.

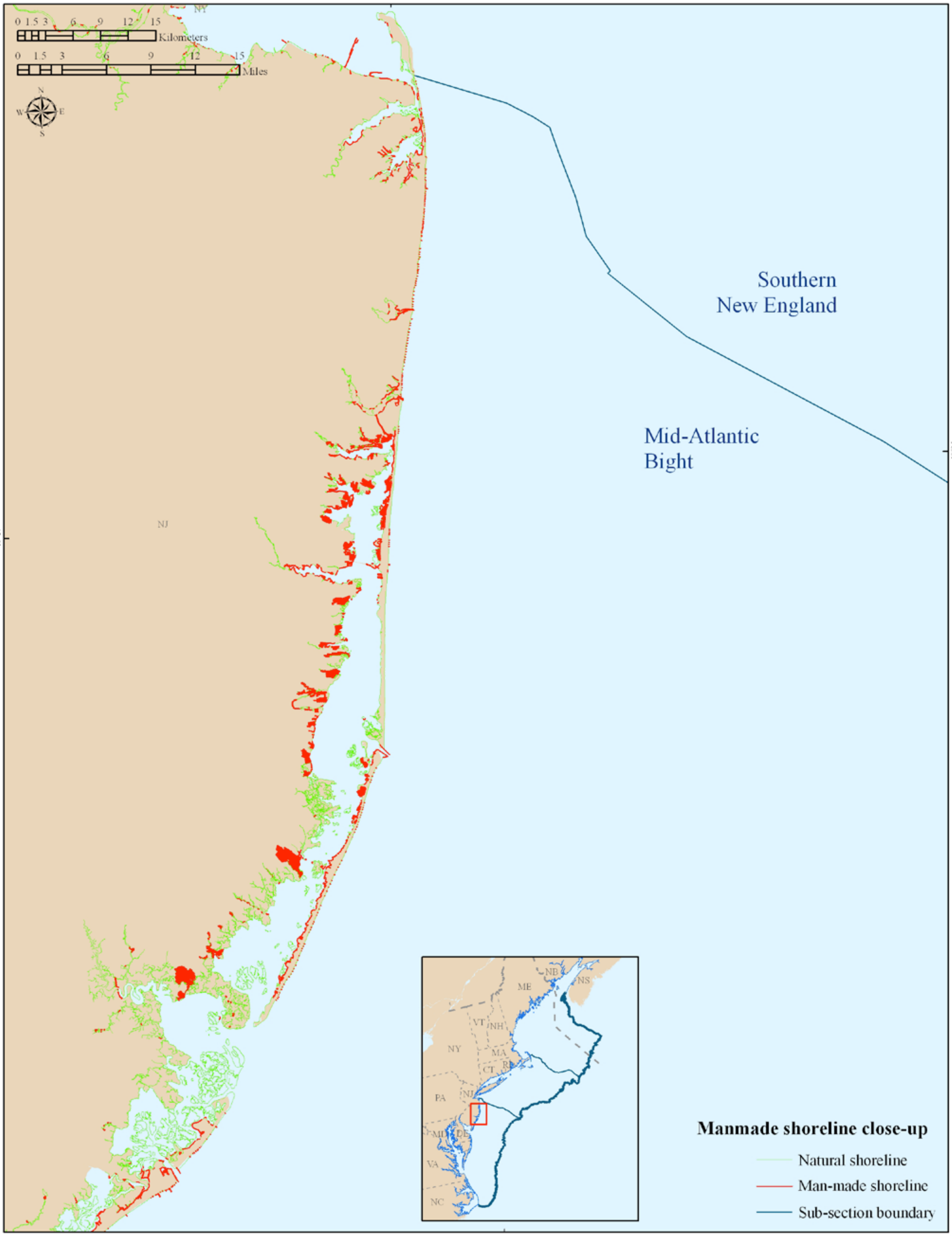

Figure 2-17. An example from Southern New England of the extent of man-made shoreline.

be very informative in assessing relative value of CSUs for coastal marine species. Sinuosity, basically the ratio of edge to area, reflects the amount of marsh/tidal creek edge per unit area. There is evidence from estuarine systems around the world that the value of estuarine habitats for marine species increases as spatial complexity (patch density), sinuosity, and functional connectivity among habitats increase. These are attributes one could theoretically calculate using GIS models. However, because of the need to further define indicators for these attributes that would be most relevant ecologically, as well as time constraints, and limitations of the relevant spatial data available region-wide, these analyses have not yet been attempted.

CSU Condition

A significant proportion of the shoreline of the Northwest Atlantic region is now man-made or heavily altered by human structures of various kinds. The average proportion of man-made shoreline per CSU across the region is 11%. Not surprisingly, in the more industrialized and populated coast of Southern New England, the average is 15%. However, there are marked differences in the proportion of man-made shoreline in different CSUs, ranging from over 30% to near zero (Figure 2-17).

To examine the condition of nearshore land, both the natural land within 2 m elevation and the natural land within a 300 m horizontal buffer were calculated. In the Gulf of Maine where the topography tends to be steeper, the area within 2 m elevation of the shore is only 15% of the area within the 300 m horizontal buffer. In Southern New England the area within 2 m elevation of shore is 25% of the area covered by the 300 m buffer, whereas in the flatter Mid-Atlantic Bight, the area covered by the 2 m elevation rise is 12% *larger* than the area within the 300 m horizontal buffer (Figure 2-18).

In the Gulf of Maine, there are fewer than 2,428 hectares within 2 m vertical elevation of the ocean shore in most CSUs. In contrast, in the Mid-Atlantic there are usually over 53,014 hectares per CSU within the same area. As such, across the entire region, a 2 m rise in sea level might inundate or significantly increase the tidal influence on almost 1 million hectares, (with a disproportionate effect to the south), of which 41%, or almost 415,000 hectares, is wetlands. The Mid-Atlantic Bight contributes over 800,000 hectares to the total projected inundated hectares and over 385,000 hectares of wetlands below 2 m elevation.

Within the 2 m vertical elevation zone, the proportion of that land with natural cover varies by subregion. The Gulf of Maine has the highest proportion of natural cover (average of 78% per CSU) followed by the Mid-Atlantic (69% natural cover) and Southern New England (56% natural cover). Yet within each subregion there are some CSUs with a very high proportion of natural cover within the 2 m elevation zone (the maximums for Gulf of Maine, Southern New England and the Mid-Atlantic are 96%, 95%, and 92%, respectively) and some with very little (the minimums for Gulf of Maine, Southern New England and the Mid-Atlantic Bight are 20%, 7%, and 47%, respectively). The horizontal buffer tells the same story: The average proportion of natural cover in this buffer per CSU in the Gulf of Maine, Southern New England, and the Mid-Atlantic Bight is 78%, 57%, and 70%, respectively.

The land cover/land use of the watershed, as with the proportion of man-made shoreline, shows marked differences geographically and among CSUs of the same estuarine type. Previous research suggests that watersheds with higher percentages of urban and agricultural land are associated with lower estuarine benthic indicators of condition and biodiversity (Hale et al. 2004) and reduced submerged aquatic vegetation (Li et al. 2007). Freshwater aquatic systems also become seriously impacted when impervious cover exceeds 10% (CWP 2003), and reductions in certain taxa sensitive to urban contaminants and habitat disturbance have been found where as little as 3% of the land cover of the watershed is urban (Coles et al. 2004). The average proportion of developed land within the watersheds of CSUs in Southern New England is 29%, and average impervious surface is 9%. A recent study by the Connecticut Department of Environmental Protection (CTDEP) using satellite-based land cover data combined with chemical and biological data from

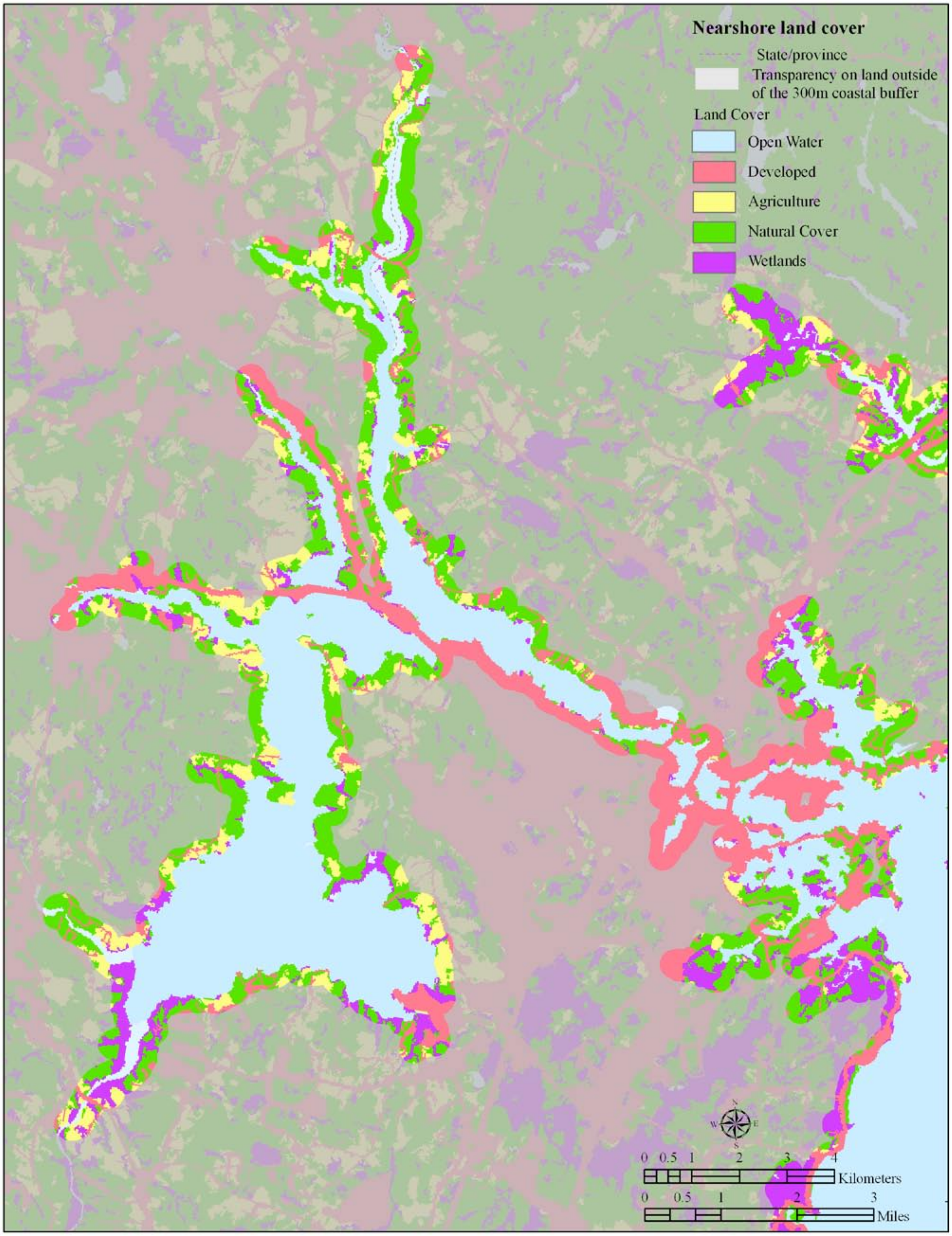

Figure 2-18. Condition of nearshore land within a 300 m buffer.

streams across the state found that "no segment of stream in Connecticut with > 12% Impervious Cover upstream of the sampling location was able to meet Connecticut Water Quality Standard for aquatic life" (CTDEP 2009). In contrast, the averages of proportion of developed land in Mid-Atlantic and Gulf of Maine watersheds are both 9% and their average impervious surface only 2 and 3% respectively. The Mid-Atlantic, however, has much more agriculture in most of its coastal watersheds. However, within each CMECS class and subregion there are some CSUs in very natural condition and others that are much more developed.

A comparison with the NOAA National Estuarine Eutrophication Assessment in some cases corroborates and parallels the watershed land cover characterization, but not in all cases. For example, Massachusetts Bay, classified by NOAA as moderate to high overall eutrophication, has one of the highest percentages of impervious surface, 23.7%. In contrast, the Neuse Riverine CSU in the Mid-Atlantic is classified as having high overall eutrophication although it is not among the highest in developed/agricultural land or impervious surface (Figure 2-19).

Nearshore Shellfish Distribution

Figure 2-9, 2-10, 2-11, and 2-12 show the reported 1995 regional distribution of oysters, hard clams, softshell clams, and bay scallops, respectively. Recent landings versus historic maxima are shown as shaded areas. Blue mussels and ribbed mussels are distributed throughout the region, but spatial data are not available.

With respect to shellfish species viability, we cautiously assert that regional patterns of weak recent harvests relative to benchmarks indicate low-density populations at risk of spawning failure in some areas. In particular, Eastern oyster landings are < 10% of historic highs in eight of 11 reporting states, and bay scallop landings are < 10% in all six reporting states. Hard clam landings are ≤ 10% in four states and < 25% in three other states, also suggesting spawning limitations. Softshell clam populations may be in slightly better condition, with only five of 10 states reporting recent landings < 25% of maxima.

Human Interactions

Natural Shoreline Communities

Most of the coastal areas in the northern half of the region were covered with ice less than 20,000 years ago. This reality speaks to the adaptability and resilience of many of the plants and animals now using these habitats. Today, however, a variety of pressures, including oil spills, climate change, invasive species introductions, eutrophication, and the impending squeeze between the rising sea and human development are rapidly threatening the biological and human communities which rely upon our coasts and estuaries.

Coastal Development

The squeeze of coastal habitats between human coastal development and sea level rise is and will continue to be a major threat, as long as there is a societal desire to engineer less stable shoreline types in an effort to protect vulnerable real estate from inundation and erosion. Coastal development also brings with it increased inputs of nutrients and toxins, alterations of tidal flow, and overland freshwater input, all of which can impact shoreline systems.

Shoreline Stabilization, Altered Sediment Regimes

Barrier islands and riverine deltas are the habitat types probably threatened most by storms and erosion, as they are the most geologically unstable and therefore likely to be impacted directly and indirectly by engineering that alters natural sediment supplies. Alteration of sediment dynamics by creation and maintenance of inlets to embayments, coastal salt ponds, and lagoons also impacts tidal amplitudes, residence times, temperature, and salinity, as well as the export and import of dissolved and particulate nutrients for entire systems. At a smaller scale, channel dredging can impact adjacent shores as sediments accumulate in the deeper channels rather than near the adjacent shores. Similarly, nearshore sand mining can starve some beaches of their natural sand supply in an attempt to nourish other beaches.

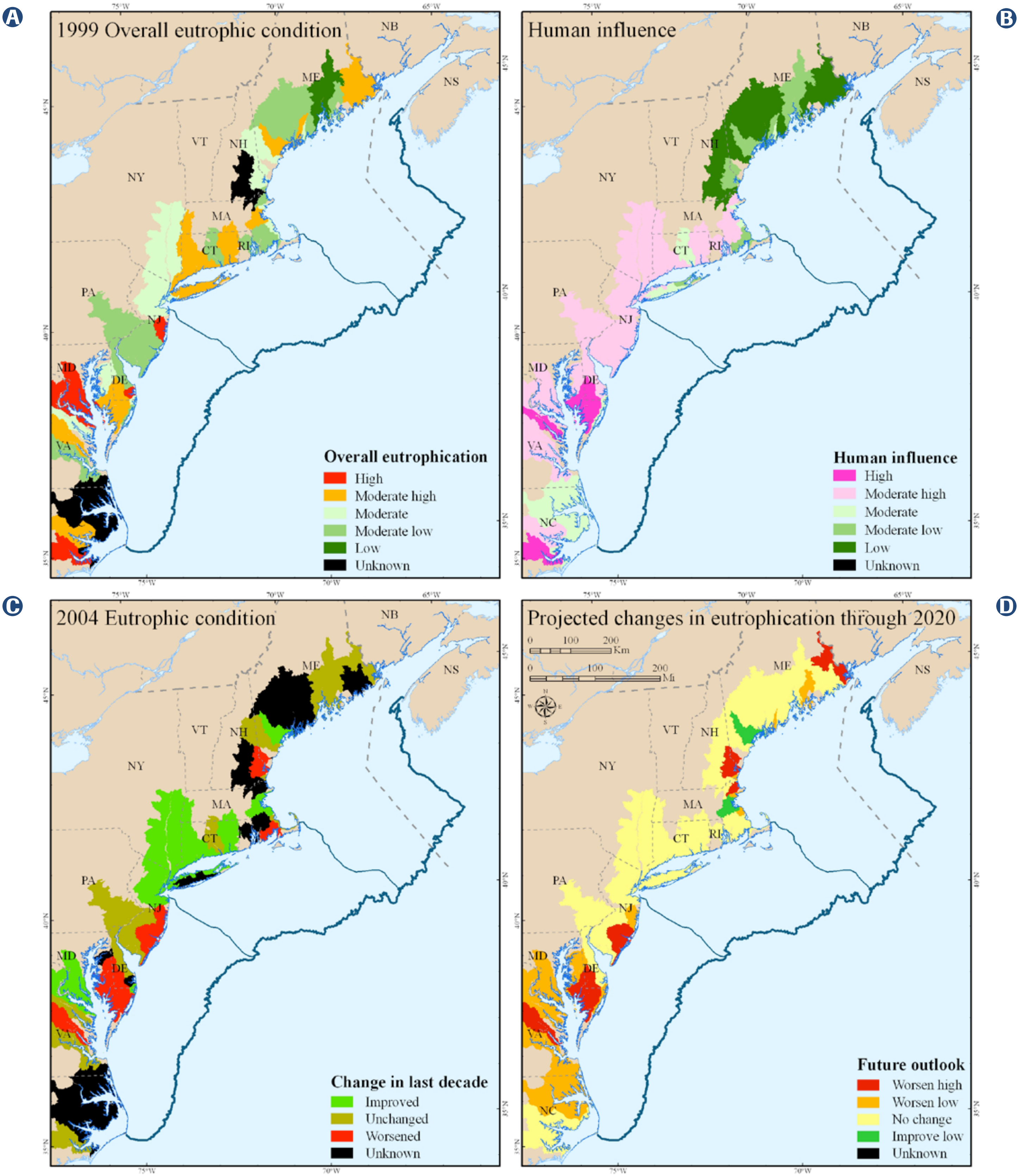

Figure 2-19. Eutrophic conditions in 1999 and 2004, human influence, and projected changes in eutrophication through 2020.

Shoreline armoring of all types (groins, bulkheading, rip rap, gambion, etc.) often causes direct loss of habitat, most often impacting adjacent properties (Nordstrom et al. 2003). There are legislative protections against dredging, filling, and bulkheading vegetated wetlands and/or sandy ocean beaches in some states. However, there is less protective legislation preventing the future armoring of shorelines in the sheltered coast. By their very nature, rocky shorelines are already hardened and more stable. With few exceptions, rocky coasts have been less subjected to anthropogenic shoreline armoring, and when present these structures have less of an ecological impact than they do when they are constructed on more geologically dynamic shoreline types.

Oil Spills

Oil spills are a significant threat to both marine and terrestrial wildlife along the shore. The potential threat of large-scale oil spills is related to the proximity of large shipping, storage, and/or oil and gas exploration operations. Appropriate regulations and precautions can be used to mitigate the potential for harmful spills in areas where the drilling and transport of oil occurs. ESI maps features sensitive to oil spills to facilitate rapid response.

Invasive Species

New exotic marine species can have major impacts on marine and coastal systems through competition with native species, predation (e.g. green crabs on clams), or actual habitat impacts. By the time they are detected, marine invasive species are virtually impossible to eradicate. The ecological consequences of recent marine invasions in this region are uncertain. Global shipping and aquaculture are the main vectors for introduction of exotic marine species and marine disease invasions. In salt marshes, the European genotype of common reed *(Phragmites australis)* is an aggressive competitor capable of forming dense monocultures that crowd out native salt-tolerant plant communities.

Sea Level Rise

Accelerated sea level rise due to global warming is a threat to all coastal targets. An in-depth look at this topic is addressed in the following section.

Seagrass Meadows

The mechanisms of seagrass loss can be characterized as direct or indirect. Examples of direct mechanisms include the uprooting of plants while harvesting shellfish, destruction of plants when motorized boats run aground, and a species-specific "wasting disease" which decimated many eelgrass beds in the last century. There is more uncertainty in the assessment of indirect threats to seagrass, some of which are correlated with each other and are likely to have cumulative and synergistic impacts, such as the direct physiological impacts of increased nutrient loading and the consequences of shading by chronic algal blooms and excessive siltation. Threats which characteristically impact the grasses' key ecological attributes include eutrophication, algal blooms, alterations to water temperature regime, benthic organism harvest methods, boating activities, shoreline armoring and impediments to natural sediment movements, barrier island and inlet stabilization approaches, invasive species (especially green crabs), toxins, excessive macroalgae, altered seed predation regime, dredging, decreased abundance of native shellfish, disease, and herbivory.

Nearshore Shellfish

Five critical threats to nearshore shellfish assemblages in the Northwest Atlantic region were identified:

Overharvest

Evidence of harvest of oysters, bay scallops, hard clams, and softshell clams, all valuable commercial species today, precedes written history. Despite management by state agencies, many historic populations have been exploited to levels too low for successful regeneration. For oysters, long-term harvest reports show that landings may have peaked for some regions as early as the 1880s (Stanley and Sellers 1986; Kirby 2004). Recent data show oyster landings on the United States East Coast at a mere 2% of historic highs (Eastern Oyster Biological Review Team

2007). A similar, albeit less drastic, pattern of regional resource exploitation is evident for hard clams (Stanley and DeWitt 1983), softshell clams (Abraham and Dillon 1986), and bay scallops (Fay et al. 1983). Overharvest is typically of most concern for repeat spawners like oysters and clams; scallops die after they spawn and therefore may be less susceptible to damaging impacts from late-season harvest.

Direct removal of shellfish brood stock has most certainly diminished populations, but indirect impacts from fishing activities, including dragging, dredging, and boat wakes, also threaten shellfish beds by damaging habitat. Fishing activities can scour benthic habitats, destroy hard substrates and seagrass beds critical for spawning, and suspend sediments that deposit silt on intertidal beds and cloud seagrasses. Destruction and removal of shell substrate during oyster harvesting eliminates the foundation on which future generations of oysters will settle.

Pollution

Pollution inputs from nutrient and sediment sources are a long-standing and accelerating problem for estuarine and coastal waters along the entire Atlantic coast. The most recent EPA National Coastal Condition report (2004) ranked the Maine-to-Virginia section of coast with its lowest national ratings for sediment quality and benthic indices, and its second-to-worst rating for water quality. In particular, nutrient pollution is extensive in the heavily populated region. High or moderate eutrophic conditions (i.e. elevated chlorophyll, low dissolved oxygen, extensive macroalgae, and diminished seagrasses) were detected in two thirds of the region's estuaries, with conditions in most expected to worsen by 2020 (Bricker et al. 1999).

Shellfish suffer from pollution from a number of sources, but direct and indirect effects of algae blooms are among the worst, as nutrient-mediated phytoplankton blooms (i.e., green, brown, and red tides) inhibit growth and cause recruitment failures (Summerson and Peterson 1990; Kraeuter and Castagna 2001). Dense beds of macroalgae, such as *Ulva,* disrupt filter feeding and eliminate suitable settling areas (Galtsoff 1964).

Sediment pollution is also major threat, as resuspended sediments and siltation events harm shellfish gills, interrupt feeding, and lower recruitment success (Kennedy et al. 1996). Marine shellfish ingest, retain, and bio-accumulate toxic metals and organic compounds from filtered seawater. Elevated levels of organic contaminants and metals found in shellfish tissue have been shown to inhibit growth and disrupt reproductive functions (Kennedy et al. 1996; Kraeuter and Castagna 2001).

Parasites, Diseases, and Invasive Species

Harmful parasites are prevalent in filter-feeding bivalves, especially oysters and hard clams. In particular, oyster populations in the region suffer from high infection rates by the protozoans Dermo *(Perkinsus marinus)* and MSX *(Haplosporidium nelsoni)* (Kennedy et al. 1996). These diseases may be limiting factors in the re-establishment of healthy oyster populations in many parts of the region, from Chesapeake Bay to New Hampshire. Likewise, hard clams suffer from a parasite known as Quahog Parasite Unknown (X) or QPX that causes wide-spread but less catastrophic mortality in beds from Canada to Virginia (Lyons et al. 2007).

The invasive European green crab *(Carcinus maenas)* is considered omnivorous and known to be an important predator of many shellfish species. In current areas of abundance from Gulf of Maine to Delaware Bay, this species can cause significant losses of shellfish populations, especially for clams and mussels (Kraeuter and Castagna 2001).

Altered Freshwater Regime

Human activities that result in freshwater diversions (e.g., dams, impoundments, freshwater withdrawals) can produce stressful conditions and higher mortality in estuarine shellfish populations. Lethal disease outbreaks in oysters are linked to higher salinity conditions (Kennedy et al. 1996), and several common shellfish predators such as the oyster drill *(Thais haemastoma),* starfish *(Asterias forbesi)*, and whelk *(Fasciolaria hunteria)* are limited in distribution to higher salinity areas (Kennedy et al. 1996).

Climate Change

Extreme precipitation events and warming sea surface temperatures due to global climate change are likely to disrupt shellfish recruitment strategies that rely on strong seasonal patterns of temperature, salinity, and circulation. As nearshore waters warm with climate change, range expansion of shellfish predators enhances the likelihood of locally heavy predation losses for shellfish beds in northern areas of the region. Warmer water is likely a factor in the spread of Dermo (Kennedy et al. 1996). In addition, lower ocean pH due to elevated global CO_2 concentrations (ocean acidification) may inhibit biochemical processes that bivalves rely on for shell development (Beesley et al. 2008). Below is an in-depth look at sea level rise, which discusses relative vulnerability, ecological resilience, and potential strategies for enhancing resilience of coastal systems.

Management and Conservation

Regulatory Authorities

Management of the coastal zone involves a myriad of state and federal agencies whose jurisdictions and authorities overlap in complex ways. Most states have further delegated authority for certain management activities to individual coastal towns, whether for zoning and permitting of development or shellfish management. One unifying federal program is the Coastal Zone Management Act which provides federal funding to each state to carry out research and outreach that may facilitate or enhance regulation but is not directly regulatory itself. Regulatory authority for specific activities within the coastal zone is still most often administered separately by different municipal, state, and federal agencies.

Given the wide variety of uses and activities in the coastal zone, it is not surprising that there is a complex mosaic of management authorities. Municipal, state, and federal authorities often overlap in the same geographic coastal areas and regulation of certain activities may require the involvement of multiple agencies at multiple levels of government. Current efforts being undertaken by the Obama Administration, such as the emerging National Ocean Policy and the framework for coastal and marine spatial planning, hold promise for additional coordination and improvement in coastal resource regulation and management.

All of the states in this region participate in the voluntary Coastal Zone Management Program, under the Coastal Zone Management Act of 1972, and have federally-approved management plans including regulatory authorities to protect and conserve coastal resources. Depending on the individual state, regulatory controls are exercised by a single state coastal agency or by a network of environmental, wildlife, and conservation agencies. The overall program objectives of the CZMA are to "preserve, protect, develop, and where possible, to restore or enhance the resources of the nation's coastal zone." The CZMA includes two national programs, the National Coastal Zone Management Program and the National Estuarine Research Reserve System. The state coastal programs aim to balance competing land and water issues in the coastal zone, while estuarine reserves serve as field laboratories to provide a greater understanding of estuaries and how humans impact them. In addition to regulatory approaches, most coastal programs have a local grants component and outreach and education programs and include emphases on such topics as nonpoint source pollution, habitat restoration and land conservation.

The extent and type of home rule authority granted to local governments varies considerably from state to state; in most states land use controls including zoning and land development permitting are exercised by local and/or county governments. Some states have delegated additional authorities to municipalities and other units of government for other management activities that concern coastal resources, such as, for example shellfish management, harbor management and wetland management.

The United States Exclusive Economic Zone (EEZ) extends from the outer boundary of state waters (3 miles) out to 200 miles from shore. However, the federal government's legal authority in navigation, commerce and security extends shoreward into state waters. The federal agencies that have a role in regulation or review of activities in state waters include NMFS, USFWS, EPA, United States Army Corps of Engineers (USACE), United States Coast Guard (USCG), and the Federal Energy Regulatory Commission (FERC).

Unlike groundfishing and mid-water trawling for forage fish or shrimp, nearshore shellfish harvest and aquaculture are regulated at the state level, with no overarching federal or regional management authorities, other than the Food and Drug Administration's oversight responsibilities for ensuring public health in relation to commercially harvested shellfish. Within Food and Drug Administration constraints, state, or in some areas, town shellfish managers set harvest limits and regulations, and shellfish sanitation commissions control the opening or closing of areas to harvest and consumption. Harvest of mussels is often unregulated.

Current Conservation Efforts

Conservation efforts on behalf of the many features and values of the coastal zone are as many and varied as the regulatory jurisdictions, with the addition of activities by a host of private organizations from global, such as TNC, to bay-specific. These are too numerous and varied to summarize here. Most have a specific geographic focus, and aim to link land-based activities with the health of the estuary and in turn the health of the estuary to the values to the human communities that border them. A notable feature of coastal zone conservation is the numerous examples of public-private partnerships and programs such as the National Estuary Program (EPA), the National Estuarine Research Reserve Program (NOAA), and the Chesapeake Bay Program, which are designed to engage stakeholders and foster broad partnerships and are often paralleled by complementary private organizations such as the Chesapeake Bay Foundation and Friends of Casco Bay.

Shellfish restoration activities provide one example of the varied players in these coastal estuarine programs. The NOAA Restoration Center is a primary provider of funding for shellfish restoration projects and activities, especially for oysters and hard clams. These programs are augmented by state-level programs for certain conservation activities, such as shell management for restoration in the Carolinas and private non-profit efforts such as those of TNC in Great South Bay, Long Island, New York. Restoration funding for shellfish often requires protection from harvesting, which is most often accomplished by siting projects in areas closed due to poor water quality. A combined focus on restoration and conservation has led to the concept of protected spawner sanctuaries in some areas. Oyster restoration projects in the Chesapeake Bay and Delaware Bay are particularly prominent in this region, although these large-scale projects also include harvest provisions.

The United States Department of Agriculture Natural Resources Conservation Service is another provider of funding for oyster restoration, especially in the context of expanded aquaculture operations that provide restoration benefits. This funding model has been successfully developed in Rhode Island, Virginia, and other Atlantic states.

In-depth Look: Sea Level Rise

Assessing Relative Vulnerability and Ecological Resilience to Sea Level Rise

Sea level rise is already impacting coastal communities and natural habitats along the East Coast of the United States. In the coming century, potentially accelerated rates of sea level rise could significantly impact coastal ecosystems and human communities. The assessment team recognized the challenge of including long term threats, such as climate change and sea level rise, in conservation planning efforts. For this reason, a subteam was established to review the state of the science and management of sea level rise within coastal systems. This is a departure from earlier terrestrial ecoregional assessments along the eastern seaboard completed by TNC in recent years. These included analyses of the status of coastal species and ecosystems, but climate change impacts were not considered, particularly the consequences of predicted sea level rise. The best available science indicates coastal species and ecosystems throughout the region are at risk of alteration and loss due to sea level rise (Titus 1990; Markham 1996; Feagin et al. 2005; Nicholls et al. 2007).

Of course, sea level rise and increasingly frequent intense storms will not be the only climatic impacts to Northwest Atlantic marine ecosystems. Other potential impacts such as increased water and air temperature and ocean acidification are addressed elsewhere in this report.

In order to inform prioritization of conservation locations and strategies in the face of climate change impacts to coastal ecosystems, the sea level rise team sought to:

1. Apply principles of vulnerability and resilience to sea level rise and storm impacts to the region's coastal ecosystems;
2. Compile existing information on sea level rise impact studies and on-going adaptation strategies for the Northwest Atlantic coast;
3. Assess additional information or analysis needs and appropriate data availability;
4. Determine potential next steps to further inform conservation action in the coastal zone.

How High and How Fast?

Twentieth century global sea level has been steadily rising at a rate of ~1.7 to 1.8 mm yr^{-1}, increasing to over 3 mm yr^{-1} within the last decade (IPCC 2007). Most of this increase comes from warming of the world's oceans (nearly 60%) and melting of mountain glaciers (~30%), which have receded dramatically in many places especially within the last few decades (IPCC 2007). However, the IPCC projections of an 18 to 59 cm sea level rise by 2100 may underestimate potential polar ice sheet contributions. Recent trends from Greenland and the West Antarctic ice sheet raise concern (Shepherd and Wingham 2007; Velicogna and Wahr 2006a; Thomas et al. 2006). Satellites detect a thinning of parts of the Greenland Ice Sheet at lower elevations, and glaciers are disgorging ice into the ocean more rapidly, adding 0.23 to 0.57 mm yr^{-1} to the sea within the last decade (Rignot and Kanagaratnam 2006). The West Antarctic Ice Sheet may also be thinning (~0.4 mm yr^{-1} from 2002- 2005). The combined ice sheet melting of Greenland and Antarctica from the 1990s to the present is adding some 0.35 mm yr^{-1} to sea level rise (Shepherd and Wingham 2007).

Global warming could cause further thinning of these ice sheets. Either ice sheet, if melted completely, contains enough ice to raise sea level by around 7 m. By contrast, mountain glaciers hold the equivalent of only ~0.5 m of potential sea level rise. A regional temperature rise of only 3°C (Gregory et al., 2004) or 3.2E- 6.2EC (IPCC 2007) may be enough to destabilize Greenland irreversibly. While such temperature increases fall within the range of several future climate projections by 2100, major breakdown of the ice sheet would probably lag warming by several centuries. If basal melting rates for buttressing Antarctic ice shelves exceed 5-10 m yr^{-1}, the West Antarctic Ice Sheet could break up within several centuries (Alley et al. 2005).

A recent study modeling ocean currents in response to sea level predicts that the Northwest Atlantic will experience even higher sea levels than the global average because of anticipated slowdowns of ocean currents in response to global warming (Yin et al. 2009). It is also important to point out that even with stabilization of global temperatures sea level is expected to continue to rise for centuries (Wigley 2005).

Several factors that contribute to relative sea level change vary geospatially. Locally-specific parameters include water surface elevation and land movement attributable to isostatic adjustment of the Earth's crust after the most recent ice age. The Columbia Center for Climate Systems Research and the Goddard Institute for Space Studies (CCCSR/GISS) recently produced projections of sea level rise for Long Island and Long Island Sound for TNC's Long Island coastal resilience project (http://coastalresilience.org) using seven of the IPCC Global Climate Models (GCMs) that are capable of producing projections for sea level rise, three emissions scenarios, and a parameter representing rapid ice sheet melting. These projections clustered around 1 m of rise by the end of the century in the absence of rapid ice sheet melting, and around 2 m by the end of the century with a rapid ice melt parameter included (GISS/CCCSR 2008). It should be noted that the local parameters in these projections are specific to the Long Island study area, and it is not clear how much of the assessment study area would be covered by the local adjustments made. Many stakeholders and scientists and planners associated with the project agree that these 1 and 2 m projections within this century are conservative.

While the Long Island project is a good example of downscaling climate data to generate locally relevant applications from GCMs, it is not possible to select the "true" model, as by their nature projections of SLR are uncertain. However, given the risks and potential costs of *in*action and under-prediction, it is essential to imagine potential impacts and develop plans and strategies that address these potential outcomes. Several state governments and other entities have confronted this uncertainty by selecting a value (in an informed, but necessarily arbitrary way) and requiring agencies to make plans that account for that amount of sea level change. For example, the State of Maine's Coastal Sand Dune Rules plans for two ft of sea level rise in 100 years; the state of Maryland's Department of Natural Resources uses a policy guidance document that plans for 2-3 ft of sea level rise in 100 years; and Rhode Island's Coastal Resources Management Council plans around an expected 3-5 ft of sea level rise in 100 years. Rhode Island's projection is consistent with TNC's recommendation of 1 and 2 m in 100 years as conservative projections for this region for the purposes of this review and proposed future analyses. However, it should be noted that the pace of sea level rise is as critical as the endpoint. If that change were to occur in 20 years rather than steadily over a century, it is much less likely that any natural systems would be able to adjust to keep up (Bricker-Urso 1989).

Multiple Climate Change Effects on Coastal Systems

In evaluating climate change's impact, one must consider the synergistic interactions of its effects. Combined impacts from sea level rise, increased precipitation, and intensity and frequency of storms and storm surges will include:

- both permanent inundation and increased flooding associated with episodic events
- increased salinities in tidal wetlands
- increased saline intrusion into coastal groundwater
- increased tidal velocities, and
- increased freshwater discharges and altered hydrology of tidal rivers

All of these impacts are likely, in turn, to cause increased erosion and wash-overs (French 2008), and 1) shrinking or disappearance of some islands, 2) landward migration of beaches and coastal wetlands where possible, 3) increased storm water run-off carrying pollutants, 4) increased eutrophication and contamination due to synergistic effects of impacts above in combination with rising water temperatures (EPA 2008), 5) alteration and conversion of high marsh to low marsh, and conversion of low marsh to unvegetated wetlands, and 6) loss of some wetlands, with associated loss of flood control, buffering, and nursery, foraging, and spawning areas for diverse marine fauna (http://www.fws.gov/chesapeakebay/slamm) and (http://www.slammview.org).

All of these first and second order impacts have significant implications for coastal habitat conservation and many are likely to lead to intense conflicts between flood defense and habitat restoration and protection objectives (French 2008). There are also likely to be significant implications for species whose populations are small or declining, especially species dependent on lower tidal elevation marsh habitats such as salt marsh sparrows, and beach-dependent species, such as piping plovers, horseshoe crabs and migratory shorebirds (Nicholls et al. 2007). There will also be significant costs for coastal communities beyond the most obvious impacts of flooded public and private infrastructure, including salt water intrusion into drinking water, overwhelmed storm water discharge systems, and the presence of hazardous waste at sites below projected flood levels (Cooper et al. 2008). Some human responses to protect life and property from sea level rise impacts will exacerbate negative impacts to natural systems (e.g., shoreline hardening) while others may facilitate ecosystem resilience and the persistence of critical habitats (e.g., living shorelines, coastal retreat).

Vulnerability and Resilience

For the purposes of this assessment, it is imperative to assess coastal system types in the context of both likely vulnerability and potential resilience to impacts from rising sea levels, storm surges, and flooding from increasingly frequent and intensified storms. *Vulnerability* is defined here as the relative impact sea level rise will have on a given system, and *resilience* as the ability of the system to adapt and persist in the face of these predicted effects. In particular, this assessment focused on 1) coastal beach and dune complexes and 2) salt marshes and other tidal wetlands, along with the species that depend on them, as the most vulnerable to sea level rise and associated impacts.

Coastal marshes and beaches of the Northwest Atlantic are naturally dynamic systems which characteristically vary both spatially and temporally. Specifically, they have been adapting to changes in relative sea level during all of the Holocene. However, it is the *rate* of change associated with contemporary sea level rise that is predicted to be a significant stressor. While all coastal systems are vulnerable to impacts from sea level rise to an extent, some are more vulnerable than others. Projecting *vulnerability* to sea level rise is, first and foremost, a matter of predicting extents and depths of storm surge and inundation and, in the case of tidal rivers, the distance of upstream salt wedge migration. These are driven by regional differences in geomorphology, coastal slope, relative sea-level change, shoreline erosion/accretion, mean tide range, and mean wave height (Coastal Vulnerability Index (CVI); Thieler and Hammer-Klose 1999). For instance, the CVI analysis by the United State Geological Service predicts that the rocky coast of the Gulf of Maine is much less vulnerable to sea level rise and erosion associated with storm surges than the relatively low-lying wetlands along Chesapeake Bay (Figure 2-20). However, the CVI is a relatively coarse scale analysis. Conservation investments, whether in land preservation or restoration activities, will be most effective when informed by finer scale spatial data regarding local variation in both vulnerability and resilience to sea level rise impacts. Local scale characterizations of predicted vulnerability and resilience require finer-scale datasets than are currently unavailable for most of the Northwest Atlantic coast.

Predicting relative *resilience* is in large part a matter of estimating the potential for natural systems to “migrate” (i.e. to move upslope and away from the sea) and adapt in the face of that inundation. However, the other existing stresses faced by a given site or ecosystem is essential information. Multiple additional stressors are likely to further reduce a site or ecosystem’s resilience. It should be emphasized that human activity on the coast can potentially *increase* the vulnerability of an ecosystem and subsequently *decrease* its resilience (Leslie and Kinzig 2009). For example, permitting nearshore development adjacent to at-risk habitats inhibits their ability to migrate, and consequently increases their vulnerability and reduces their resilience. Similarly, shoreline armoring inhibits cross- and long-shore sediment movement and thereby increases the vulnerability of nearshore beaches and wetlands that rely on natural transport processes to maintain elevation. Accordingly, the human response to coastal risk is likely to be a major driver of both vulnerability and resilience to sea level rise and accompanying hazards.

A number of studies of the potential impacts of projected sea level rise have been conducted in and near the Northwest Atlantic region, including in Assateague Island National Seashore and the Virginia Coast Reserve (Pendleton et al. 2004), Chesapeake Bay, the New Jersey coast (Zhang et al. 2004), Long Island (New York) (Goddard Institute 2008), the Mid-Atlantic coast from New York to North Carolina (Titus and Wang 2008; Titus and Strange 2008; Titus et al. 2008; Reed et al. 2008; CCSP 2009), Quonochontaug Pond, Rhode Island (Vinhateiro 2008), Scarborough Marsh, Maine (Slovinsky and Dixon 2008), and Albermarle Sound, North Carolina (http://www.nature.org/initiatives/climatechange/work/art26197.html). See individual references for more information about each of these programs. Also, see TNC’s coastal resilience project where notable subregional and site-specific examples of sea level rise impacts within the Northwest Atlantic region are being compiled (http://coastalresilience.org).

Predicting Ecological Resilience

While these studies offer information on the likely vulnerability of specific coastal areas and some provide predictions of potential beach and marsh migration, most do not provide comparative predictions of resilience for multiple sites. Are there attributes of particular coastal systems or classes of systems that would make them more or less ecologically resilient? Here the concept of *ecological resilience* is used as a predictor of persistence of the ecosystem type over time, with recognition that it may not persist in the same location with all of the same species. For instance, a fringing beach backed by a bedrock headland will likely disappear as sea levels rise; such a beach is not resilient to sea level rise once a certain threshold is reached. In contrast, a large and unconstrained barrier beach and dune system with a salt marsh behind it may be able to migrate and persist over time, as such beaches have done historically. Note that this use of resilience is distinct from the concept of *coastal hazards resilience* used by NOAA and others, which focuses primarily on attributes of human communities rather than natural systems. We believe assessing coastal systems' ecological resilience may be a useful additional method for prioritizing conservation investments and in choosing restoration and adaptation approaches.

Key attributes to consider in evaluating relative ecological resilience of coastal systems

Size

In general, there is a large body of conservation biology literature speaking to the greater resilience of larger systems versus smaller, e.g. the minimum dynamic area and minimum dynamic reserve concepts (Pickett and Thompson 1978; Leroux et al. 2007). Larger marshes are likely to have more microhabitats and more room to adjust. Larger beach and dune systems typically have more available sand and thus may be able to adjust up and away from the rising sea better than low narrow beaches.

Landward Topography and Barriers to marsh movement upslope

In order to keep pace with sea level rise, salt marshes must grow in two directions: horizontally and vertically. Horizontal growth occurs via migration into adjacent upland areas where the marshes are unimpeded by steep natural slopes or shoreline hardening and development; vertical growth occurs through the accumulation of mineral and biologic sedimentary materials that form the peat substrate. Likewise, tidal marshes with adjacent low-lying land normally can migrate into these lands unless the slopes are too steep or there are man-made or natural physical barriers (Titus et al. 1991). Along the Maine coast, there are a number of salt marshes with old tree stumps protruding or buried in the marsh peat attesting to such landward migration over the last several thousand years (Dickson, personal communication). However, in many places roads, railroads and buildings now crowd the marsh edge and various kinds of structures are in place to protect that infrastructure from infringing high water. Furthermore, there are many areas where additional barriers may likely to be constructed to protect current or planned human infrastructure. The presence of existing or potentially planned human infrastructure is an additional potential factor influencing the landward and upslope movement of both marshes and beaches.

Barriers to beach movement long-shore and landward

When subjected to rising sea levels, beaches may translate upward and landward. This concept applies when there is physical space in which to migrate horizontally unimpeded by obstructions and simultaneous sand accretion to build the beach vertically at a pace to keep up with sea level rise (Pilkey and Dixon 1996). Where there are subtidal supplies of sand, coastal storms can help replenish sediment by moving sand up the beach profile from offshore deposits (Cooper et al. 2008). However, if either of these conditions is absent, or if the pace of sea level rise is too rapid, a beach will subsequently erode and eventually become submerged.

In recognition of the importance of barrier beaches to the tidal wetlands and lagoons behind them, many states have taken action to protect their barrier beaches by preventing additional structures that might impede their natural accretion or migration (e.g. Massachusetts Barrier Beach Inventory and Executive Order restricting further building on barrier beaches).

Longitudinal upstream connectivity

As sea level rises the salt wedge will intrude farther upstream in coastal rivers (Najjar et al. 2000). Thus, where now there may be fringing salt marshes at the seaward end of estuaries and brackish and then freshwater tidal wetlands fringing farther upstream, in the future all these may become salt (if they remain elevated enough to be vegetated at all.) However, in some larger coastal rivers there is plenty of longitudinal space for these fringing tidal marshes to migrate upstream as the sea level rises and tidal influence and salt intrude farther. On the other hand, where coastal river continuity is truncated by natural falls, dams, or restricting culverts that would prevent a tidal wetland from moving upstream, it is likely that the freshwater and brackish tidal wetlands will disappear and/or become entirely saline. Note however, that modeling such changes specifically is complicated by the need to take into account changes in the river's hydrology due to potential changes in the rates and volumes of freshwater flow.

Rate of accretion/erosion

Tidal wetlands and other shorefront habitats can persist in the face of moderate rates of sea level rise through accretion, supported by sedimentation and organic matter accumulation (Chmura et al. 2003). However, if relative sea level change exceeds net elevation change (the net effect of accretion and compaction), wetlands and beaches will be inundated and ultimately lost (Peterson et al. 2008). In general, over the last century, salt marshes have accreted sediment at a rate to keep up with rising seas (Hartig et al. 2002; Najjar et al. 2000; Roman et al. 1997). Recently, however, several authors have predicted that salt marshes will not be able to accrete fast enough to keep up with predicted sea level rise and the result will be outright inundation in some cases or at the least major losses of *Spartina patens* dominated marsh and expansion of *Spartina alterniflora* dominated marsh (Gornitz et al. 2004; Morris et al. 2005).

Not all tidal wetlands accrete at the same rates. Some, such as freshwater tidal wetlands that may have sparse plant cover but harbor many rare plant species, are more dependent for accretion on sediment input from rivers than salt marshes (Neubauer 2008). Salt marshes are more dependent on vegetative accretion than sediment inputs and the vegetative production may be dependent on the stimulus of flooding (Nyman et al. 2006). In some areas warmer temperatures associated with climate change may increase marsh productivity and subsequently increase organic sediment accretion rates (Langley et al. 2009). However, this effect may be more pronounced in freshwater than saltwater systems and background accretion and erosion rates are a fairly site-specific phenomenon, depending on a variety of local factors not easily predicted without detailed studies. Titus (2008) has compiled maps that depict site-specific scenarios for wetland accretion along the Mid-Atlantic coast from New York to Virginia. Other authors have determined accretion rates in other states (e.g., CT: Orson et al. 1998; Warren and Niering 1993; RI: Bricker-Urso et al. 1989).

Potential Resilience Attributes to be Assessed at Regional Scales

Given data gaps and data resolution, comparative resilience is probably best addressed at an estuary or CSU level, rather than at a beach by beach or marsh by marsh level (EPA 2008). A logical start would be to build from some of the following system-specific attributes.

Beaches

Size

The area of all beach and dune systems in the Northwest Atlantic has been calculated using GIS data from TNC's Northern Appalachian and North Atlantic Coast ecoregional plans and generated for Chesapeake Bay based on the NWI, ESI, and National Land Cover Dataset (NLCD). It would be advisable to update these measurements using LiDAR data when available. Length can be reasonably measured from existing data sources. However, the width and height of beach/dune systems are key aspects of beach size related to resilience that are much more difficult to measure without extensive mapping efforts derived from orthophotography or localized geologic studies.

Appropriate adjacent habitat
Beaches could be assessed using shoreline (e.g. ESI), estuarine (e.g. NWI), and land cover classifications in addition to elevation to indicate whether they are backed by a headland, dunes, coastal wetlands, or forest types. Those backed by headland could be further characterized using geological data sources as to whether the headland is of unconsolidated material (sand, mud, gravel, which presumably could contribute to accretion of beach material) or bedrock.

Presence/Absence of artificial barriers to natural beach movement
Barriers could be assessed using NOAA structures data for piers, groins, and jetties, and NLCD or NOAA Coastal Change Analysis Program (CCAP) Land Use Land Cover data for roads and houses on the beach-dune. However, these are generally out of date and incomplete. Some states in the region have recently completed or are in the process of completing coast-wide coastal structures inventories. These datasets are likely to be the best approach to assessing this attribute on a regional basis. For the CSU analysis, the percent of total CSU length that was "man-made" was measured using ESI line type coding and, where this did not exist in Maine and Canada, by overlapping EPA and Canadian Department of Natural Resources and Energy data.

Shoreline Change Rates may be one of the most important factors in predicting beach resilience to sea level rise. Where local studies have been done or are underway these should be factored in.

Tidal Wetlands

Size
For the CSU characterization described above, the area of all tidal wetlands was calculated using GIS. Patches were grouped according to an algorithm based on adjacency and hydrological connections (e.g. marsh patches on either side of a tidal inlet or river) as above.

Landward topography
This parameter refers to the amount of adjacent land at less than 1 and 2 m elevation. For accuracy this would need to be calculated using LiDAR when available. Analysis of landward topography, that is, slope and amount of adjacent land under a particular elevation, is the primary approach of most of the studies of sea level rise impacts to coastal habitats cited above.

Presence/absence of artificial barriers to upslope movement
This parameter could be assessed using the NLCD or CCAP land cover data on natural versus developed cover types plus a transportation layer. On a site-specific scale these barriers can also be assessed in some areas by compiled maps of hardened shorelines or by analysis of digital orthophotos. These constraints to upslope migration are built into some, but not all, of the site-specific models of inundation (See U Arizona web-based model in addition to the SLAMM references).

Longitudinal Connectedness Upstream
There is no region-wide GIS dataset that would allow determination of natural or anthropogenic barriers to upstream migration of fringing tidal wetlands or salt wedges. However, this parameter could be determined on a site-specific basis by consulting local datasets and examination of aerial photos and contour and bathymetry maps.

Putting It All Together

Analyzing key ecological attributes from beach and tidal wetland ecosystems can support the growing understanding of resilience. Weighting, combining, and ranking these attributes to produce relative scales of resilience can further our ability to assess ecosystem structure and function in the face of climate change. Research and design of such methods are an important next steps in the Northwest Atlantic coastal system as we identify conservation priorities and strategies for taking action to protect specific places. For example, a relative scale of tidal salt marsh resilience could be evaluated in the context of current land use and conservation protection. This analysis may identify the protection of individual, relatively more resilient sites while also determining the need to secure or maintain protection of adjacent freshwater wetlands and uplands within 2 m of high water to give them space to migrate and persist in the future.

Much more research and modeling are needed regarding how coastal systems will react and adapt to sea level rise and what factors impede or facilitate resilience. Detailed scientific studies will necessarily focus on a relatively small scale, rather than the entire region, and should take place over multiple years (for instance, National Science Foundation funded research underway at TNC's Virginia Coast Reserve). For purposes of this assessment, the ultimate goal is to use site-specific assessments of sea level rise vulnerability and resilience in the prioritization of strategies and places for conservation and restoration. We hope that as federal and state coastal inundation analyses proceed they factor in some attributes relevant to resilience to add to collective knowledge.

We wish to reiterate that the vulnerability of human infrastructure and likely societal responses to protect infrastructure pose significant threats to the resilience of coastal systems which may compound and exacerbate natural impacts. It would be appropriate to take these into account in comparing vulnerability and resilience of various parts of the coast or one bay versus another (Titus and Wang 2008; Titus et al. 2009).

NOAA's Digital Coast Partnership

NOAA Coastal Services Center leads the Digital Coast effort, envisioned as an information delivery system that efficiently provides not only data, but also the training, tools, and examples needed to turn data into useful information for the management of coastal resources (http://csc.noaa.gov/digitalcoast/index.html). An important part of the Digital Coast is the partnership network, the guiding team that represents user groups and content providers. As a member of the partner network, TNC has been contributing to Digital Coast specifically by providing case studies. One study done in conjunction with this assessment was the development of a regional framework for assessing coastal vulnerability to sea level rise in southern New England (Cape Cod, Massachusetts to Long Island, New York).

The Southern New England Coastal Vulnerability study imposes an assessment of future coastal development and ecological resources on a regional framework based on coastal topography. This framework will help illustrate the current limitations of, and opportunities for, mapping SLR at regional scales, considering the relative vulnerability of human communities and deciphering whether the presence and contribution of coastal ecosystems presents a viable opportunity for adaptation solutions. With this study, TNC and its partners hope to add value to the growing field of coastal resilience and adaptation planning through the development of this initial regional framework (see http://webqa.csc.noaa.gov/digitalcoast/action/hazards/slr-newengland.html). In addition, the complete case study will be included in the Coastal Inundation Toolkit (http://csc.noaa.gov/digitalcoast/inundation/discover.html) by spring 2010.

TNC is working nationally with NOAA's Digital Coast program as well as in different geographies across the United States on issues of vulnerability and resilience as they pertain to sea level rise and coastal inundation. Please refer to TNC's climate change initiative (http://www.nature.org/initiatives/climatechange/work) for additional information.

Potential Strategies for Enhancing Resilience of Coastal Systems

The vulnerability of human infrastructure and likely societal responses to threats to that infrastructure will impact the resilience of coastal systems. While it will be important to maintain certain aspects of the built environment that protect and provide important services to human communities, this must be balanced with attempts to maintain natural diversity and natural infrastructure of coastal habitats, many of which provide vital services to those same communities.

It is imperative that government agencies and the public begin constructive discussions about appropriate responses to the new stresses climate change will place on already stressed coastal environments. Fortunately, many states are already engaged in such discussions and planning. A variety of strategies for increasing the long term resilience of coastal ecosystems should be considered, along with the appropriate means of mitigating the short term collateral impacts of such strategies on coastal landowners and municipalities:

- Acquiring low-lying natural land adjacent to beaches and marshes for conservation
- Inclusion of future habitats in land use planning
- Removing barriers to upstream connectivity, e.g., dams, roads, or dikes across marshes with narrow culverts
- Preventing armoring of beaches and building on dune systems
- Removing or preventing man-made barriers to upslope connectivity such as development adjacent to marshes
- Not rebuilding or removing armoring and seawalls; realigning and redesigning built “defenses” necessary to protect infrastructure to have less impact on natural systems
- Where stabilization is absolutely essential, supporting development of “soft solutions” and/or Living Shorelines instead of hardened shorelines for areas where complete retreat is not an option
- Reducing and mitigating impacts of other stresses, such as excessive nutrients (inadequate wastewater treatment, combined sewer overflows, etc.), incompatible development, and invasive species
- Avoiding beach replenishments which are often extremely expensive, temporary in impacts, and counter-productive, with impacts to beach fauna and subtidal shoal habitats; however in some cases beach nourishment can be beneficial by simulating a natural bypassing of sediment that would occur in the absence of an armoring structure.

In 2009, on Earth Day, the Heinz Center and Ceres released a “Resilience Coasts Blueprint” outlining proposed policy changes and local actions that could significantly reduce future United States coastal losses due to sea level rise and storm impacts. This report was endorsed by a diverse group including NOAA, representatives of major insurers, and The Nature Conservancy. In January of 2009, the EPA released an in depth document on coastal sensitivity to sea level rise with a focus on the Mid-Atlantic region which includes comprehensive overview of various response options and the federal and state policy implications for adaptation (CCSP 2009). These and other strategies should be assessed more completely in the future, and methods for prioritizing locations for deployment of site-specific strategies should be developed.

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