THE VULNERABILITIES OF NORTHEASTERN FISH AND WILDLIFE HABITATS TO SEA LEVEL RISE

National Wildlife Federation and Manomet Center for Conservation Sciences

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A Report to the Northeastern Association of Fish and Wildlife Agencies and to the North Atlantic Landscape Conservation Cooperative

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EXECUTIVE SUMMARY

Sea level rise poses a major new threat to the conservation of important coastal ecological resources in the Northeast and elsewhere. As yet, our ability to project habitat and species vulnerabilities to this threat is constrained by methodological limitations and a lack of research. Nevertheless, if we are to manage and conserve these resources, on which huge investments have been made over the last few decades, it is vital that we begin to understand vulnerabilities and the factors responsible for them. In this report we review the scientific literature to evaluate our current understanding of the vulnerabilities of fish and wildlife habitats in the northeastern coastal zone to sea level rise (SLR); identify the major sources of uncertainty; and suggest future research that will help us continue to conserve these coastal ecological resources. Specifically, we evaluate the extent to which existing studies, data sets and tools allow us to infer reliable conclusions about the likely vulnerabilities and fates of coastal habitats for fish and wildlife, the uncertainties that surround these conclusions due to the shortcomings of the existing datasets and tools, and how future research and conservation activities might help reduce such uncertainties. By bringing together the current scientific information on climate change and coastal ecological resource vulnerabilities in the Northeast, this review is intended primarily for resource managers who are charged with making practical decisions about land management. The following main conclusions can be drawn from this review:

- Data from all 35 tide gauges along the northeastern coastline from Virginia to Maine unanimously show that sea levels have been rising for at least the last 90 years.

- Throughout the Northeast Region, the mean rate of sea level rise, as measured at the tide gauge stations, has varied between about 2 mm/yr and greater than 5 mm/yr during the 20th and 21st centuries.

- The rate of SLR is highest in the Mid-Atlantic states of Virginia and Maryland, and lower in the more northern states.

- There is evidence from the northeastern tide gauge data that the rate of SLR has accelerated over the last century.

- The more recent projections of future global SLR vary among studies, between about 50 cm and 2 m by the year 2100. These estimates vary depending mainly on assumptions about the rate and extent of future and current ice sheet and glacier melt.

- For this study we assumed two SLR scenarios for the Northeast: 1 m and 2 m, globally, by 2100.

- Combining the above two SLR scenarios with local rates of SLR (from the tide gauge data) leads to projections of 21st century sea level rise in the Northeast of between 1.4 m and 2.4 m in the southern states and 1.2 m and 2.2 m in the more northern states.

- The ecological impacts of rising sea levels will likely be exacerbated by coastal storms and tidal surges, as happened during Hurricane Katrina and Superstorm Sandy. These events suggest that the impacts of SLR on coastal ecosystems might not be gradual and linear, but could be sudden and irreversible.

- Modeling studies suggest that the severity of North Atlantic storms will increase as the planet continues to warm. There is evidence that this may already be happening. Such changes in stochastic events, when combined with long-term SLR, could pose additional serious risk to the extent and condition of coastal ecosystems.

- SLAMM modeling analyses at 28 coastal National Wildlife Refuges (NWRs) in the Northeast Region indicate that SLR assumptions of 1 m and 2 m could result in major changes in the wildlife habitats currently present on the reserves over the remainder of this century.

- Across the 28 NWRs, the SLAMM analyses project major losses in saltmarsh and oceanic and estuarine beach habitat, with the losses being greater under the 2 m SLR scenario. Conversely, tidal flats across the 28 NWRs are projected to greatly increase in extent, with the greatest increases occurring under the 2 m scenario. The SLAMM results are not consistent across all study sites and this may be due, at least partly, to inaccuracies in the input data.

- Many important wildlife populations are dependent on the two habitats that are projected by SLAMM to decrease in extent at the NWRs (marshland birds, other wading birds, piping plovers and skimmers for example), while others may benefit from the region-wide projected increase in tidal flats (migratory shorebirds and waterfowl, for example).

- Three northern NWR sites differ in their projections from the other 25 that were analyzed using SLAMM: Parker River NWR, Petit Manan NWR, and Rachel Carson NWR. These apparent differences could be an artifact of the lack of LiDAR data availability at these sites when the analyses were performed.

- The SLAMM modeling studies that are described in this review have a number of extrinsic and intrinsic uncertainties, including:

    - Some of the analyses relied on comparatively imprecise DEM data at sites where few or no LiDAR data were available
    - Many of the analyses relied on older and less precise data from the NWI to describe current distributions of wetland habitats
    - The SLAMM model might not accurately reflect dynamic coastal geophysical processes, such as the accretion and erosion rates of sediments
    - Perhaps the greatest source of uncertainty is that we cannot be definitive about the future extent of SLR, with estimates varying from 0.5 m to 2 m by 2100.

- Results from modeling the potential impacts of SLR and storm surges on the nesting habitat of piping plovers in the Northeast tend to disagree in some respects with the results of the SLAMM modeling at 28 NWRs. Specifically, the piping plover studies project increases in the extent of breeding habitat, unlike SLAMM, which projected losses of oceanic and estuarine beach. These differences may be due to methodological differences or to the fact that the consequences of SLR and tidal surges vary among sites.

- The piping plover studies agree that if sites or habitats are constrained in their ability to move inland or upslope (by topography or human developments) the result is likely to be habitat loss and the losses will increase with increasing SLR. However, if the sites or habitats are able to migrate under SLR then new habitat would be created and the total area of piping plover nesting habitat might be expanded by SLR (assuming that there is enough sand in the system). However, if more intense or frequent coastal storms and surges accompany SLR (as seems likely – see Chapter 2), piping plover nesting habitat could be significantly reduced.

- Uncertainties in the piping plover modeling include:

    - The role of human development. It is not completely clear how the development of beach habitat and barriers to inland migration of coasts may interact with rising sea levels and storm surges to affect nesting habitat suitability.
    - The geomorphology of beach creation. The studies suggest that SLR and storm surges could create new nesting beaches for the plovers. However, this is dependent on an adequate supply of sand being available. We do not know whether and where this may be the case.

- Ten coastal northeastern states have carried out analyses of the implications of SLR for ecological resources. Virtually all performed analyses of the expected degree of SLR, the implications for infrastructure and for ecological resources. Many of these analyses were based on state-level LiDAR data, though not all. These analyses showed that if adequate accretion of sediments was allowed to occur at sites then coastal wetlands could keep up with SLR and habitats might not be lost.

- Ocean beaches and brackish marsh were found to be the most vulnerable habitats.

- Significant uncertainties were found across all of the reviewed studies, including:

    - The extent of future SLR. While we are better able to project SLR in the near term (the next few decades), projection beyond that time horizon is beset with greater uncertainty (due to our inability to adequately estimate climate change impacts on ice caps and glaciers). We are probably not able to significantly reduce this uncertainty in the near term; only future empirical data will do so.
    - Model uncertainties and limitations, specifically how well they project important geophysical processes such as sediment accretion rates.
    - Human responses to SLR in the coastal zone (e.g., future development patterns and coastal armoring) may be as important as any other factors.
    - Real topographical and geophysical differences among sites may make inter-site generalizations about habitat vulnerability problematic.

- There are also a number of ecological uncertainties that complicate the translation of habitat vulnerability patterns into the responses of organisms. These include:

    - Uncertainty about the factors that determine habitat carrying capacity for organisms such as migratory wildlife.
    - Uncertainty about the adaptive capacities of impacted wildlife populations.
    - Uncertainty about the meta-population dynamics of widely dispersed sites (how important is any one site (to migratory organisms, for example) in a coastline where a number of sites exist?)
    - The fates of many migratory species may be affected by climate changes distant from the northeastern study area (for example, in the arctic breeding areas of waterfowl and shorebirds, or in their wintering areas in Central and South America). Therefore, threats quantified in the Northeast may not adequately reflect the ultimate fates of these organisms.

- These uncertainties will only be resolved with a better understanding of the ecologies and habitat preferences of the organisms themselves.

CHAPTER 1. INTRODUCTION

The changing climate is now recognized as a potential major threat to fish and wildlife habitats, populations and communities (Schneider and Root, 2002; Karl *et al*., 2009; IPCC, 2007; Root and Hughes, 2005; Kelly and Goulden, 2008). Indeed, there is evidence that climate change may already be affecting ecosystems, as distributions of animals and plants change, ecological phenologies are disrupted, and community compositions and structures are altered (Parmesan and Galbraith, 2004; Parmesan, 1996; Schneider and Root, 2002; Wolfe *et al*. 2005; Primack *et al*. 2004).

Accelerating sea level rise (SLR) is one manifestation of the changing climate. Under rising global temperatures, sea water is undergoing steric expansion, and ice caps and glaciers are melting (Karl *et al*., 2009; IPCC, 2007; Rahmstorf, 2007; Pfeffer *et al*. 2008; Vermeer *et al*. 2009; Overpeck and Weiss, 2009), contributing to globally rising sea levels. SLR poses threats to coastal ecosystems that may become inundated, resulting in habitat change or loss and adverse impacts to species or communities that depend on that habitat. Indeed, it is generally considered by climate scientists that coastal ecological resources are likely to be among the most sensitive to the changing climate, and that the climate change impacts to ecosystems over the next few decades could be most marked in the planet's coastal zones (NECIA, 2007; Karl *et al*., 2009; IPCC, 2007; Jones *et al*., 2009; Erwin *et al*., 2006).

Much of the coastline is recognized as being of ecological and conservation importance. Some of this land (approximately 10% [Titus *et al.*, 2009]) is protected in local, state, and federal reserves. This protection mosaic has successfully conserved important populations of plants and animals and their habitats. Many of the reserves are recognized as "showcase" sites that demonstrate that ecological resources[1] can be conserved despite growing human pressures. However, this reserve system was established during a time when the challenge of climate change and shifting coastlines and habitats was not fully appreciated. We are now faced with a new suite of conservation questions that we have to address. How vulnerable are the various coastal habitats, plants and animals to climate change? What are our major uncertainties about the relationships among climate change, SLR, and the potential fates of plants and animals in coastal zones? Will our current conservation tools and strategies continue to conserve coastal ecosystems in an age of SLR? How, if necessary, could we modify our conservation approaches to counteract the effects of rising sea levels? And, lastly, how should this new threat affect our conservation research activities?

Before we can determine what our future conservation research activities should be in the northeastern coastal zone we need to appraise what we already know, or think we know, about the vulnerabilities of coastal resources under climate change, and what the remaining major

[1] Typically, these are populations of migratory shorebirds, migratory or breeding populations of waterfowl, or habitats for rare or restricted species such as saltmarsh sparrows, piping plovers or least terns.

uncertainties are. In this report[2] we review the scientific literature to evaluate what we think we know about the vulnerabilities of fish and wildlife habitats in the northeastern coastal zone to SLR, identify the major sources of uncertainty, and suggest future research that will help us continue to conserve coastal ecological resources. Specifically, we evaluate the extent to which existing studies, data sets and tools allow us to infer reliable conclusions about the likely vulnerabilities and fates of coastal habitats for fish and wildlife, the uncertainties that surround these conclusions due to the shortcomings of the existing datasets and tools, and how future research and conservation activities might help reduce such uncertainties. This review is intended primarily for resource managers who are charged with making practical decisions about land management, despite uncertainty, rather than scientific specialists.

Chapter 2 describes what is known about past and current rates of SLR in the Northeast Region[3], based on empirical tide gauge data, and what scientific studies tell us about future SLR. Chapter 2 also includes information about how extreme events like storm and tidal surges complicate the extrapolation of geophysical and ecological impacts. Chapter 3 reviews the relevant scientific literature to draw conclusions about what existing studies tell us about coastal habitat vulnerabilities. It does so by considering three categories of studies: recent Sea Level Affecting Marshes Modeling at coastal National Wildlife Refuges, and other modeling exercises; modeling of potential SLR impacts to piping plover breeding habitat (largely oceanic and estuarine beaches); and other modeling studies of SLR potential impacts to coastal wetlands. Uncertainties associated with all of these studies and procedures are discussed in Chapter 3. Chapter 4 identifies and describes our main areas of uncertainty about the potential vulnerabilities and fates of coastal habitats and how these could be reduced (or not) by further study.

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[2] supported by the North Atlantic Landscape Conservation Cooperative (NALCC) and the Northeastern Association of Fish and Wildlife Agencies (NEAFWA)

[3] The 11 coastal states from Virginia north to Maine (Virginia, Delaware, Maryland, New Jersey, New York, Pennsylvania, Rhode Island, Connecticut, Massachusetts, New Hampshire, and Maine).

CHAPTER 2. CURRENT AND FUTURE SEA LEVEL RISE IN THE NORTHEAST

Historic and Current Sea Level Rise

Sea levels have been rising globally since the last glaciation drew to a close about 12,000 years ago and when, with warming temperatures, the ice caps and glaciers began to melt. Prior to this, so much of the planet's water was locked up in ice that the prevailing global sea level was about 120 m lower than at present. Most of the post-glacial rise in global sea levels had taken place by about 6,000 years ago, after which the rate of SLR slowed to about 0.1 mm to 0.2 mm per year (Lambeck and Bard, 2000; Church *et al*., 2004)[4]. Beginning in the last century, however, the rate of sea level rise began to accelerate. Global climate change is contributing to this due to the thermal expansion of ocean waters and the melting of glaciers and ice fields (IPCC, 2007). The average global sea level rose during the 20th century at an average rate of 1.7 mm per year - about 10 times faster than the average rate of sea level rise during the last 3,000 years (IPCC, 2007). This recent acceleration has also been detected in tide gauge data from the Northeast (Boon, 2012). Importantly, sea level rise is not uniform across the globe – it varies based on a range of factors, including crustal processes (uplift and subsidence), ocean circulation patterns, variations in temperature and salinity, and the earth's rotation and shape. Also, human activities, such as nearshore oil and gas extraction or trapping of sediments by dams, can cause subsidence and local SLR. Evidence suggests that the Atlantic Coast of North America is a "hot spot" for a relatively higher rate of sea level rise than the global average (Sallenger *et al*., 2012). For example, recent rates of SLR in Chesapeake Bay exceed global rates by a factor of about two (Najjar *et al*., 2010; Boesch *et al*., 2013). In the coming decades, the average rate of sea level rise is expected to accelerate further (see next section), even under the most aggressive scenarios for reducing global emissions of greenhouse gases.

Our ability to quantify more recent changes in sea level in the Northeast began in the early 20th century when tide gauges began to be installed along the Atlantic coastline and empirical measurements became available. Table 1 shows results from 35 tide gauge stations on the northeastern coast from Virginia north to Maine. Figures 1 and 2 show two examples of the time-series data obtained from tide gauges in Virginia and New York, respectively. Mean current rates of SLR for each state with more than one gauging station are shown in Figure 3.

The data in Table 1 and Figure 3 confirm that sea levels in the Northeast are rising. Furthermore, there is consistent geographical variation across the region in the rates of 20th century sea level rise. Rates tend to be highest in the south, where they may exceed 5 mm/yr, but decrease to the north, where they may be lower than 2 mm/yr. As stated above, these differences between sites and areas are due to local factors (subsidence rates, sediment deposition, etc.) and not to measurement error. The states with the highest SLR rates are Virginia, Maryland, Delaware, and

[4] There were short periods at the end of the last glaciation, about 11,000 years BP, when SLR was more rapid than over the longer 6,000 year time scale.

New Jersey, while those with the lowest rates are Rhode Island, Connecticut, Massachusetts, and Maine.

Table 1. Historic rates of SLR (since about 1930 until present) and estimated future SLR in the Northeast (extrapolating the historic rate to 2100, and adding 1 m and 2 m SLR).

Site	Historic rate of rise (mm/yr)	2100 at historic rate (mm)	2100 at historic rate + 1 meter (mm)	2100 at historic rate + 2 meters (mm)
Virginia:				
Kiptopeke	3.48	309.72	1309.72	2309.72
Colonial Beach	4.78	425.42	1425.42	2425.42
Lewisetta	4.97	442.3	1442.3	2442.3
Gloucester Point	3.81	339.09	1339.09	2339.09
Sewell's Point	4.44	395.16	1395.16	2395.16
Portsmouth	3.76	334.64	1334.64	2334.64
Chesapeake Bay	6.05	538.4	1538.4	2538.4
Pennsylvania:				
Philadelphia	2.79	248.31	1248.31	2248.31
Maryland:				
Ocean City	5.48	487.72	1487.72	2487.72
Cambridge	3.48	309.72	1309.72	2309.72
Chesapeake City	3.78	336.42	1336.42	2336.42
Baltimore	3.08	274.12	1274.12	2274.12
Annapolis	3.44	306.16	1306.16	2306.16
Solomon's Island	3.41	303.49	1303.49	2303.49
Delaware:				
Reedy Point	3.46	307.94	1307.94	2307.94
Lewes	3.20	284.8	1284.8	2284.8
New Jersey:				
Sandy Hook	3.90	347.1	1347.1	2347.1
Atlantic City	3.99	355.1	1355.1	2355.1
Cape May	4.06	361.34	1361.34	2361.34
Washington, DC	3.16	281.24	1281.24	2281.24
New York:				
Montauk	2.78	247.42	1247.42	2247.42
Port Jefferson	2.44	217.6	1217.6	2217.6
Kings Point	2.35	209.15	1209.15	2209.15
The Battery	2.77	246.53	1246.53	2246.53
Connecticut:				
New London	2.25	200.25	1200.25	2200.25
Bridgeport	2.56	227.84	1227.84	2227.84
Rhode Island:				
Newport	2.58	229.62	1229.62	2229.62
Providence	1.95	173.55	1173.55	2173.55
Massachusetts:				
Boston	2.63	234.07	1234.07	2234.07
Woods Hole	2.61	232.29	1232.29	2232.29
Nantucket Island	2.95	262.55	1262.55	2262.55
Maine:				
Eastport	2.00	178	1178	2178
Bar Harbor	2.04	181.56	1181.56	2181.56
Portland	1.82	161.98	1161.98	2161.98
Seavey Island	1.76	156.64	156.64	156.64

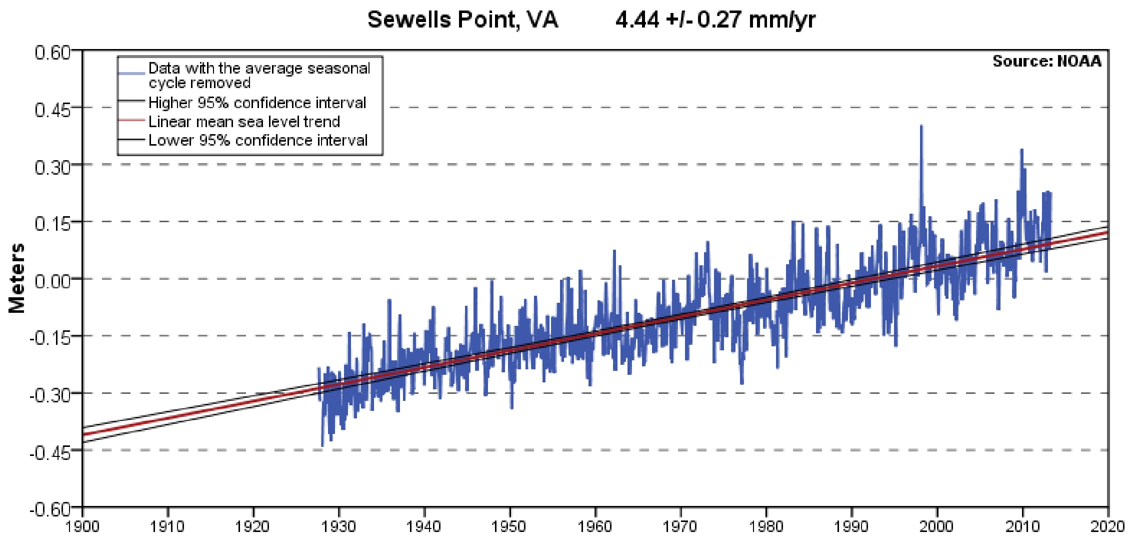

Figure 1. Sea level rise at Sewell's Point, Virginia. Image from http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8638610

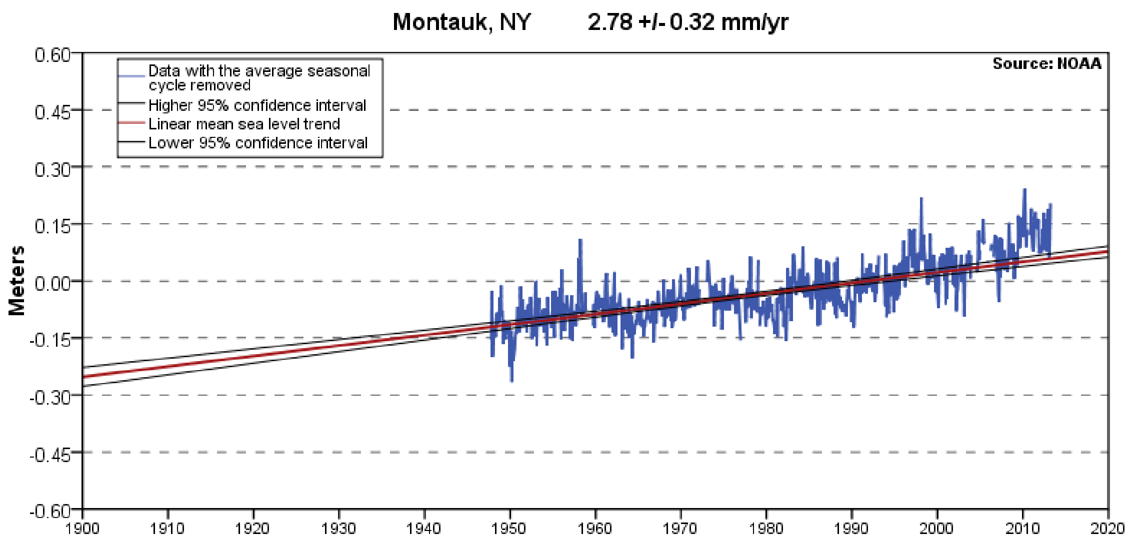

Figure 2. Sea level rise at Montauk, New York. Image from http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8510560

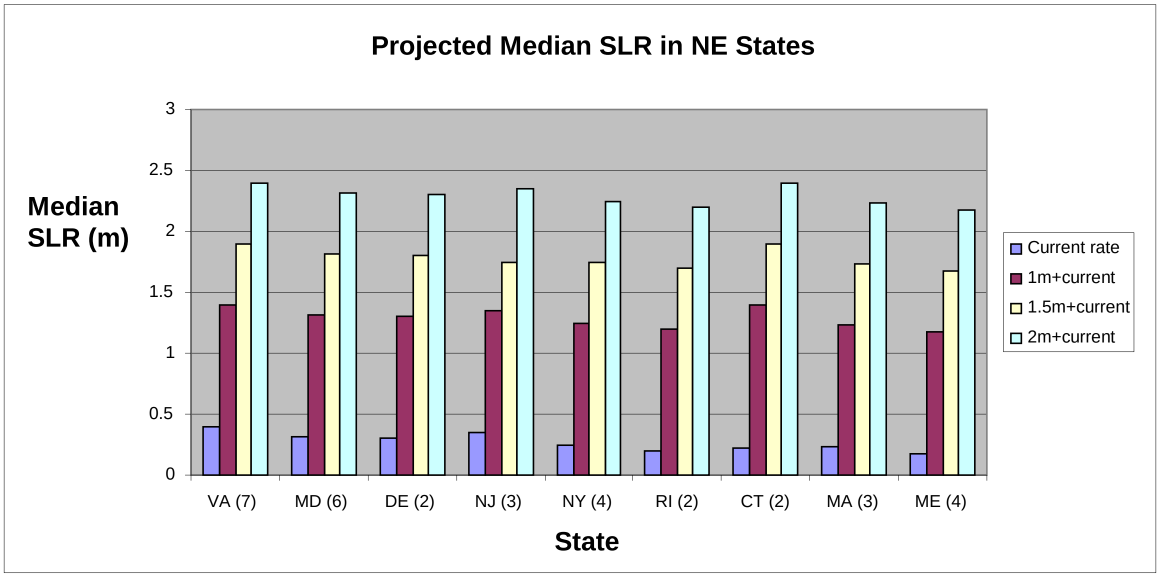

Figure 3. Projected level of sea level rise by 2100 across varying potential rates in sea level rise for Northeast Region states with coastline.

Future Sea Level Rise Projections

Future sea level rise projections have evolved over the last two decades (Figure 4). Earlier estimates were that the global mean sea level would rise over the course of this century by between about 10 cm and 60 cm. The most recent IPCC estimates (IPCC, 2007) were between about 18 cm and 59 cm, depending on the greenhouse gas emissions scenario[5]. However, other studies (Figure 4) that include more recent measurements of Arctic and Antarctic ice melt have produced larger estimates. Rahmstorf (2007), Pfeffer *et al*. (2008), Vermeer *et al*. (2009), Overpeck and Weiss (2009), and Jevrejeva *et al*. (2010) project estimates of between 0.5 m and 2.0 m, depending on the emissions scenario. It should be noted that the higher recent estimates are not "worst case scenarios." They are based on a projected tripling of greenhouse gas concentrations in the atmosphere, a target that will likely be reached over the next 90 years[6]. Table 1 and Figure 3 show projected SLR based on the combination of the historic rate of SLR at each of the northeastern tide gauges plus an additional 1 m and 2 m of SLR. We cannot precisely predict the rate and magnitude of future SLR[7], but we believe that these projections bracket the most likely outcomes, based on our current scientific understanding. Based on these data, it is reasonable to assume that by the end of this century mean sea levels in the Northeast Region will have risen by between about 1 and 2 meters, with the greatest increases in the more southern states.

[5] Most studies have assumed and compared two IPCC emissions scenarios: one that leads to a doubling of atmospheric CO_2 over the course of this century, and another that will result in a tripling. These are the B1 and the A1FI scenarios, respectively (SRES, 2002).
[6] Recent CO_2 emissions rates exceed the highest IPCC emissions scenarios (Karl *et al*., 2009).
[7] Our ability to project future SLR becomes less certain the further into the future we try to project. This is largely due to uncertainties about the melting of ice caps, ice sheets, and glaciers beyond the next few decades.

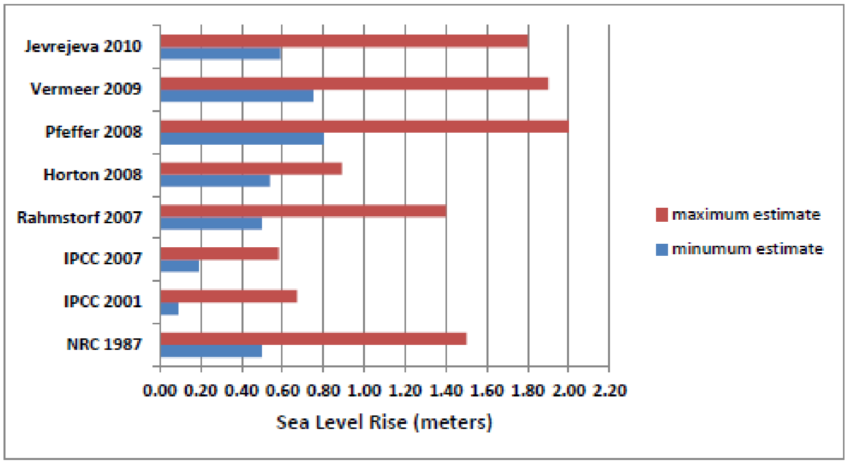

Figure 4. Projections of future global sea level rise.

Coastal Storms and Storm Surges

Considering sea level rise over a period of decades may lead to a misapprehension that the changes that will occur in coastal ecological systems as they are inundated will be slow and linear. However, this may not be the case. Stochastic events, particularly storm-driven surges, could cause non-linear ecological changes extending beyond the brief lifetime of the event itself. While coastal storms may be beneficial to coastal habitats, through the redistribution of sediments for example (Cahoon, 2006), extreme storms can be destructive. The history of coastal storm events that resulted in the exacerbation of the impacts of high tides on the Atlantic and Gulf coasts of North America is well known. Hurricane Katrina in 2005, for example, not only destroyed lives and human infrastructure on a massive scale, it also caused extensive destruction to coastal saltmarshes along the coast of the Gulf of Mexico. A high tide event was amplified by the hurricane force winds and driven inland onto ecosystems that would not otherwise have been impacted. Over 60 square miles of Lake Pontchartrain's wetlands were destroyed by the winds and the tidal surge over a 24-hour period, and barrier islands and coastal beaches were also inundated, stripped of their sand, and destroyed. While it is possible that some of these losses may be reversed by future natural marsh-building processes, some might be permanent (Morton and Barras, 2011). In the Northeast, Cahoon (2006) found that storm surges can affect coastal habitats through changes in soil surface elevation and by disrupting ecological processes.

Several studies have found a positive correlation between average oceanic temperatures and the intensities of tropical storms and hurricanes (Emanuel 2005; Trenberth *et al*., 2007; Webster *et al*. 2005), and there is evidence of an increase in intense tropical cyclone activity and in summer sea surface temperature in the North Atlantic over the past 40 years (Webster *et al*. 2005; Meehl *et al*. 2007). Based on this evidence, the trend toward more intense storms will continue in the coming decades as the oceans continue to warm (Oouchi *et al*. 2006; Holland and Webster 2007; Mann *et al*. 2007; Trenberth *et al*. 2007). Oouchi *et al*. (2006) suggest that the number of storms in the North Atlantic could increase this century by as much as 34 percent. Furthermore, storms are likely to become more destructive in the future as SLR contributes to higher storm surges (Anthes *et al*. 2006).

Tebaldi *et al*. (2012) projected future change in frequency of today's 100-year flooding events through the year 2050 and estimated return frequencies of 5 years for Portland, ME, 30 years for Boston, MA and 10 years for Providence, RI. Figure 5 depicts the projected return frequencies for all of the tide gauges included in the Tebaldi *et al*. (2012) study.

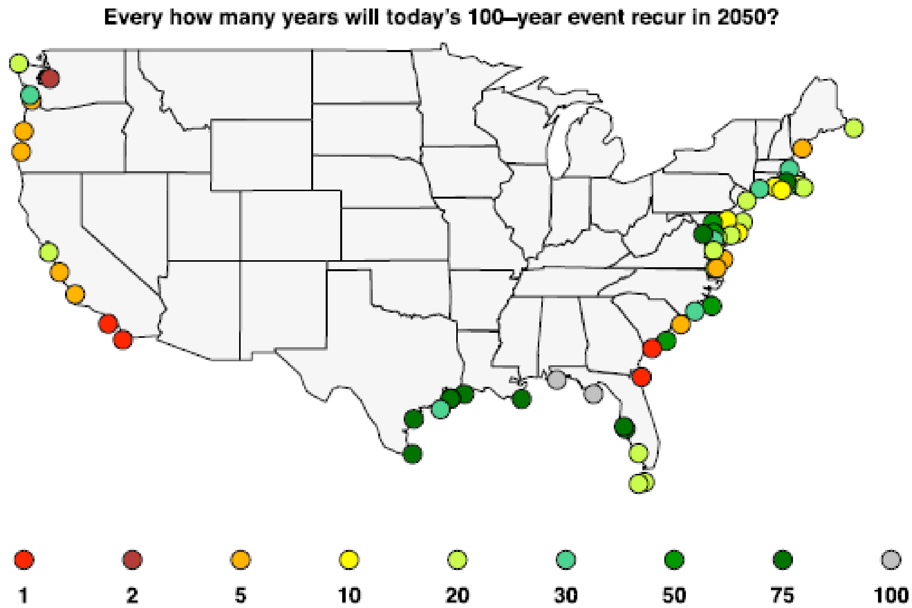

Figure 5. Projected return frequencies of 100-yr storm events by 2050 at tide gauge stations (from Tebaldi *et al.*, 2012).

The combination of rising sea levels and more frequent and intense storm events with their associated tidal surges could mean that habitat changes could occur earlier and be more marked than would be expected assuming a conceptual model of long, slow mean sea level change.

CHAPTER 3. HABITAT VULNERABILITIES

In this chapter we review the existing studies that have focused on the vulnerabilities of coastal habitats to SLR, concentrating on oceanic and estuarine beaches, tidal flats, and saltmarshes. These three main habitats provide essential habitat for valued fish and wildlife populations. Tidal flats are important feeding areas for important populations of migratory shorebirds, waterfowl, mollusks and, at high tide, for fish. Oceanic and estuarine beaches provide breeding habitat for state and federally listed bird species including piping plovers, black skimmers, and least terns. Saltmarshes provide feeding habitat for waterfowl and raptors, roosting sites for shorebird flocks, breeding habitat for saltmarsh sparrows, nursery areas for fish, and nesting and breeding sites for many mammal, bird and invertebrate species.

Much of this habitat vulnerability work has been undertaken in protected areas such as National Wildlife Refuges (NWRs) and state owned or managed reserves, areas that typically support important ecological habitats, populations and communities. Other areas have received less attention. However, it is our contention that the results from the former, while not exactly transferable, are relevant to the latter. Future conservation needs to encompass all areas of coastline with ecological resources. Our focus on the NWRs in this review is due in large part to data availability. Most of the recent work modeling potential SLR impacts on coastal fish and wildlife habitats was undertaken and completed using the Sea Level Affecting Marshes Model (SLAMM) applied to NWRs.

SLAMM Modeling in the Northeast

Beginning in 2008 and funded by the U.S. Fish and Wildlife Service (FWS), the SLAMM model was applied to 28 coastal NWRs in the Northeast Region (Figure 6 and Table 2). At first the version of SLAMM that was used was the 5th (SLAMM5). However, beginning in 2009, a new version (SLAMM6) was used. SLAMM6 differs from SLAMM5 in several ways, including that feedbacks based on wetland elevation, distance to channel, and salinity can be specified; multiple time-variable freshwater flows can be specified; salinity can be estimated and mapped; etc. In general, SLAMM6 continues a tradition of incorporating increasing sophistication into the SLAMM modeling process.

The SLAMM modeling process projects habitat change at coastal sites based on a digital elevation model (DEM), a map of the current distributions of wetland habitats, assumptions about future SLR, accretion and erosion rates, and other site specific topographic and physical factors[8]. While these studies are confined to NWRs, they are the most comprehensive and consistent set of studies performed thus far on northeastern coastal habitat vulnerabilities, and comprise a highly important data set.

[8] Its focus on these local processes and on vegetation transitions distinguishes the modern "process models," like SLAMM from simpler so-called "bathtub models" which do not incorporate elevation change due to sedimentation and/or erosion (Fagherazzi *et al*., 2012)

Tables 3 and 4 show the results of the SLAMM modeling at the 28 northeastern coastal NWRs, assuming 1 m and 2 m SLR[9] .The data in tables 3 and 4 were obtained from Warren Pinnacle Consulting, Inc. (available online from http://warrenpinnacle.com/prof/SLAMM/USFWS/), the consulting firm that executed the SLAMM analyses for U.S. FWS. Information on which version of SLAMM was used to model a particular refuge is also available from the relevant report on the Warren Pinnacle website.

The data in these tables project major habitat changes at most sites under both SLR scenarios. They also show that the three habitats differ in their projected vulnerabilities to SLR. From a region-wide perspective, the area of tidal flats is projected to greatly increase (by 1 and 20 orders of magnitude under the 1 m and 2 m SLR scenarios, respectively). Oceanic and estuarine beaches are projected to be reduced by about 20% and 75% under the 1 m and 2 m scenarios, respectively, and saltmarshes are projected to be reduced by approximately 45% and 65% under the SLR scenarios[10]. Thus, over the entire region, the SLAMM modeling projects major gains in the extent of tidal flats, and large-scale reductions in oceanic and estuarine beaches and saltmarshes (even under the more modest 1 m SLR scenario).

These habitat changes could have serious implications for the abilities of northeastern coastal sites to continue to provide adequate habitat for important animal populations. Even shorebirds (Galbraith *et al*., 2002; Galbraith *et al.*, *in press*), which might be expected to benefit from the increasing extent of their tidal flat feeding areas, might be adversely affected by the decreasing availability of saltmarsh roost sites. Saltmarsh sparrows might lose important nesting habitat as saltmarshes are inundated, and piping plovers might lose important beach nesting habitats.

[9] Only 16 of the 28 reserves were subjected to 2 meter change modeling.

[10] There is evidence that northeastern saltmarshes are already showing signs of degradation due to SLR. For example, on Cape Cod they are being fragmented and replaced by open water panes (Smith, 2009).

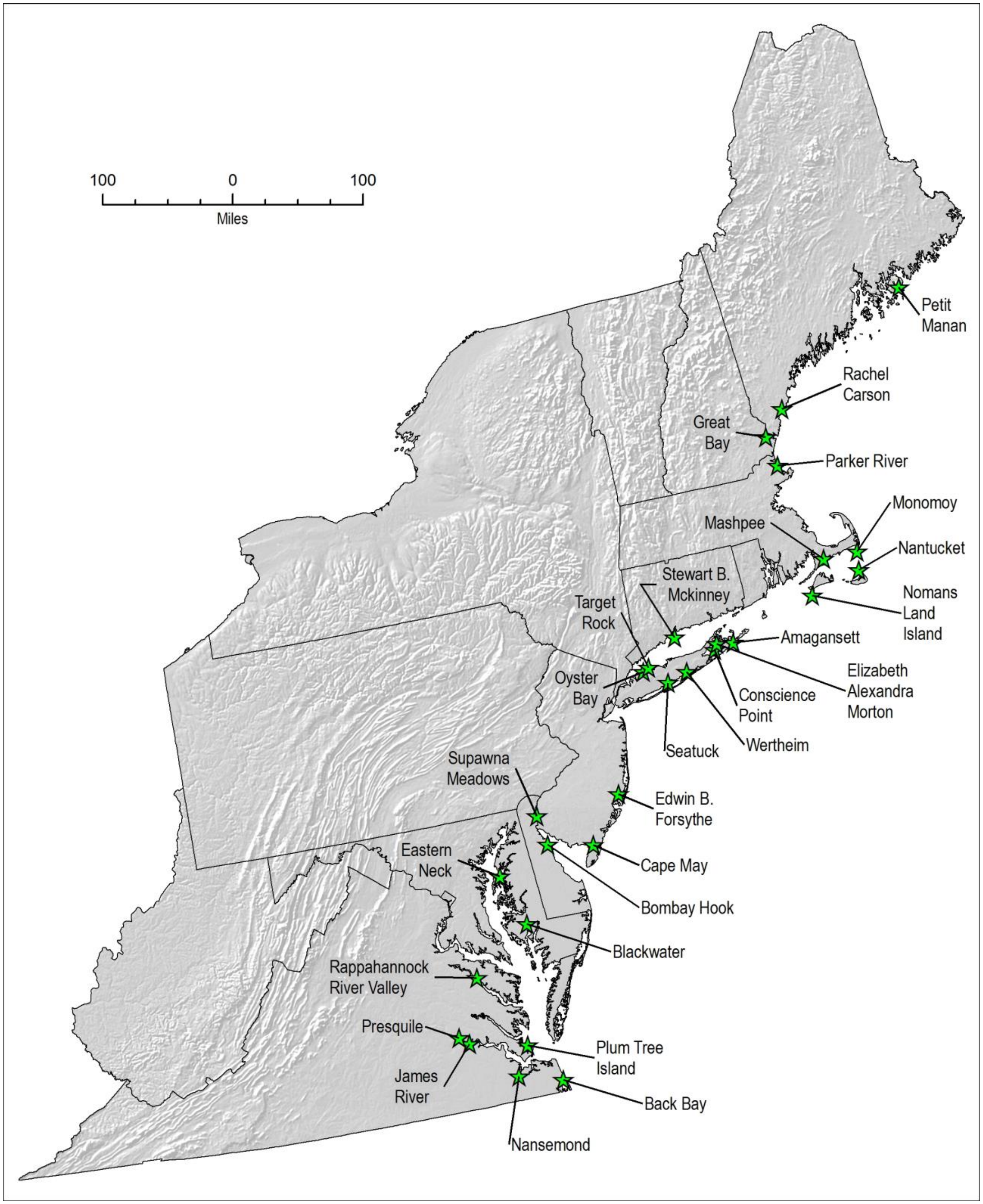

Figure 6. Locations of 28 National Wildlife Refuges in the Northeast Region for which SLAMM modeling has been performed.

Table 2. National Wildlife Refuges (NWR) in U.S. Fish and Wildlife Service Northeast Region in which SLAMM modeling has been completed. NED stands for the National Elevation Dataset, and LiDAR stands for Light Detection and Ranging. Sea level rise assumptions are the global sea level rise scenario for the year 2100.

State	NWR	Year	Area (ha)	Digital Elevation Data	Sea Level Rise Assumptions (m)
Maine	Petit Manan	2010	3,702	LiDAR/NED	0.39, 0.69, 1.0, 1.5, 2.0
	Rachel Carson	2008	3,563	LiDAR/NED	0.39, 0.69, 1.0, 1.5
New Hampshire	Great Bay	2009	405	NED	0.39, 0.69, 1.0, 1.5
Massachusetts	Parker River	2009	2,580	LiDAR/NED	0.39, 0.69, 1.0, 1.5
	Mashpee	2012	2,610	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
	Monomoy	2012	3,039	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
	Nantucket	2009	12	NED	0.39, 0.69, 1.0, 1.5
	Nomans Land	2009	688	NED	0.39, 0.69, 1.0, 1.5
Connecticut	Stewart McKinney	2009	445	LiDAR/NED	0.39, 0.69, 1.0, 1.5
New York	Amagansett	2009	16	LiDAR	0.39, 0.69, 1.0, 1.5
	Conscience Point	2009	24	NED	0.39, 0.69, 1.0, 1.5
	E.A. Morton	2008	72	NED	0.39, 0.69, 1.0, 1.5
	Oyster Bay	2009	1,376	NED	0.39, 0.69, 1.0, 1.5
	Seatuck	2009	81	NED	0.39, 0.69, 1.0, 1.5
	Target Rock	2009	32	NED	0.39, 0.69, 1.0, 1.5, 2.0
	Wertheim	2008	1,093	LiDAR/NED	0.39, 0.69, 1.0, 1.5
New Jersey	Cape May	2011	8,664	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
	E.B. Forsythe	2012	29,150	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
	Supawna Meadow	2009	1,822	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
Maryland	Blackwater	2009	10,121	NED/LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
	Eastern Neck	2009	847	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
Delaware	Bombay Hook	2010	8,502	LiDAR/NED	0.39, 0.69, 1.0, 1.5, 2.0
Virginia	Back Bay	2011	6,478	LiDAR	0.39, 0.69, 1.0, 1.5, 2.0
	James River	2010	1,822	2' contour	0.39, 0.69, 1.0, 1.5, 2.0
	Nansemond	2009	170	NED	0.39, 0.69, 1.0, 1.5, 2.0
	Plum Tree Island	2009	2,024	NED	0.39, 0.69, 1.0, 1.5, 2.0
	Presquile	2009	526	NED	0.39, 0.69, 1.0, 1.5, 2.0
	Rapahannock	2009	115,385	NED	0.39, 0.69, 1.0, 1.5, 2.0

Table 3. Current and projected future area of three habitats found on National Wildlife Refuges (NWR) in U.S. Fish and Wildlife Service Northeast Region. Data shown are the expected change in extent by 2100 under a scenario of 1 m of additional sea level rise. Data are available online from Warren Pinnacle Consulting.

NWR	Tidal Flats		Oceanic / Estuarine Beach		Saltmarsh	
	Current	2100	Current	2100	Current	2100
Petit Manan	157	54	17	180	61	249
Rachel Carson	151	344	160	99	28	493
Great Bay	<1	<1	0	6	11	18
Parker River	325	155	92	129	61	771
Mashpee	0	23	<1	1	71	40
Monomoy	23	95	391	189	415	414
Nantucket	0	0	3	<1	0	0
Nomans Land Island	0	<1	4	<1	0	0
Stewart B. McKinney	0	99	56	13	49	125
Amagansett	0	0	3	<1	0	0
Conscience Point	0	<1	15	0	0	8
Elizabeth A. Morton	0	4	0	0	<1	2
Oyster Bay	6	2	7	3	19	21
Seatuck	4	<1	0	9	3	4
Target Rock	0	0	<1	<1	<1	1
Wertheim	0	<1	3	18	258	98
Cape May	4	96	6	16	1,520	3,118
Edwin B. Forsythe	216	7,174	221	241	13,794	2,072
Supawna Meadows	2	26	0	0	858	777
Blackwater	30	526	157	5	9,296	3,857
Eastern Neck	0	34	0	0	158	175
Bombay Hook	17	321	410	402	5,501	5,631
Back Bay	0	730	27	108	1,895	621
James River	0	36	0	0	0	51
Nansemond	0	50	3	0	86	4
Rappahannock	0	306	95	0	3,707	1,771
Presquile	0	0	3	0	4	103
Plum Tree Island	0	157	71	0	908	8
All	**934**	**10,249**	**1,747**	**1,423**	**38,204**	**20,438**

Table 4. Current and projected future area of three habitats found on National Wildlife Refuges (NWRs) in U.S. Fish and Wildlife Service Northeast Region. Data shown are the expected change in extent by 2100 under a scenario of 2 m of additional sea level rise. NWRs for which 2 m of additional seal level rise was not modeled have no predictions for 2100 (but see Table 3 for predictions under a scenario of 1 m additional sea level rise). Data are available online from Warren Pinnacle Consulting.

NWR	Tidal Flats		Oceanic / Estuarine Beach		Saltmarsh	
	Current	2100	Current	2100	Current	2100
Petit Manan	157	36	17	85	61	258
Rachel Carson	151		160		28	
Great Bay	<1		0		11	
Parker River	325		92		61	
Mashpee	0	20	<1	3	71	55
Monomoy	23	139	391	3	415	276
Nantucket	0		3		0	
Nomans Land Island	0		4		0	
Stewart B. McKinney	0		56		49	
Amagansett	0		3		0	
Conscience Point	0		15		0	
Elizabeth A. Morton	0		0		<1	
Oyster Bay	6		7		19	
Seatuck	4		0		3	
Target Rock	0	0	<1	<1	<1	2
Wertheim	0		3		258	
Cape May	4	1,471	6	25	1,520	2,618
Edwin B. Forsythe	216	1,169	221	141	13,794	2,062
Supawna Meadows	1	336	0	0	858	466
Blackwater	30	987	157	2	9,296	3,620
Eastern Neck	0	17	0	0	158	106
Bombay Hook	17	3,789	410	20	5,501	561
Back Bay	0	570	27	79	1,895	273
James River	0	51	0	0	0	29
Nansemond	0	<1	3	0	85	14
Rappahannock	0	143	95	0	3,207	3,173
Presquile	0	0	4	0	4	217
Plum Tree Island	0	8	71	0	908	77
All	**449**	**8,738**	**1,404**	**358**	**37,776**	**13,810**

Though these region-wide habitat vulnerabilities are obvious from Tables 3 and 4, it is important to note that they are not completely consistent between sites. For example, the SLAMM modeling projects that tidal flats will suffer net losses, not gains, at a few sites (Petit Manan and Parker River, for example). In fact, much of the regional projected gains in tidal flats will occur, according to the SLAMM modeling, in the Mid-Atlantic states. Similarly, oceanic and estuarine beaches are not projected to be similarly vulnerable at all sites: they are projected to show gains, not losses, at Petit Manan and Parker River NWRs, and to change little at some other NWRs. The same is true for saltmarsh extent at Petit Manan, Parker River, and Rachel Carson NWRs. Thus, there are site-specific differences in the model projections, with the three northern NWRs

(Petit Manan, Rachel Carson and Parker River) being exceptions to the broad patterns of change that are projected for many of the other sites.

The reasons underlying the differences between the three northern NWRs and the others are not entirely clear, but could be due to methodological problems in applying the SLAMM model. When the analyses were performed, only limited LiDAR (Light Detection and Ranging) data had been gathered at Parker River, Petit Manan and Rachel Carson NWRs, and less accurate NED (National Elevation Dataset) data were used. The differences observed between these three reserves and the others could therefore be an artifact of data precision (although note these were not the only NWRs lacking accurate elevation data). It is possible that the results from these sites (at least for the 1 m and 1.5 m scenarios) are so compromised as to be misleading. For the sake of completeness, we have presented the data here, but readers should be aware of this potential flaw in the results. More recently, LiDAR data have been collected at the three northern sites. If the SLAMM were rerun using the LiDAR data, we might obtain different results, perhaps more in line with the other NWR projections.

The differences among sites, if real, could be ecologically significant because the Parker River and Rachel Carson NWRs are very important to migratory shorebirds on the Atlantic Flyway. The migratory shorebirds that use the northeastern NWRs as stopover sites might benefit from the tidal flat increases projected for the more southern states, but it is not known to what extent they will be adversely impacted by the loss of feeding habitat at more northern "migration stepping-stones," such as Parker River NWR. The impacts of changes in feeding habitat availability among the migration "stepping stones" could be as important as, or outweigh, overall gains or losses in the region. We simply do not know enough about the regional metapopulation ecology of these organisms to say.

Uncertainties in SLAMM modeling

Like all predictive models, SLAMM is vulnerable to uncertainties in the input variables. In the past, high levels of uncertainty were associated with input digital elevation models (DEMs), the maps of current wetland distribution, and the SLR assumptions. Historically, the only DEMs that were available were derived from relatively inaccurate remote sensing (aerial photographs). Consequently, the accuracy of the DEMs used might vary by up to 20 feet, rendering problematic projections about processes that worked at a scale of much less than this (e.g., SLR, which operates at a scale of at most 2 m). Of the 28 NWRs analyzed in the study described above, exclusively DEM data were used for 12 NWRs (Table 2).

In recent years, this constraint on the accuracy of SLR modeling has been mitigated by the advent of LiDAR measurements of surface elevation. In contrast to the older methods of obtaining DEMs, LiDAR data can provide accuracies of about 6 cm to 15 cm. Half of the NWRs in the study described above had some combination of LiDAR and older DEM data incorporated into the modeling, while eight NWRs had complete LiDAR coverage.

While LiDAR data are generally more accurate, they also have some uncertainty. For example, the accuracy of LiDAR sensing may be compromised by vegetation height: in a habitat that is dominated by tall vegetation, LiDAR may confuse the vegetation height with the land surface. In the most recent LiDAR studies this uncertainty is addressed by “bare-earthing,” in which ground-based studies that provide a correction factor in cases where such confusion is likely. Another source of uncertainty for LiDAR data is that it can be of variable accuracy below mean tide level.

Most of the SLAMM studies described above used the U.S. FWS National Wetland Inventory (NWI) maps to estimate current wetland distribution. Estuarine and coastal ecological systems are notoriously dynamic, shifting in space and time. In some cases, older wetland maps (going back in some cases to the 1990s) were used. For such areas, there is greater uncertainty that the actual current habitat distributions match what is mapped. Much of the NWI data are not tidally coordinated, meaning that the initial conditions for these flats may be undercounted at some locations (J. Clough, *pers. comm.*). Also, NWI maps may not adequately capture fringe wetlands and the classifications themselves may be subject to inaccuracies. Recently, some northeastern states have begun mapping the distributions of coastal wetlands, rather than rely entirely on the NWI data. In Massachusetts, for example, the state Department of Environmental Protection has mapped coastal wetlands at a scale of 1:12,000. These maps are probably preferable to the older and less precise NWI maps. It is to be hoped that other northeastern states will follow this example.

Another source of uncertainty is associated with the SLR projections that are used in SLAMM modeling. We cannot definitively predict how much global and local sea levels will change over the remainder of this century. We are better able to project over the next few decades than we can into the second half of the century (due to longer term uncertainty about how ice sheets, ice caps and glaciers will behave). In most studies this uncertainty is “bookended” by assuming a range of sea level changes – often 0.39 m to 2 m. It is not possible at this time to assign a probability to values in this range; they all have some plausibility. Nevertheless, a 1 m difference in future conditions has enormous implications for habitat impacts. It can be seen by comparing Tables 3 and 4 that moving from 1 m to 2 m SLR may as much as double the estimated habitat area change. In the absence of a fail-proof crystal ball, we cannot eliminate this source of uncertainty from our modeling; we must learn how to live with it.

SLAMM modeling has also been criticized in the past because it may not represent adequately all of the dynamic processes that occur in coastal systems and that help determine habitat distribution. For example, it is important to be able to mirror potential future accretion processes. Efforts are currently underway to try to improve our modeling abilities by addressing these limitations. However, the results of these endeavors will not eliminate other major sources of uncertainty, such as those that beset mapping wetland distributions or SLR predictions. So, switching to a model that more accurately incorporates erosion and/or sedimentation processes, while desirable, may not greatly reduce the overall uncertainty that is associated with projecting the effects of SLR on tidally-influenced habitats, populations, and communities.

We have shown above that the SLAMM modeling process is subject to uncertainty, depending on the input data and the model itself. How does this affect the results of the NWR analyses reported in the previous section? Given that at least some of these uncertainties coalesce around tidal flats (limitations in the LiDAR data, the NWI data, and uncertainties about sediment supply) we should focus on the major conclusion from the studies that tidal flats may increase in area due to SLR. It is possible that this conclusion is an artifact of the data and the modeling process. However, the fact that the result was consistent across 15 of the 28 NWRs suggests that the result may be robust.

Other uncertainties are ecological in nature and not confined to the SLAMM models. We cannot yet project how ecological communities and populations will respond to a predicted change in habitat extent. For example, if, as is projected in Table 3, a 1 m SLR reduces the extent of tidal flats at Parker River NWR by approximately 50%, how will the shorebird and waterfowl populations for which this site is famous respond? The answer hinges on our assumptions about the extent to which these populations are habitat-limited and the carrying capacities of sites. Population/community response to habitat changes will be mediated through a number of factors, including the quality of the habitat that is lost, the relative importance of a site as a flyway “stepping stone,” the age structures of the affected organisms, and the amount of “superfluous” habitat that exists along the flyway. The important point here is that we are unable, at this juncture, to make quantitative and precise predictions about the relationships between habitat extent and quality and population change. This constraint is not due to shortcomings in our physical modeling capabilities, but instead to our lack of understanding about ecological relationships, and applies to any habitat change models, including but not limited to SLAMM.

SLR and Piping Plover Breeding Habitat in the Northeast

While the following discussion focuses on beach-nesting piping plovers in the Northeast, it should be recognized that other species, such as oystercatchers, skimmers and least terns, also use this habitat. All of these are currently the focus of intense conservation efforts. Thus, piping plovers can be seen as a surrogate for these other species.

Sims (2012) modeled the consequences of SLR over the next 100 years for piping plover nesting habitat in Rhode Island. The study focused on five mainland beaches that are currently used by the birds as breeding sites. The SLR scenarios used in the study were increases of 0.5 m, 1 m, and 1.5 m. For each magnitude of SLR, three rates were also modeled. In the first, rapid SLR disrupted the inland migration of the sites (the “stationary model”). In the second, the pace of SLR allowed the inland migration of the coastal system (the “migration without development model”). In the third, the pace of SLR allowed the inland migration of nesting habitat, but migration was inhibited by current development (the “migration with development model”). Sims (2012) modeled the migration potential for Rhode Island barrier beaches by modifying a model previously developed by Seavey *et al*. (2011) for barrier islands in New York**.**

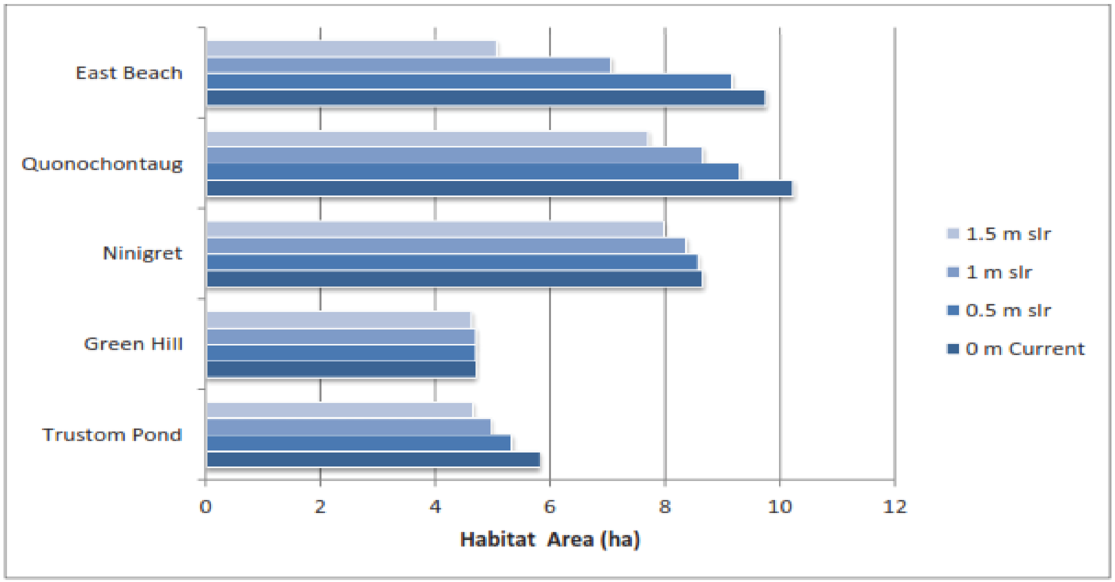

Figure 7. Predicted beach habitat area (in ha) at five sites in Rhode Island under the "stationary model," in which rapid SLR disrupts the inland migration of the site (from Sims, 2012).

Sims (2012) found that under the stationary model the area of habitat available to the piping plovers would decrease by different extents at all five sites and that the amount of reduction would be a function of the degree of SLR, with greater SLR resulting in more habitat loss (Figure 7). Under the migration without development model (Figure 8)**,** four of five sites showed large increases in beach habitat extent under all simulated levels of SLR, although one showed no change at the 1.5 m SLR scenario. Under the migration with development model (Figure 9), the results were mixed, with three sites showing habitat increasing in extent relative to the current area even at the 1.5 m SLR scenario and the other two sites showing some habitat reduction at the 1.5 SLR scenarios. These results emphasize two important points: first that the rate of SLR will be as important as the extent; and that human responses to SLR (e.g., installation of sea level protection structures) will be critical in determining the future of habitats. Sims (2012) noted that model accuracy is limited by uncertainties related to factors such as landform movement; dynamic sediment budgets, including erosion and storm effects; and vegetation responses. For example, extensive creation of increased beach habitat would not be expected without an additional sand source. However, the model serves to help to predict potential beach habitat migration pathways—and blockages—through the coastal landscape.

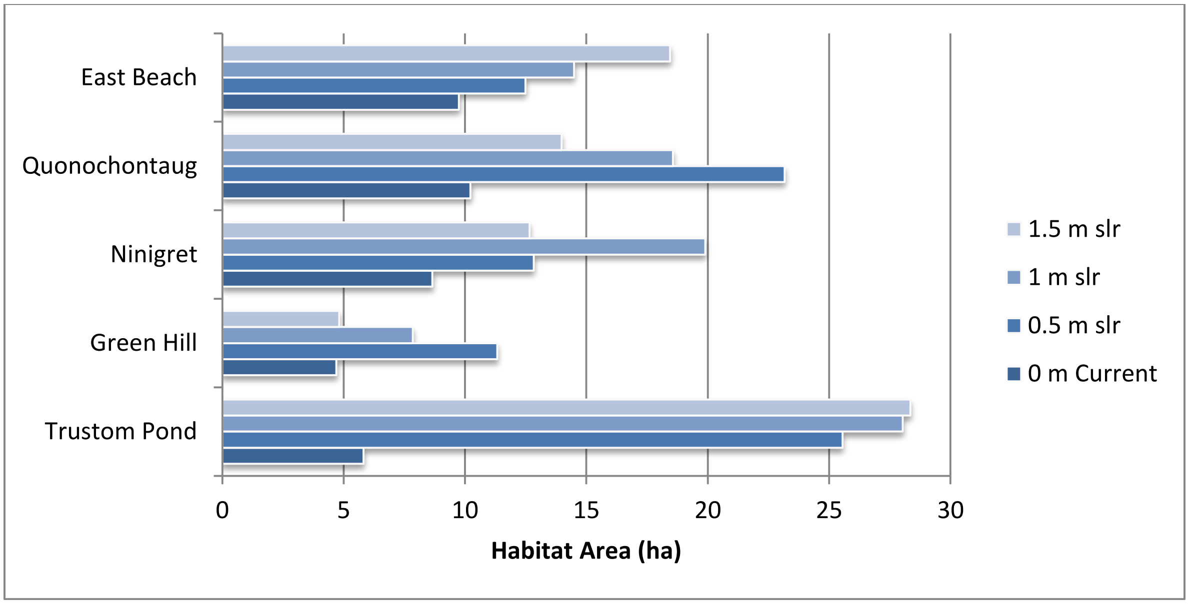

Figure 8. Predicted beach habitat area (in ha) at five sites in Rhode Island under the "migration without development model," in which the pace of SLR allowed the inland migration of the coastal system (from Sims, 2012).

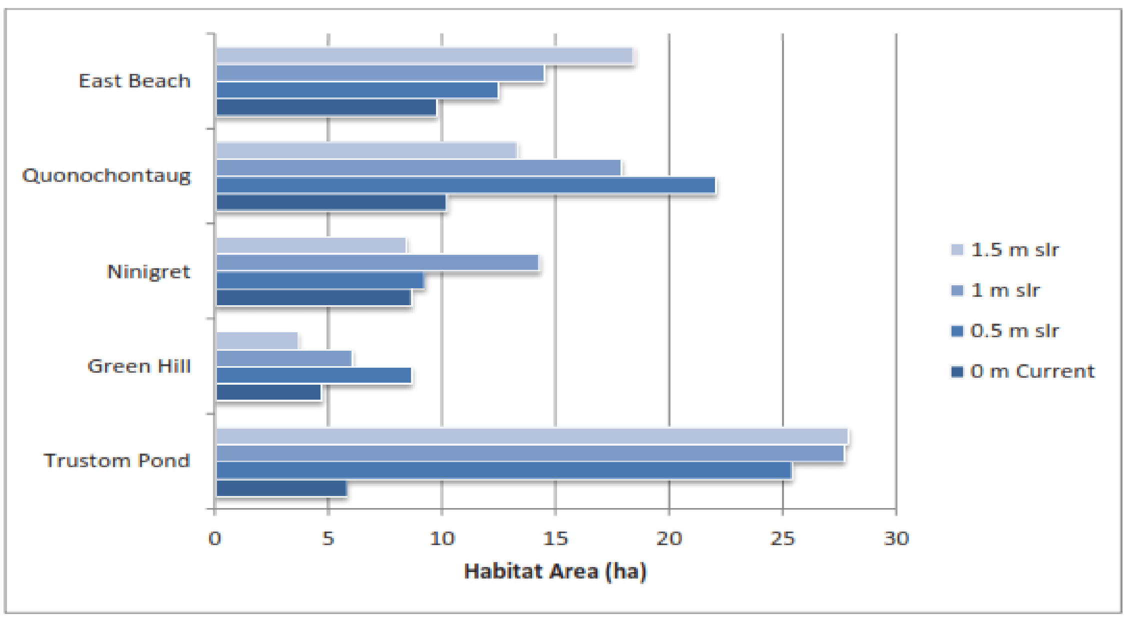

Figure 9. Predicted beach habitat area (in ha) at five sites in Rhode Island under the "migration with development model," in which the pace of SLR allowed the inland migration of nesting habitat, but migration was inhibited by current development (from Sims, 2012).

Seavey (2009) and Seavey *et al*. (2011) modeled the potential impacts of SLR, storm frequencies and intensities, and development over the next 100 years on piping plover barrier beach nesting habitats on Long Island, New York. The four SLR scenarios that were included were 0.38 m, 0.47 m, 0.5 m, and 1.5 m. Another important component of this study measured the limiting effects of density dependence on piping plover productivity at the study sites: higher breeding densities resulted in reduced productivity.

Two geomorphological scenarios were assumed: first, a static response model where breeding beaches were unable to move inland in response to rising sea levels, and so habitats within each of the study sites were inundated without being able to shift within the sites; and second**,** a dynamic response model where, though the sites were unable to move laterally in response to SLR, the beach habitats within the sites were able to move upward in elevation within the site. A third possible response model – dynamic landform and dynamic habitats (where both the site and the habitats were able to migrate in response to SLR**)** was not considered due to the difficulties in projecting barrier beach landform migration. Seavey (2009) also modeled a scenario that assumed that the current development footprint would block creation of habitat.

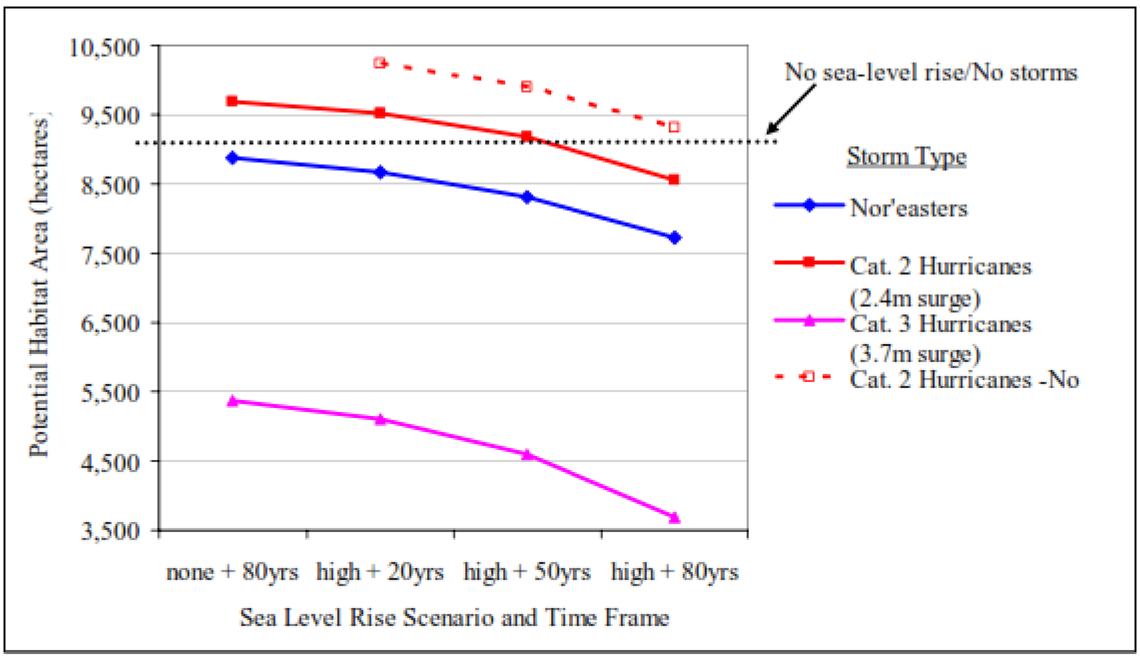

Figure 10. Storm and sea level rise impacts on piping plover nesting habitat on the barrier islands of Suffolk County, New York. The red dashed line shows category two hurricanes under "high" sea-level change without development in the model. The black dashed line shows the amount of potential habitat with no changes in sea-level or storms (from Seavey, 2009 [Figure 3.5]).

The results showed that if the rate of SLR overwhelmed the ability of habitats or landforms to move the result would be large habitat losses for piping plovers. In contrast, if the habitats were able to move upward in elevation (albeit on a static landform), habitat for piping plovers was projected to increase with increasing SLR. These results are all similar to those obtained by Sims (2012) in Rhode Island. The studies also considered the effects of storms on habitat extent independent of SLR. Seavey (2009) and Seavey *et al*. (2011) found that category two hurricanes were likely to increase piping plover habitat (beach areas), but category three hurricanes and nor'easters could result in habitat loss through storm inundation of nesting areas (Figure 10).

Seavey (2009) and Seavey *et al*. (2011) also factored current development into the analysis. For a given level of SLR, and assuming a dynamic response model, the greatest amount of habitat creation occurs in the absence of development (Figure 11). Assuming a given SLR and assuming a dynamic response model and the presence of all three classes of current development (high, medium and low intensity), the least amount of habitat creation occurs. Thus far, these results are relatively straightforward to conceptualize. However, when considering individual development classes, there is no conceptually simple relationship between amount of development and habitat loss or gain, with the highest density of development contributing to the highest rate of habitat creation, and the lowest density of development contributing to the lowest rate of habitat gain. The results may be due to the particular quantity and configuration of the intensity classes in this

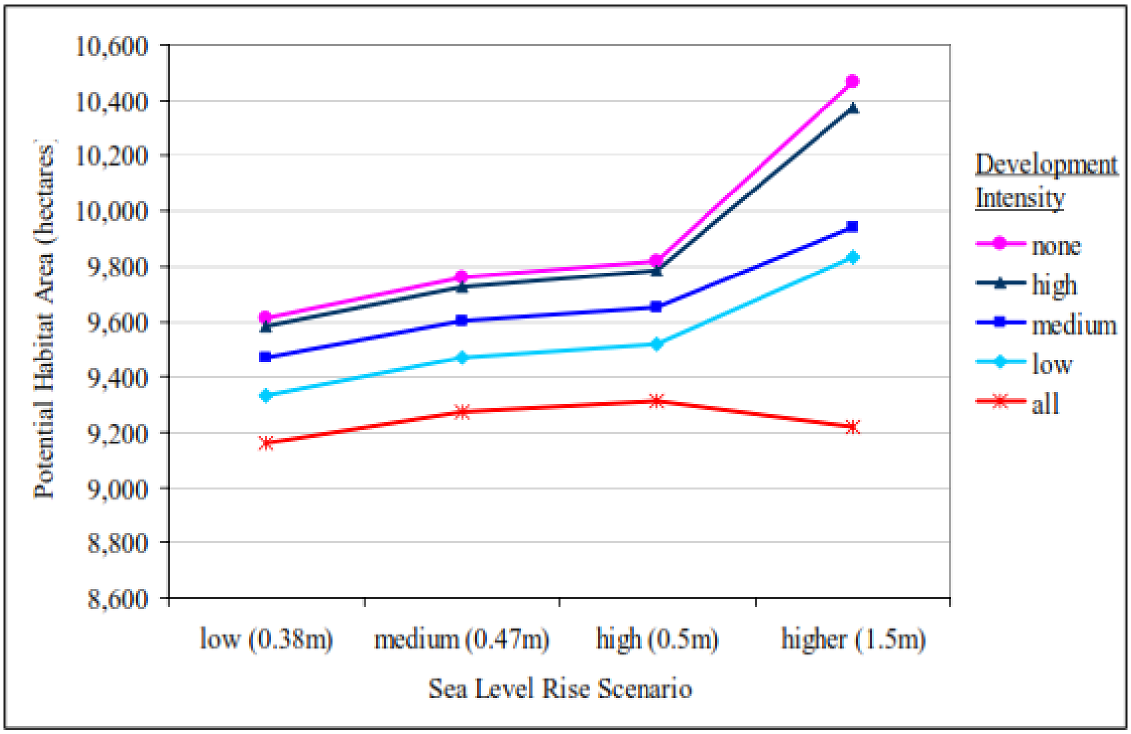

Figure 11. Predicted area of piping plover habitat (ha) on the barrier islands of Suffolk County, New York under five development intensity levels, four SLR scenarios, and a dynamic habitat response (from Seavey, 2009 [Figure 3.3]). Note, 19% of Seavey's study area was developed: 7% in low intensity, 10% in medium intensity, and 2% in high intensity development. This figure represents model outputs when the intensity of development is allowed to affect habitat loss and creation.

study. For example, high intensity development was the least prevalent development class and it was more distant from existing habitat.

Shorebirds in general appear to avoid potential nesting areas where structures, trees or bushes could harbor predators (Galbraith, 1989). This probably also applies to piping plovers (under normal circumstances). However, when modeling future piping plover habitat at her sites, Seavey (2009) classified beach habitat separating structures as suitable for breeding territories, as she did find some plovers nesting in such habitats during her study (Sims, *pers. comm.*). But, as acknowledged by the authors, their analyses may have overestimated the amount of habitat that would be suitable under the dynamic scenario with development.

The results from the Sims (2012), Seavey (2009), and Seavey *et al*. (2011) analyses suggest that the implications of SLR for nesting habitat of piping plovers in the Northeast may be complicated. The studies agree that if sites or habitats are constrained in their ability to move inland or upslope the result is likely to be habitat loss and the losses will increase with increasing SLR. However, if sites or habitats are able to migrate under SLR, new habitat may be created and the total area of piping plover nesting habitat might be expanded by SLR (however, this assumption is based on there being enough sand in the system). However, if more intense or frequent coastal storms and surges accompany SLR (as seems likely, see Chapter 2), piping plover nesting habitat could be significantly reduced.

Uncertainties in Piping Plover Modeling.

Both of the studies reported above were well-planned and executed, and have advanced our understanding of how SLR might affect piping plover habitat and populations in the Northeast**.** Nevertheless, as with all predictive modeling studies, they incorporate, by necessity, unknown future conditions, processes, and variables. There are, therefore, some significant uncertainties regarding their main conclusions when the research is put into a larger social-ecological perspective:

1. SLR could create significant new areas of suitable piping plover nesting habitat. This conclusion postulates that under the higher SLR scenarios in areas that are less constrained by development and where habitats are able to shift upward in elevation significant new areas of habitat may be created by beach-building processes. Indeed, it might even be the case that the net extent of habitat after SLR is greater than before. However, this conclusion relies on the assumption that sand will be available for building all these new beach areas (which will be created through the process of transfer of sand from the marine environment to the beach). In fact, we do not know that this is the case. Sand availability will ultimately be limiting to this process and it may be that at some sites, at least, we may already be close to this limit. Both Sims (2012) and Seavey (2009) noted model limitations related to the unknowns of future landform movement, sand budgets, and vegetation response.

2. We assume that the timing of the destruction of existing habitat and creation of new habitat will facilitate the movement of piping plovers from the former to the latter. However, this may not be the case. It is at least equally probable that there could be a lag between these events and that plovers evicted by habitat change or inundation from the existing nesting sites may not have new sites to move to, or that the new sites may not yet be large enough to accept all of the displaced birds. Also, the results from Seavey (2009) indicate that increased storm surges could impact the piping plovers that nest in the existing habitat before they are evicted by rising sea levels. If these storm surges increase in frequency and severity enough to depress the productivity of plovers to a level where populations are reduced, there may not be many plovers left to make the transfer when new habitat is created.

3. The Seavey (2009) and Seavey *et al*. (2011) studies make the assumptions that piping plover may nest in areas between or near development (e.g., houses and driveways) and that habitat might be created behind current structures (i.e., seawalls) as sea level rises. However, the former assumption was based on Seavey's observation that piping plovers have nested near development on her study sites. This was not true for the study sites of Sims (2012), and it may not apply to other avian sandy beach nesters (Galbraith *et al*., 2002). Assuming that sand can migrate freely behind and around structures may lead to an overestimate of the areal extent of new habitat created using Seavey's modeling methodology.

4. Human populations and development on the northeastern coasts have been increasing for several decades. Also, human recreation on the coast has increased and methods of recreation have changed to forms that result in greater levels of disturbance to nesting piping plovers (Elliot-Smith and Haig, 2004). Disturbance by humans and their pets is now a major limitation on the productivity of piping plovers, and demand for recreational experiences on areas that serve as piping plover nesting habitat is expected to increase in the future. Thus, even if new habitat is being created, without limitations on human access it may not support adequate plover productivity to be self-sustaining.

Other Habitat Vulnerability Approaches

Analyses by Northeastern States.

Table 5. State-level progress in completing analyses of sea level rise, habitat vulnerability, and infrastructure vulnerability; LiDAR data was used for analyses in some states.

State	Sea level rise analysis?	Habitat Analysis?	Infrastructure Analysis?	LiDAR data?
Virginia	Yes	Yes	No	No
Maryland	Yes	Yes	Yes	Yes
Delaware	In process	In process	In process	Yes
New Jersey	Yes	Yes	Yes	Yes
New York	Yes	Yes	Yes	No
Connecticut	Yes	Yes	Yes	No
Massachusetts	Yes	Yes	Yes	Yes
New Hampshire	Yes	Yes	Yes	No
Rhode Island	Yes	Yes	Yes	Yes
Maine	Yes	Yes	Yes	Yes

Ten coastal northeastern states have completed or have in progress analyses of the implications of SLR for ecological resources (Table 5). More detailed descriptions of the state activities are presented in Attachment A to this report. Virtually all the northeastern states have performed analyses of the expected degree of SLR, and the implications for infrastructure and for ecological resources. Many of these analyses were based on state-level LiDAR data, though not all.

Table 6. Coastal habitat vulnerability assessments, including tools used to generate them, such as habitat change model version and type of elevation data used as input, for the 10 coastal northeastern states.

State	Habitat Vulnerability Assessment	Habitat Change Model and Elevation Data Used
VA	*Vulnerability of Shallow Tidal Water Habitats in Virginia to Climate Change*	Topographic data (National Elevation Dataset (NED); Digital Terrain Model); bathymetric digital sounding data
	Sea-Level Rise and Coastal Habitats in the Chesapeake Bay Region Technical Report (covers MD and DE as well)	SLAMM 5.0, NED, and LiDAR where available,
	Coastal Vulnerability Index (Assateague NWR)	Uses relative rate of sea level rise
	Eastern Shore NWR Complex Refuge Vulnerability Assessment	SLAMM 6.0 and NOAA CAP
	Hampton Roads PDC Adaptation effort	EPA elevation data (no seamless LiDAR for region)
MD	Sea-level Rise Vulnerable Wetlands data layer (Coastal Atlas)	SLAMM, high resolution LiDAR
	Sea-level Rise Vulnerability data layer (Coastal Atlas)	Bathtub model
	Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change Phase I: Sea-Level Rise and Coastal Storms	N/A
	Blackwater NWR Inundation Model	LiDAR
DE	Marsh Vulnerability Index	N/A
	Application of Ecological and Economic Models of the Impacts of Sea-Level Rise to the Delaware Estuary	SLAMM, Habitat Equivalency Analysis
	Prime Hook SLAMM Analysis	SLAMM, LiDAR, Digital Elevation Model (DEM)
NJ	*Future Sea Level Rise and the New Jersey Coast* (2005)	DEM
	Vulnerability of New Jersey's Coastal Habitats to Sea Level Rise (2007)	DEM
	Climate Change Habitat Vulnerability Assessment	N/A
NY	New York Sea Level Rise Task Force Report	N/A
	Target Rock NWR SLAMM Analysis	SLAMM, NED
CT	*The Climate Change Impacts on Connecticut Natural Resources*	N/A
	Coastal Hazards Mapping Tool	Bare earth LiDAR; DEM
	SET monitoring with NY	N/A
MA	*Climate Change and Massachusetts Fish and Wildlife: Volume 2 Habitat and Species Vulnerability*	N/A
	Vulnerability Assessments in Support of the Climate Ready Estuaries Program: A Novel Approach Using Expert Judgment, Volume II: Results for the Massachusetts Bays Program	N/A
NH	Vulnerability of Coastal Habitats to Climate Change in New Hampshire	N/A
RI	Mapping Assets Vulnerable to Sea Level Rise North Kingstown, RI Building Blocks for Climate Change Adaptation	LiDAR
	Using SLAMM 6.0.1 to Model Likely Paths for Salt Marsh Migration in North Kingstown, Rhode Island in Response to Sea Level Rise	SLAMM 6.0.1, LiDAR
	Hancock R (2009) Using GIS and simulation modeling to assess the impact of sea level rise on coastal salt marshes. Master's project. University of Rhode Island, Kingston, RI. Projected major losses of saltmarsh habitats	SLAMM, LiDAR
ME	Impacts of Future Sea Level Rise on the Coastal Floodplain.	LiDAR

As shown in Tables 5 and 6, all of the coastal northeastern states have assessed or are assessing the potential impacts of SLR on their coastal environments. However, the degree to which they are determining coastal habitat vulnerability to sea level rise varies greatly. Also, between states, and even within states, different methodologies, datasets, and sea-level rise assumptions are being used for projecting SLR and its potential impacts. Additionally, states use different nomenclature for coastal habitats, adding to the challenge of making region-wide comparisons. These inconsistencies make it difficult to generalize at a regional level about which coastal habitats are most vulnerable. However, there are some general conclusions that can be drawn from a review of the states' efforts, noting that the conclusions do not necessarily apply to all states:

- There appears to be regional consensus that if salt marsh habitat can accrete at a rate that keeps pace with SLR (which depends on a number of factors including sediment deposition rates, limited storm surge disturbance, and effective managed retreat policy), and the marsh is in areas that are free of obstructions to inland migration, such as hardened shorelines, then salt marsh may be less vulnerable to sea level rise than other habitats.

- Transitional marsh and estuarine beaches are also likely to be less vulnerable to sea level rise; however, this varies between studies.

- The vulnerability of tidal flats to sea level rise may vary across the region.

- Brackish marsh (or irregularly flooded marsh) seems to be the most vulnerable habitat across studies and states.

- Ocean beaches were listed as more vulnerable when they were included in analysis.

NOAA's Sea Level Rise and Coastal Flooding Impacts Viewer. This is a web-based interactive tool developed as part of NOAA's Digital Coast program. It is intended to provide planners, educators, local authorities, etc. with a method of evaluating the potential effects of various SLR scenarios on coastlines, infrastructure, and ecological systems. It can be accessed at http://www.csc.noaa.gov/digitalcoast/tools/slrviewer.

This tool is based on a modified bathtub model that combines the best available digital elevation data, SLR assumptions (up to 6 ft), and a digitized map of the current distribution of coastal resources (including habitats) to model future inundation and habitat changes. It does not incorporate information about storm surges, or coastal sediment processes (accretion or erosion rates), and is, therefore, a relatively simple model. Relevant habitats that are included are unconsolidated shoreline (combined beaches and tidal sand and mudflats), saltwater marsh (saltmarsh), brackish/transitional tidal marsh, and freshwater marsh.

This is no doubt a useful tool for local and regional planners who are carrying out screening level analyses of coastal vulnerabilities. However, its usefulness as a predictive ecological change model on which site specific vulnerabilities and adaptation actions could be based is compromised by major uncertainties. First, it does not include erosion/accretion components.

Secondly, it does not incorporate future change in coastal geomorphology (which renders marsh migration results uncertain). Lastly, it does not discriminate among quite different habitat types (mudflats, sandflats, beaches). Because of these uncertainties, this model and viewer should not be used for site specific analyses.

CHAPTER 4. CONCLUSIONS, UNCERTAINTIES AND FUTURE FOCUS

When comparing habitat vulnerability and projected impact studies that have been performed by states and federal agencies there is limited agreement, and often wide variation, in the conclusions reached about the vulnerabilities of tidally influenced habitats. In the SLAMM NWR study, tidal flats were projected to benefit or greatly benefit under SLR at many sites (though not all). This was not so unambiguously the case with the state analyses, where tidal flats were scored as either vulnerable or less vulnerable. Oceanic and estuarine beaches were categorized in the SLAMM NWR study as being vulnerable to SLR and expected to manifest losses under all SLR scenarios. However, this was not generally the conclusion of the state studies where beaches were determined to be less vulnerable, although again these results varied. The piping plover studies projected that coastal beaches might increase in extent under SLR, provided they were able to respond by migrating and no infrastructure barriers were placed in their way. Two of the studies or groups of studies that were reviewed indicate that vulnerability may vary with site. Thus, the SLAMM NWR results show that while vulnerability determinations may be generally consistent across the region, they are less consistent at the inter-site level (Tables 3 and 4). For saltmarshes, the SLAMM NWR modeling determined that they were highly vulnerable and that they would undergo major contractions under SLR. However, the state studies generally conclude that so long as there are no barriers to migration saltmarshes may move inland and not be adversely affected.

Much of the variability and contradictions in the results of these studies can be assigned to the methods used and the data sets that were evaluated. The NWR study relied wholly on SLAMM modeling, the piping plover analyses used a modified bucket model, and the state studies used a mixture of approaches. Also, different studies varied in their input data sources: some used bare-earthed LiDAR data with a high level of accuracy and precision, while others used much less accurate and considerably older DEM data based on aerial photographs and satellite sensing. However, even if we control for study type, the input data, and the assumptions used, we still find major differences in habitat projections. For example, if we look only at the NWR SLAMM studies, standardize at a 1 meter SLR, and consider only sites that had LiDAR data available, we still find considerable variance in results. For example, in general, tidal flats seem to benefit from SLR (Table 3), however this varies a lot between sites. At Parker River NWR the SLAMM modeling projects a 50% loss of tidal flats, while at Monomoy (less than 100 miles farther south) the projection is for an increase in tidal flats by a factor of about 5. Obviously, variability is introduced into the results by site-specific factors, making it difficult to generalize among sites or develop a regional consensus. It appears that the answer to the question: is a given habitat type vulnerable to SLR, is that it depends! While it is obvious from the results reviewed above that tidally-influenced habitats, in general, are vulnerable to SLR and likely to change in their distributions and extents (with some potentially benefiting under some sets of assumptions), assigning relative vulnerabilities is much more problematic.

This leads to the overarching question: how do we move forward with a science-based approach to provide predictive information that will enable conservation agencies to better assess likely vulnerabilities and fates and plan effective conservation strategies? Several potential research areas are possible, and they are described and evaluated below:

Develop new habitat change models. Any assessment of the likely loss or gain of habitats at a site hinges upon a number of factors including assumptions about the future extent of SLR (i.e., will it be 0.5 m, 1 m, or 2 m?), the accuracy of the existing wetlands maps and the digital elevation data, information about future accretion and erosion rates, and, finally, how well the habitat change model captures and quantifies likely future change in habitat distributions. The most frequently used model is the SLAMM, which has been criticized for not accurately reproducing future conditions and specifically for its ability to incorporate accretion and erosion processes and rates. While the criticisms may be valid, it should be recognized that all models will be unrealistic to some extent (Rybczyk and Calloway, 2009). The real question is: will developing and using alternatives sufficiently reduce the net uncertainty associated with projecting future change in habitat distributions and extents under SLR to justify the time and expense in its development, given the overall biological and social uncertainty that planners and managers have to deal with in making conservation decisions at coastal sites?

Refine assumptions about SLR. Perhaps the greatest source of uncertainty affecting the development of strategies for adapting to SLR is the extent to which sea levels will rise over the next few decades. By 2100 SLR may be 0.5 m, 1 m, 2 m, or more. Given that the rate of melting of ice caps and glaciers is uncertain, and changes in oceanic currents and human responses to SLR are even more so, substantial uncertainty about the magnitude of SLR is currently unavoidable. These uncertainties may dwarf modeling uncertainties in how fish and wildlife habitats respond to SLR.

Study human responses to SLR. Faced with rising sea levels, human societies will be forced to make decisions about how to deal with this slow-motion crisis. Some communities may choose to retreat inland and abandon threatened areas. In other cases, the high population densities and investments that have been made by communities in the coastal zones may steer them toward coastal defenses against SLR. These decisions will have major implications the continued existence of coastal habitats and other ecological resources. Previous studies, for example Sims (2012), Seavey (2009), Galbraith *et al*. (2002), and Fish *et al*. (2008), have shown that the continued existence of coastal habitats will be greatly affected by how society answers this basic question – to armor or to withdraw. It may well be that current settlement patterns will dictate the answer to this question: in areas that are already densely settled coastal armoring may be the "solution," while in less densely settled areas, perhaps predominantly agricultural, human settlement will move inland. This is already happening in areas elsewhere in the Northern Hemisphere, such as the low-lying areas of agricultural eastern England and the Netherlands. The problem is that there are many sites that support important coastal ecological resources in the Northeast that are also close to or abut densely settled areas. Importantly, if future habitat change models are to better predict the impacts of SLR, they may need to go beyond the geophysical and ecological processes and incorporate potential societal responses.

Understand the relationship between shifting coastlines, land ownership and future conservation. While a great deal of attention has been focused on projecting potential *in situ* change in fish and wildlife habitats in the northeastern coastal zone (for example, the SLAMM NWR analyses), far less has been focused on understanding the locations where these coastal systems will "want" to migrate. However, this issue may be among the most important uncertainties that affect conservation planning for coastal resources. We know that under SLR, the coastal system will migrate inland. However, we do not know where it will move, whether it will retreat from protected areas (such as federal and state reserves), or who will have ownership or jurisdiction over newly coastal lands. Under this background of change and multi-stakeholder involvement, how do we conserve important resources? We must do more to fully address these uncertainties. Doing so will require a combination of good science (e.g., using the available LiDAR data to map the future inland migration of coastal zones), and a strong stakeholder process, so that conservationists and land owners can begin to develop options in advance of coastal migration. What are most needed are a few coastal case studies at complex sites to establish models and precedents for this necessary work.

Study populations and metapopulations from a region-wide context
Most coastal habitat vulnerability and SLR impacts studies thus far have focused on individual sites (e.g., the piping plover and NWR SLAMM studies described above), and have attempted to describe how a given site or sites will be impacted by SLR. While this research is important, by focusing on the small site-specific scale, these types of studies of necessity exclude an important aspect of the biological importance of the northeastern coastal sites: their role in wildlife migrations. The northeastern coast is important for its populations of migratory wildlife. Although most shorebirds and waterfowl breed north of the "Northeast Region," they use habitats along the northeastern coast during their semiannual migrations. On these migratory journeys they use the northeastern coastal sites as "stepping stones" and "refueling areas" where they rest and replace the fat reserves metabolized during migration flight. For example, a southbound migrating shorebird could begin by fattening up at a Massachusetts refuge, then fly to a New Jersey site to replenish its fat reserves, then to a site farther south in Virginia, before leaving the region.

If we view the northeastern coastal zone as a map of these functionally interconnected geographical nodes, several questions arise. Are some sites more or less important than others? What happens if we lose particular sites? Will the birds or other organisms be able to adapt by increasing their attention on surviving sites? How much tidal flat feeding area or saltmarsh at a site can be lost before it impacts the carrying capacity for organisms? Are some sites "expendable," and if so, which? How might wildlife be affected if we lost all of the comparatively small sites in the more northern states but retained the larger sites in the Mid-Atlantic? What is more important to the organisms, the regional extent of a particular habitat or its distribution relative to their migratory needs? All of these questions remain to be answered.

Incorporate climate change impacts elsewhere

> Many of the ecological resources that society values in northeastern coastal habitats are highly migratory. For example, many shorebirds and waterfowl span the entire western hemisphere during their migrations, breeding in the arctic and wintering in the southern U.S. or Central or South America. When moving between these geographical extremes they use a number of migration "stepping stone" sites, where they replenish fat reserves depleted during migratory flight. Evaluating the overall or life-cycle vulnerabilities of such species requires more than just focusing on a few migration sites. A species that is shown to be relatively unaffected by habitat loss at one of the NWRs in the Northeast, could, nevertheless, be greatly impacted by habitat loss in the arctic or in its wintering range. Thus, vulnerability studies at northeastern sites may not accurately reflect the true vulnerabilities of some species to the global process of climate change. Galbraith *et al*. (*in press*) have attempted to perform such a life-cycle analysis for North American shorebirds. This shows that many species that are not particularly vulnerable on their migration sites are highly vulnerable due to the scale of ecological changes projected in their northern breeding areas.

These issues translate into important uncertainties for conservationists and managers. It is very difficult for a conservation agency to answer the question: if we lose this particular saltmarsh, area of tidal flats, or oceanic beach, how important is that in a regional context? For breeding bird species whose populations and distributions are well known in the Northeast, such as piping plovers or least terns, we know a lot about the relative regional importance of each site. However, for the majority of species (for example most waterfowl and virtually all migratory shorebirds, songbirds, or birds of prey) we do not have this information. We are even less able, as discussed above, to extrapolate from acres of habitat affected by SLR to regional or metapopulation impacts. It is conceivable that a large area of a particular habitat at a site might be lost with little appreciable impact on the regional population, but it is also possible that even small losses at one or two sites could have adverse effects on that population. Ideally, we need a map of the distribution of priority taxa and habitats in the region that can be used to evaluate the regional importance of patches or local populations. We have the information to construct such a map for some well-studied species (e.g., a few bird species), but it is lacking for others. Without such a map or gazetteer of regional importance it is difficult to gauge the importance of projected habitat losses.

In summary, a number of important research needs related to the impacts of SLR remain. One includes refining the habitat change models that are available. More challenging at present, and likely involving a greater degree of uncertainty, are issues like obtaining more accurate estimates of future SLR and better understanding the adaptive capacity of organisms. Other uncertainties are due to the fact that we do not know enough about the ecologies and interconnectedness of coastal sites and their species. In this context, the important research questions are what are the carrying capacities of sites, and how do we translate projected habitat losses into changes in carrying capacities? In a regional context, how important are individual sites for taxa and habitats and how will regional populations be affected by impacts to these sites? How do we anticipate and manage inland migration of sites to protect coastal ecological resources, particularly when the resources are moving out of protected areas and into areas of stakeholder complexity? Finally, the responses of coastal communities to SLR could have major impacts on the resiliencies of important sites. If our goal is to assist in transitions at important sites with the smallest possible ecological injury, how do we quantify the potential impacts of societal responses on a site-by-site basis, and use that information to develop and implement effective conservation strategies?

REFERENCES

Anthes, R.A., R.W. Corell, G. Holland, J.W. Hurrell, M.C. MacCracken, and K.E. Trenberth. 2006. Hurricanes and global warming: Potential linkages and consequences. *Bulletin of the American Meteorological Society* 87: 623-628.

Boesch, D. F., L. P. Atkinson, W. C. Boicourt, J. D. Boon, D. R. Cahoon, R. A.

Boon, J.D. 2012. Evidence of sea level acceleration at US and Canadian tide gauge stations, Atlantic Coast, North America. *Journal of Coastal Research* 28:1437-1445.

Cahoon, D.R. 2006. A review of major storm impacts on coastal wetland elevation. *Estuaries and Coasts* 29: 889-898.

Church, John, J. A. Neil, N. J. White, R. Coleman, K. Lambeck, J. X. Mitrovica, 2004: Estimates of the Regional Distribution of Sea Level Rise over the 1950–2000 Period. *J. Climate*, 17:, 2609–2625.

Dalrymple, R. Ezer, B. P. Horton, Z. P. Johnson, R. E. Kopp, M. Li, R. H. Moss, A.

Elliot-Smith, E., and S.M. Haig. 2004. The Piping Plover. In The Birds of North America Online. (A. Poole, Ed). Cornell Lab of Ornithology, Ithaca.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436: 686-688.

Erwin, R.M., D.R. Cahoon, D.J. Prosser, G.M. Sanders, and P. Hensel. 2006. Surface elevation dynamics in vegetated Spartina marshes versus unvegetated tidal ponds along the Mid-Atlantic Coast, USA, with implications to waterbirds. *Estuaries and Coasts* 29:96-106.

Fagherrazi, S., M.L. Kirwan, S.M. Mudd, G.R. Guntespergen, S. Temmerman, A. D'Alpaos, J. van de Koppel, J.M. Rybczyk, E. Reyes, C. Craft, and J. Clough. 2012. Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. *Rev. Geophysics* 50:1-28.

Fish, M.R., Cote I.M., Horrocks J.A., Mulligan B., Watkinson A.R., and Jones A.P. (2008). Construction setback regulations and sea level rise: Mitigating sea turtle nesting beach loss. *Ocean and Coast. Manage*. 51:330-341

Galbraith, H. 1989. Arrival and Habitat Use by Lapwings in the Early Breeding Season. *Ibis* 1312: 377-388.

Galbraith, H., D.W. Desrochers, S. Brown,' and M. Reed. *In press*. Predicting the vulnerabilities of North American shorebirds to climate change. *Global Change Biology*.

Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002. Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. *Waterbirds* 25: 173-183.

Hancock, R. (2009).. Using GIS and simulation modeling to assess the impact of sea level rise on coastal salt marshes. Master's project. University of Rhode Island, Kingston, RI.

Holland, G.J., and P.J. Webster. 2007. Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philosophical Transactions of the Royal Society* A. doi:10.1098/rsta.2007.2083

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.) Cambridge University Press, Cambridge, UK.

Jevrejeva, S., J.C. Moore, and A. Grinsted. 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophysical Research Letters* 37, L07703, doi:10.1029/2010GL042947.

Jones, A.S. C. Bosch, and E. Strange. 2009. Vulnerable Species: the Effects of Sea Level Rise on Coastal Habitats. Chapter 4. Synthesis and Analysis Plan. USEPA, Washington, DC

Karl, T.R., J.M. Melillo, and T.C. Peterson. 2009. Global Climate Change Impacts in the United States. Cambridge University Press.

Kelly, A.E. and M.L. Goulden. 2008. Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences* 105: 11823-11826.

Lambeck, K., and E. Bard,. 2000:. Sea level changes along the French Mediterranean coast since the time of the last glacial maximum. *Earth Planet. Sci. Lett*, **175,** 203–222.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Reaper, and Z. Zhao. 2007. Global Climate Projections. In: S. Solomon, D. Qun, M. Manning, M. Marquis, K. Averyt, M.M.B. Tignor, H.L. Miller, Jr., and Z. Chen (eds.) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, U.K.: Cambridge University Press.

Morton, R.A. and J.A. Barras (. 2011). Hurricane Impacts on Coastal Wetlands: A Half-Century Record of Storm-Generated Features from Southern Louisiana. *Journal of Coastal Research*: Volume 27, Issue 6A: pp. 27 – 43.

Najjar, R.G., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M.R. Mulholland, M. Paolisso, D. Secor, K. Stellner, D. Wardrop, and R. Wood. 2010. Potential climate-change impacts on the Chesapeake Bay. *Estuarine Coastal and Shelf Science* 86:1-20.

Northeast Climate Impacts Assessment (NECIA)., 2006. Climate Change in the U.S. Northeast. A report of the Northeast Climate Impacts Assessment. Union of Concerned Scientists, Cambridge, MA.

Oouchi, K., J. Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki, and A. Noda. 2006. Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: Frequency and wind intensity analysis. *Journal of the Meteorological Society of Japan* 84: 259-276.

Overpeck, J.T. and J.L. Weiss. 2009. Projections of future sea level becoming more dire. *Proceedings of the National Academy of Sciences* 106: 21461-21462.

Parmesan, C. 1996. Climate and species'range. *Nature* 382: 765-766.

Parmesan, C., and H. Galbraith. 2004. Observed impacts of global climate change in the U.S. Report of Pew Center on Global Climate Change. Washington, DC.

Parris, and C. K. Sommerfield. 2013. Updating Maryland's Sea-level Rise Projections.

Pfeffer, W.T., J.T. Harper, and S.O. O'Neel. 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, 321: 1340-1343.

Primack, D., C. Imbres, R.B. Primack, A.J. Miller-Rushing, and P. Del Tredici. 2004. Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. *American Journal of Botany* 91: 1260-1264.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315: 368-370.

Root, T.L. and L. Hughes. 2005. Present and future phenological changes in wild plants and animals. In: T.E. Lovejoy and L. Hannah (eds.) Climate Change and Biodiversity. Yale University Press, New Haven, CT.

Rybczk, J.M., and J.C. Calloway. 2009. Surface Elevation Models. In: Coastal Wetlands: an integrated ecosystem approach. Elsevier, NY.

Sallenger, A.H., Jr., K.S. Doran, and P.A. Howd. 2012. Hotspot of accelerated sea-level rise on the Atlantic Coast of North America. *Nature Climate Change*, doi:10.1038/NCLIMATE1597.

Schneider, S.H., and T.L. Root. 2002. Wildlife Responses to Climate Change. North American Case Studies. Island Press. Washington.

Seavey, J.R. 2009. Piping Plover (Charadrius Melodius) Conservation on the Barrier Islands of New York: Habitat Quality and Implications in a Changing Climate. Open Access Dissertations. Paper 120. http://scholarworks.umass.edu/open_access_dissertations/120

Seavey, J.R., Gilmer, B., McGarigal, K.M (. 2011). Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. *Biol. Conserv*. 144: 393-401.

Sims, S.A. 2012. Effects of Projected Sea Level Rise on Piping Plover (*Charadrius melodus*) Nesting Habitat in Rhode Island. MSc. Thesis to the Department of Environmental Studies, Antioch University New England. July 2012.

Smith, S.M. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: photographic analyses of vegetation loss, species shifts, and geomorphic change. *Northeastern Naturalist* 16: 183-208.

Special Report of the Scientific and Technical Working Group to the Maryland Climate Commission. University of Maryland Center for Environmental science, Cambridge, MD.

Special Report on Emissions Scenarios (SRES). 2002. Emissions Scenarios: Summary for Policy Makers. Intergovernmental Panel on Climate Change Special Report.

Tebaldi, C., Strauss, B.H. & and Zervas, C.E. 2012. Modelling sea level rise impacts on storm surges along US coasts. *Environ. Res. Lett.* **7**.

Titus J.G., D.E. Hudgens, D.L. Trescott, M. Craghan, W.H. Nuckols, C.H. Hershner, J.M. Kassakian, C.J. Linn, P.G. Merritt, T.M. McCue, J.F. O'Connell, J. Tanski. (2009). State and local governments plan for development of most land vulnerable to rising sea level along the U.S. Atlantic coast. *Environ. Res. Lett.* (online) 4:044008

Trenberth, K.E., P.D. Jones, A. Ambenje, R. Bojariu, D. Easterling, A.K. Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden, and P. Zhai. 2007. Observations: Surface and atmospheric climate change. In: S. Solomon, D. Qun, M. Manning, M. Marquis, K. Averyt, M.M.B. Tignor, H.L. Miller, Jr., and Z. Chen (eds.) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, U.K.: Cambridge University Press.

Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences* 106: 21527.

Webster, P.J., G.J. Holland, J.A. Curry, and H.-R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309: 1844-1846.

Wolfe, D.W., M.D. Schwartz, A. Lakso, Y. Otsuki, R. Pool, and N. Shaulis. 2005. Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *International Journal of Biometeorology* 49: 303-309.

Attachment A

Description of Northeastern State Activities in Evaluating Potential Impacts of SLR on Ecological Resources

Virginia

Prior to LiDAR data becoming available state-wide, there were efforts that utilized locality-specific LiDAR data. For example, LiDAR data was used in concert with wetlands boundaries delineated from 2007 high resolution imagery and projections of SLR to assess wetland vulnerabilities in the Lynnhaven River Watershed out to the year 2010.

At the state level, the primary coastal habitat vulnerability assessment was conducted by the Virginia Institute of Marine Science, and the 2009 report is entitled *Vulnerability of Shallow Tidal Water Habitats in Virginia to Climate Change* (Bilkovic *et al*., 2009). This analysis focused on projecting the broad scale changes in the distribution and abundance of shallow-water areas, tidal wetlands, submerged aquatic vegetation and estuarine beaches, using an inundation model based on changes in sea level rise, temperature, precipitation, and salinity changes. The inundation model was based on existing topographic data (from the Virginia Base Mapping Program's Digital Terrain Model) and bathymetric digital sounding data (from NOAA's National Ocean Service Hydrographic Database), as the state does not have LiDAR data for the entire coast. Maps and an online viewer are available.

Other assessments have been completed for certain areas of Virginia. Coastal habitat vulnerability assessments have been completed for Assateague NWR as well as the Eastern Shore Complex NWR. The Assateague assessment was part of the U.S. Geological Survey's (USGS) effort to develop a Coastal Vulnerability Index (CVI), and Assateague was a pilot project of that effort (Pendleton *et al.*, 2004). The CVI looks at six variables (geomorphology, shoreline change, coastal slope, relative sea level rise, significant wave height, and tidal range), which are put into an attribute table using a 1-minute (approximately 1.5 km) grid.[11] The CVI allows the six variables to be related in a way that shows the relative vulnerability of the coast to physical changes due to future sea level rise. This can then be displayed on a map.

The assessment for the Eastern Shore NWR Complex was part of a U.S. Fish and Wildlife Service and NatureServe project to develop a refuge vulnerability assessment framework and guide (Bullock *et al*., 2011). The assessment includes modeling the potential impacts of salt-water inundation and habitat loss from sea level rise and increased storm surges as well as changes in ecosystem and habitat composition due to changes in land use and land cover. This assessment looked at all major coastal habitats present in the NWR complex. It used the Sea-Level Affecting Marshes Model (SLAMM) (Version 6) to assess sea level rise impacts on the habitats, and it used NOAA C-CAP land cover in the SLAMM model for land cover. LiDAR data was not used.

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[11] Note that many other coastal vulnerability indexes are based on the same or similar six variables.

The National Wildlife Federation also used SLAMM (Version 5) to assess wetland change from sea level rise in parts of Virginia, Maryland, and Delaware (Glick et al., 2008). Additionally, at the local level several Planning District Commissions (PDC) have begun planning for sea level rise, including developing local sea level rise models. The Hampton Roads PDC recently published a report that includes sea level rise projections for the area, including high value ecological areas. The analysis did not use LiDAR data as no seamless LiDAR data is available for the PDC region; instead it used an EPA dataset based on the National Elevation Dataset (HRPDC, 2012).

Maryland

Maryland has completed an extensive coastal habitat vulnerability assessment at the statewide level. Maryland Department of Natural Resources (MD DNR) developed a sea level rise vulnerable wetlands data layer that is housed in its Coastal Atlas – an online data viewer and tool. The sea level rise vulnerable wetlands layer is based on SLAMM (Version 6.0.1), and the state used high resolution LiDAR data. The model shows wetlands in their current state and projects their change in 2050 and 2100. It also highlights new wetland areas in both 2050 and 2010. The model was run at the county level, using local erosion, sedimentation, and accretion rates as well as a sea level rise projection of 3.4 feet by 2100 as described in Maryland's Climate Action Plan. The Coastal Atlas also includes a Wetlands Adaptation Area layer that uses the SLAMM output to help identify areas for that may be important for conserving or restoring for future wetlands adaptation (MD DNR, 2012).

Maryland's Commission on Climate Change Adaptation and Response Working Group completed *Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change Phase I: Sea-Level Rise and Coastal Storms* in 2008. This is a state-level sea level rise action plan that includes projections of sea level rise throughout the state using both high and low emission scenarios and taking into account land subsidence. The plan also includes a section on the vulnerability state's coastal natural resources (MD Commission on Climate Change, 2008). Additionally, several counties (Anne Arundel, Dorchester, Worchester, and Somerset) and Annapolis have local sea level rise plans, some of which include modeling future sea level rise (Worchester, Anne Arundel, and Somerset) and most make a general mention of impacts to coastal/ natural resources. The Anne Arundel and Worchester have the more extensive sea level rise analysis using specific inundation models. Anne Arundel also used LiDAR data.
Finally, there are some location-specific efforts. For example, the USGS developed the Blackwater NWR Inundation Model using LiDAR to help managers identify current marsh zones and predict future zones given projected sea level rise (Larsen *et al*., 2008). The Conservation Fund and Maryland Audubon are working to identify marsh migration corridors and priority areas for protection given sea level rise projections in the Blackwater NWR area. The Maryland DNR Natural Heritage and Wildlife Division has also used the SLAMM results to compare to bog turtle nesting habitat along coastal beaches to try to identify how good habitat for nesting could change as sea levels rise (*pers. comm*.).

Delaware

Delaware has a Sea-Level Rise Adaptation Initiative that is administered through the Delaware Coastal Programs. Through this initiative the state will have a sea level rise adaptation plan that will include an assessment of sea level rise on coastal habitats (Sea-Level Rise Advisory Committee). This assessment report will contain extensive narrative, maps tables, and an analysis of sea level rise impacts on resources such as dikes and dams to industry to natural resources (*pers. comm*.). A sea level rise viewer also has been developed that depicts projected sea level rise for all of Delaware using a simple bathtub model. Elevation data in the map is based on LiDAR data. A local-scale sea level rise viewer also was developed for the city of Wilmington, Delaware. As a separate initiative, a Marsh Vulnerability Index has been developed as a health index for *Spartina alterniflora*. The MVI identifies healthy, degrading, and severely degrading *Spartina* to help assess vulnerability to sea level rise and consider marsh migration potential (Lyons, et al., 2010).

Several additional efforts also include some level of coastal habitat vulnerability analysis. Partnership for the Delaware Estuary's (PDE) *Climate Change and the Delaware Estuary* report assesses the impacts of climate change on two specific habitats – tidal wetlands and oysters. Both assessments were done through a workgroup/ panel process (PDE, 2010). An analysis of the cost of lost ecosystem services of coastal marshes as sea-levels rise was completed for PDE and the EPA. The analysis uses SLAMM as well as habitat equivalency analysis (HEA). SLAMM is used to calculate changes in habitat and HEA is used to calculate the change in ecosystem services of those habitats when they change and the cost of projects to compensate those losses (Industrial Economics Inc., 2010). Prime Hook NWR is evaluating the impacts of sea level rise on its coastal habitats as a part of its effort to update its Comprehensive Conservation Plan. To evaluate these impacts, a SLAMM analysis was completed, and the results are summarized in the report *Application of the Sea Level Rise Affecting Marsh Model (SLAMM) Using High Resolution Data at Prime Hook National Wildlife Refuge* (Scarborough, 2009). Elevation input was from 2007 LiDAR data that had a 2-meter horizontal grid spacing and 15 centimeter (cm) vertical accuracy with observed 7.5 cm average vertical accuracy. This improves upon the accuracy of earlier SLAMM models. DEM data was also used as one of several constant site inputs.

New Jersey

Two state-level sea level rise reports have been developed that include information on sea level rise impacts to coastal habitats. The first, completed in 2005 by Cooper *et al.*, includes sea level rise modeling/ projections using DEM and includes some maps of sea level rise. Statistical analyses were completed to determine the percent loss of several coastal habitats (tidal salt marsh, tidal fresh marsh, and interior wetlands) to projected rates of sea level rise. A case study was also completed that assess in more depth the impact of loss of coastal wetlands on marsh species (Cooper *et al.*, 2005). Lathrop and Love (2007) build on the 2005 report to focus more specifically on vulnerable development and how it may restrict the movement and dynamics of the natural coastline. This report maps not only shoreline development, but also undisturbed beach and dune habitat, and where coastal wetlands would have the opportunity to migrate inland (tidal marsh retreat zones). The source of elevation data for this study was 10 meter ground cell resolution DEMs from the USGS.

Several other statewide efforts also address sea level rise impacts to coastal habitats. A Coastal Vulnerability Index, like in other states, is based on six variables that help determine high hazard or vulnerable coast lines. This index can then be paired with sea level rise data (NJDEP, 2011).

Development of the CVI was part of a larger project to develop a Coastal Community Vulnerability Assessment Protocol, which has a focus on both the built and natural environment. The assessment protocol was piloted in one area, and the natural environment was assessed more in terms of storm surge rather than sea level rise (NJDEP, 2011). Finally, the New Jersey Division of Fish and Wildlife has been working with Rutgers University on a Climate Change Habitat Vulnerability Assessment for a selection of habitats from the state's Wildlife Action Plan. The assessment was conducted using an expert panel process, and coastal habitats (e.g., coastal plain tidal swamp and sandy beach) were assessed for sensitivity to sea level rise as well as other climate factors. A SLAMM analysis was completed for Supawna Meadows NWR, using a 2007 LiDAR digital elevation map (Clough and Larson, 2009).

New York

New York's Sea-Level Rise Task Force completed its sea level rise assessment report in 2010, which provides a general qualitative narrative of the vulnerabilities of coastal habitats to sea level rise (NY SLR Task Force, 2010). New York's ClimAid report also includes information on the vulnerability of coastal zone habitats to sea level rise and storms, primarily based on literature review (Rosenzweig *et al*., 2011). The New York Natural Heritage Program used the Climate Change Vulnerability Index to assess vulnerability 121 species, most of which are Species of Greatest Conservation Need. Coastal species were included in the analysis and sensitivity to sea level rise was one of the factors assessed (Schlesinger *et al*., 2011). New York is also part of *Sentinel Monitoring for Climate Change in Long Island Sound Program* (see Connecticut for more information). SLAMM modeling was completed for Target Rock NWR in New York in 2009 using SLAMM version 5.0. LiDAR data were not available; thus, elevation data was used from the National Elevation Data set (Clough and Larson, 2009 (b)).

Connecticut

In Connecticut, the primary analysis of sea level rise on coastal habitats is contained within the Governor's Steering Committee on Climate Change Adaptation Subcommittee's report *The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources and Public Health*. The 2010 report includes an Appendix *The Climate Change Impacts on Connecticut Natural Resources* that contains the results of a risk assessment (conducted through a workshop of experts) of 18 habitats within the state, including coastal habitats that prioritizes the most vulnerable habitats (GSC, 2010). It also includes an analysis of the Species of Greatest Conservation Need or State-listed species identified as likely to experience a population decrease due to projected climate change. The Connecticut Department of Energy and Environmental Protection has also developed *Facing Our Future: Adapting to Connecticut's Changing Climate*, as series of climate adaptation fact sheets on several topic areas, including natural coastal shoreline environment (CDEEP, 2009).

Connecticut also developed the *Coastal Hazards Mapping Tool*. The tool allows users to visualize sea level rise, high-resolution coastal elevation, hurricane storm surge, coastal erosion, and environmental observations such as tides, water quality, waves and currents. The tool uses bare earth LiDAR data from 2004 and 2006 by FEMA and processed by the Connecticut Department of Environmental Protection in its sea level rise projections. It uses coastal digital elevation data (2006 Coastal CT 3ft Digital Elevation Model) for visualizing topography and elevation, which is based on LiDAR data as well. This tool is a visualization tool, and it does not specifically incorporate impacts to habitats. (CDEEP, 2012). Connecticut is also part of the *Sentinel Monitoring for Climate Change in Long Island Sound Program (CT and NY*), which is a multidisciplinary scientific approach that helps to provide early warning on impacts from climate change (Barrett et al., 2011). The program is designed to provide information about climate change impacts to Long Island Sound ecosystems, species and processes to help managers prioritize climate impacts and to help with developing management decisions and adaptation actions. The data that will be collected and used will relate to suite of indicators or "sentinels" (a measurable variable in the Long Island Sound estuarine or coastal ecosystems that is likely to be affected by climate change and that can be monitored).

New Hampshire

The primary source of coastal habitat vulnerability information for the state of New Hampshire is the New Hampshire Fish and Game Department's draft vulnerability assessment for its Wildlife Action Plan. The coastal section is entitled *Vulnerability of Coastal Habitats to Climate Change in New Hampshire*. It includes a narrative description of the vulnerabilities to New Hampshire's coastal habitats. It also includes a species-specific narrative section (NHDFG, 2012). In terms of more specific sea level rise assessments and mapping, the Great Bay National Estuarine Research Reserve (NERR) assessed climate impacts the Piscataqua/Great Bay Region of the state, including an assessment of future sea level rise that includes estimated projection of sea level rise for the area, but it does not include spatially explicit sea level rise projections (Waket *et al.*, 2011). Additionally, on a smaller scale, the Town of Seabrook conducted a coastal sea level rise analysis using USACE low resolution (1998) and high resolution (2007) LiDAR data. The analysis includes an analysis of flood hazard areas and flood prone areas, but it does not include any habitat analysis (Rockingham Planning Commission, 2010).

Massachusetts

The Massachusetts Climate Change Adaptation Advisory Committee completed an adaptation report in 2011 that includes a general overview of sea level rise impacts and what that means for coastal habitats (2011). A more specific habitat vulnerability assessment was completed by Manomet Center for Conservation Sciences and the Massachusetts Division of Fish and Wildlife. Twenty habitats were analyzed including coastal habitats (e.g., salt marsh and coastal dunes), and the assessment was conducted by an expert panel (Manomet and MDFW, 2010). Also at the state level, Mass Audubon produced a 2009 report entitled *Some Anticipated Consequences of Global Warming: Implications for the Nature of Massachusetts* that looks at climate change impacts, including sea level rise on terrestrial and coastal habitats. The assessment is primarily based on literature review (Buchsbaum and Allison, 2009).

The Massachusetts Bays Program and the EPA recently completed *Vulnerability Assessments in Support of the Climate Ready Estuaries Program: A Novel Approach Using Expert Judgment, Volume II: Results for the Massachusetts Bays Program*. This vulnerability assessment focused on salt marshes and two specific marsh ecosystem processes (sediment retention and community (species) interactions), which served the basis of the analysis. It was developed through expert judgment elicitation using a workshop approach (EPA, 2011). A vulnerability assessment of coastal habitats within the Parker River NWR is also in the process of being completed (P. Glick, *pers. comm*).

Rhode Island

The University of Rhode Island's (URI) Rhode Island Sea Grant College Program, in coordination with numerous partners, collected and synthesized the best digital elevation data available for coastal Rhode Island. The partners used this data to construct a new digital elevation model (DEM) using LiDAR and other available elevation data. The state and North Kingston specific maps are meant to help resource managers and decision makers assess vulnerability to sea level rise (Sea Grant and URI EDC, 2011). A sea level rise viewer has also been created using Google Earth that shows areas that will be affected by a 5 foot projected rise in sea levels by 2100 (Jordan). TNC conducted a SLAMM for North Kingston as well, using SLAMM 6.0.1 and LiDAR data for elevation (Ruddock, 2011). Rhode Island's Narragansett Bay National Estuarine Research Reserve is also participating in the region wide sentinel monitoring program. The project involves monitoring to see how marshes change over time as sea levels rise and how marshes respond to restoration over time.

Maine

Maine's Climate Future: An Initial Assessment, published in 2009, briefly mentions sea level rise impacts on Maine's coast based on literature review (Jacobson et al., 2009). Several specific studies on projecting sea level rise have been completed in the state. The Maine Geological Survey conducted a study to compare LiDAR data to field recorded Real Time Kinematic Global Positioning for several sites. Although the project was designed as a way to test the adequacy of previously collected elevation data, the project developed several maps of current marsh boundaries as well as projected boundaries with sea level rise (Slovinsky and Dickson, 2009). An earlier project by Slovinsky and Dickson modeled a 2-foot rise in sea-level at Rachel Carson NWR, using LiDAR topographic data (Slovinsky and Dickson, 2006). Finally, Maine Natural Areas Program and the Maine Geological Service have been working on a sea level rise simulation for the southern coast of Maine (*pers. comm.*). The objective of the project is to identify areas of the landscape where tidal marshes can migrate or expand under several sea level rise scenarios, using available LiDAR data in the analysis, and to provide that information to relevant public and private planning and conservation organizations.

REFERENCES BY STATE

Virginia

Bilkovic, D.M., C. Hershner, T. Rudnicky, K. Nunez, D. Schatt, S. Killeen, and M. Berman. 2009. Vulnerability of Shallow Tidal Water Habitats in Virginia to Climate Change. Virginia Institute of Marine Science. Available at http://ccrm.vims.edu/research/climate_change/index.html

Bulluck, J, J. Weber, D. Kulas, P. Comer, and P. Crist. 2011. *Resource Vulnerability Assessment and Strategies for Management Options for the Eastern Shore of Virginia and Fisherman Island National Wildlife Refuges.* NatureServe. Arlington, Virginia.

Glick, P., J. Clough, and B. Nunley. 2008. Sea-Level Rise and Coastal Habitats in the Chesapeake Bay Region Technical Report. National Wildlife Federation. Available at http://www.nwf.org/~/media/PDFs/Global-Warming/Reports/FullSeaLevelRiseandCoastalHabitats_ChesapeakeRegion.ashx. (Also MD and DE).

Hampton Roads Planning District Commission (HRPDC). 2012. Climate Change in Hampton Roads, Phase III: Sea Level Rise in Hampton Roads, Virginia. Available at http://www.hrpdcva.gov/Documents/Phys%20Planning/2012/HRPDC_ClimateChangeReport2012_Full_Reduced.pdf)

Pendleton, Elizabeth A., S. Jeffress Williams, and E. Robert Thieler. 2004. Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea-level rise. U.S. Geological Survey Open-File Report 2004-1020, Electronic Book.

Maryland

Cole, W.D. 2008. Sea Level Rise: Technical Guidance for Dorchester County. Dorchester County. Available at http://dnr.maryland.gov/CoastSmart/pdfs/SeaLevel_Dorchester.pdf.

CSA International, Inc. 2008. Sea Level Rise Response Strategy Worcester County, Maryland. Worchester County. Available at http://dnr.maryland.gov/CoastSmart/pdfs/SeaLevel_Worcester.pdf.

Environmental Resources Management. 2011. Regulatory Response to Sea Level Rise and Storm Surge Inundation City of Annapolis, Maryland. Available at http://www.dnr.state.md.us/CoastSmart/pdfs/Annapolis_RRSLRnSSI.pdf.

Larsen, C. et al, “The Blackwater NWR Inundation Model. Rising Sea Level on a Low-lying Coast: Land Use Planning for Wetlands.” U.S. Geological Survey (August 2004). http://pubs.usgs.gov/of/2004/1302/

Maryland Commission on Climate Change Adaptation and Response Working Group (MD Commission on Climate Change). 2008. Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change Phase I: Sea-level rise and coastal storms. Available at

Maryland Department of Natural Resources (MD DNR). 2012. Maryland's Coastal Atlas Training Manual. Available at http://dnr.maryland.gov/ccp/pdfs/ca_TrainingManual.pdf.

URS and RCQuinn Consulting, Inc. 2008. Somerset County, Maryland Rising Sea Level Guidance. Somerset County, Maryland Department of Natural Resources, NOAA. Available at http://dnr.maryland.gov/CoastSmart/pdfs/SeaLevel_Somerset.pdf.

Delaware

Delaware Sea Level Rise Advisory Committee Natural Resources Workgroup (SLR Advisory Committee) webpage (http://www.dnrec.delaware.gov/coastal/Pages/SLRACNaturalResources.aspx).

Industrial Economics, Inc. 2010. Application of Ecological and Economic Models of the Impacts of Sea-Level Rise to the Delaware Estuary. Partnership for the Delaware Estuary and the Environmental Protection Agency. Available at http://www.delawareestuary.org/pdf/Climate/IEc%20Delaware%20Estuary%20SLAMM%20HEA%20-%20June%202010.pdf.

Lyons, G.C., B. Wilson, D. Carter, and R.W. Carborough. 2010. Marsh Vulnerability Index: Impacts of Rising Sea Level on Delaware's Marshes. Available at https://gsa.confex.com/gsa/2010NE/finalprogram/abstract_168368.htm.

Partnership for the Delaware Estuary (PDE). 2010. Climate Change and the Delaware Estuary. Available at http://www.delawareestuary.org/science_projects_climate_ready_products.asp.

Scarborough, R.W. 2009. Application of the Sea Level Rise Affecting Marsh Model (SLAMM) Using High Resolution Data At Prime Hook National Wildlife Refuge. Delaware Department of Natural Resources and Environmental Control, Coastal Programs. Available at http://www.dnrec.delaware.gov/coastal/Documents/PHNWR%20SLAMM.pdf.

New Jersey

Clough, J. and E. Larson. 2009. Appendix G: Application of the Sea Level Affecting Marshes Model (SLAMM 5.1) to Supawna Meadows NWR. Supawna Meadows National Wildlife Refuge Comprehensive Conservation Planning. Warren Pinnacle Consulting, Inc. Available at http://www.fws.gov/northeast/planning/supawnameadows/PDF/15_SMNWR_Final_CCP_AppG.pdf.

Cooper, M., M. Beevers, and M. Oppenheimer. 2005. Future Sea Level Rise and the New Jersey Coast: Assessing Potential Impacts and Opportunities. Woodrow Wilson School of Public and International Affairs, Princeton University. Available at http://cdn.publicinterestnetwork.org/assets/sR9NsL9cXyA7pGI_ODVlw/Future_Sea_Level_Rise.pdf.

Lathrop, R.G. and A. Love. 2007. Vulnerability of New Jersey's Coastal Habitats to Sea Level Rise. Grant F. Walton Center for Remote Sensing & Spatial Analysis, Rutgers University. Available at http://crssa.rutgers.edu/projects/coastal/sealevel/report/Vulnerability_of_New_Jersey_coastal_habitats_v4.pdf.

New Jersey Department of Environmental Protection, Office of Coastal Management (NJDEP). 2011. Coastal Community Vulnerability & Resilience Assessment Pilot: Greenwich Township, Cumberland County, NJ. Available at http://www.nj.gov/dep/cmp/docs/ccvap-greenwich.pdf.

New York

Barrett, J., J Rose, S. Deonarine, A. Clemetson, J. Pagach, M. Parker, and M. Tedesco. 2011. Sentinel Monitoring for Climate Change in the Long Island Sound Estuarine and Coastal Ecosystems of New York and Connecticut Volume 1. Available at http://longislandsoundstudy.net/research-monitoring/sentinel-monitoring/.

Clough, J. and E. Larson. 2009 (b). Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Target Rock NWR. Warren Pinnacle Consulting, Inc. Available at http://warrenpinnacle.com/prof/SLAMM/USFWS/SLAMM_TargetRock.pdf.

New York State Sea Level Rise Task Force (NY SLR Task Force). 2010. Report to the Legislature. Available at http://www.dec.ny.gov/docs/administration_pdf/slrtffinalrep.pdf.

Rosenzweig, C., W. Solecki, A. DeGaetano, M. O'Grady, S. Hassol, P. Grabhorn (Eds.). 2011. Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation. Technical Report. New York State Energy Research and Development Authority (NYSERDA), Albany, New York. www.nyserda.ny.gov.

Schlesinger, M.D., J.D. Corser, K.A. Perkins, and E.L. White. 2011. Vulnerability of at-risk species to climate change in New York. New York Natural Heritage Program, Albany, NY. Available at http://www.natureserve.org/prodServices/climatechange/pdfs/ccvi_report_ny.pdf.

Connecticut

Connecticut Department of Energy and Environmental Protection (CDEEP). 2009. Facing Our Future: Adapting to Connecticut's Changing Climate. Available at http://www.ct.gov/dep/cwp/view.asp?a=2684&q=436600&depNav_GID=1619#Sections.

Connecticut Department of Energy and Environmental Protection (CDEEP). 2012. Coastal Hazards Mapping Tool. Available at http://www.ct.gov/dep/cwp/view.asp?a=2705&q=480782&depNav_GID=2022.

Governor's Steering Committing on Climate Change, Adaptation Subcommittee (GSC). 2010. The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources and Public Health. Available at http://ctclimatechange.com/wp-content/uploads/2010/05/Impacts-of-Climate-Change-on-CT-Ag-Infr-Nat-Res-and-Pub-Health-April-2010.pdf.

Massachusetts
Buchsbaum, R. and T. Allison. 2009. Some Anticipated Consequences of Global Warming: Implications for the Nature of Massachusetts. Conservation Science and Ecological Management Division Mass Audubon. Available at http://www.massaudubon.org/PDF/cleanenergy/massaudubon_climate_change_paper.pdf

Executive Office of Energy and Environmental Affairs and the Adaptation Advisory Committee (Adaptation Advisory Committee). 2011. Massachusetts Climate Change Adaptation Report. Available at http://www.mass.gov/eea/docs/eea/energy/cca/eea-climate-adaptation-report.pdf

Manomet Center for Conservation Sciences and Massachusetts Division of Fish and Wildlife (Manomet and MDFW). 2010. Climate Change and Massachusetts Fish and Wildlife: Volume 2 Habitat and Species Vulnerability. Available at http://www.mass.gov/dfwele/dfw/habitat/cwcs/pdf/climate_change_habitat_vulnerability.pdf.

U.S. EPA. Vulnerability Assessments in Support of the Climate Ready Estuaries Program: A Novel Approach Using Expert Judgment, Volume II: Results for the Massachusetts Bays Program (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-11/058Fb, 2012. Available at http://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=241555.

New Hampshire
New Hampshire Department of Fish and Game (NHDFG). 2012. Available at http://www.wildnh.com/Wildlife/Wildlife_Plan/climate_change/PDF_Narratives/coastal_vulnerability_narrative.pdf

Rockingham Planning Commission. 2010. Adaptation Strategies to Protect Areas of Increased Risk From Coastal Flooding Due to Climate Change, Seabrook, NH. Available at http://des.nh.gov/organization/divisions/water/wmb/coastal/documents/seabrook_adaptation.pdf.

Wake, C. P., E. Burakowski, E. Kelsey, K. Hayhoe, A. Stoner, C. Watson, and E. Douglas. 2011. Climate Change in the Piscataqua/Great Bay Region: Past, Present, and Future. Carbon Solutions New England and University of New Hampshire. Available at http://carbonsolutionsne.org/resources/reports/pdf/greatbayreport_online.pdf).

Rhode Island
Jordan, P. Projected Sea Level Rise in Rhode Island by Paul Jordan. Narragansett Bay Journal. Available at http://www.nbep.org/maps-watershed.html.

Rhode Island Sea Grant College Program and University of Rhode Island Environmental Data Center (Sea Grant and URI EDC). 2011. Mapping Assets Vulnerable to Sea Level Rise North Kingstown, RI Building Blocks for Climate Change Adaptation: Tools for Community

Assessment and Planning. Available at
http://seagrant.gso.uri.edu/z_downloads/coast/coast_lidar_method.pdf;
http://www.arcgis.com/home/search.html?q=ri%20sea%20level%20rise&t=content.

Ruddock, K. 2011. Using SLAMM 6.0.1 to Model Likely Paths for Salt Marsh Migration in North Kingstown, Rhode Island in Response to Sea Level Rise. The Nature Conservancy of Rhode Island. Available at
http://seagrant.gso.uri.edu/z_downloads/coast/tools_NK_SLAMM_methods_small.pdf.

Maine

Jacobson, G.L., I.J. Fernandez, P.A. Mayewski, and C.V. Schmitt (editors). 2009. Maine's Climate Future: An Initial Assessment. Orono, ME: University of Maine.
http://www.climatechange.umaine.edu/mainesclimatefuture/.

Slovinsky, P. A. and S. M. Dickson. 2006. Impacts of Future Sea Level Rise on the Coastal Floodplain. Available at http://www.maine.gov/doc/nrimc/mgs/explore/marine/sea-level/mgs-open-file-06-14.pdf.

Slovinsky, P. A. and S. M. Dickson. 2009. Assessment of LIDAR for Simulating Existing and Potential Future Marsh Conditions in Casco Bay. Casco Bay Estuary Partnership. Available at http://www.cascobay.usm.maine.edu/pdfs/assessment_of_LIDAR_MGS_report.pdf.