Review

A synthesis of thresholds for focal species along the U.S. Atlantic and Gulf Coasts: A review of research and applications

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ABSTRACT

The impacts from climate change are increasing the possibility of vulnerable coastal species and habitats crossing critical thresholds that could spur rapid and possibly irreversible changes. For species of high conservation concern, improved knowledge of quantitative thresholds could greatly improve management. To meet this need, we synthesized information pertaining to biological responses as tipping points to sea level rise (SLR) and coastal storms for 45 fish, wildlife, and plant species along the U.S. Atlantic and Gulf Coasts and Caribbean through a literature review and expert elicitation. Although these species were selected based on their ecological, economic, and cultural importance, just over half (56%, n = 25) have quantitative threshold data currently available that can be used to assess the effects of SLR and storms during some aspect of their life history. Birds, reptiles, and plants represent the best studied coastal species. Thirteen of the species (29%) are projected to lose at least 50% of their population or habitat (e.g., foraging, nesting, spawning, or resting habitat) in some areas with a 0.5 m or greater rise in sea levels by 2100. Two species (a bird and reptile) may gain habitat from projected SLR and be resilient to future impacts. Numeric thresholds were not available for the remaining 20 species we searched for. Coastal fishes, mammals, and amphibians were among the groups representing a major information gap in this field of research. In addition, quantitative threshold responses to coastal storms were scarce for all taxa. While vulnerability assessments and qualitative research related to the impacts of SLR and storms on coastal species and habitats are increasing, work that incorporates quantitative thresholds as response and impact metrics remains limited. Additional monitoring, modeling, and research that provides multiple quantitative thresholds across species' life stages and/or latitudinal gradients is ideal to support robust coastal management and decision-making across spatio-temporal scales in the face of climate change.

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Contents

1. Introduction

Coastal ecological and human communities are increasingly vulnerable to the impacts of a changing climate. Rising sea levels and coastal storms are changing physical landscapes, disrupting natural systems, and pushing some wildlife populations to the brink of irreversible change. The U.S. Atlantic and Gulf Coasts and Caribbean are regions that are particularly vulnerable to the impacts of coastal storms and rising sea levels (Melillo et al., 2014; Dalton and Jonescomps, 2010). The Northeast coast is among the most developed in the world (Horton et al., 2014), and the Southeast is home to vital infrastructure and some of the fastest-growing coastal metropolitan areas in the country (Carter et al., 2014; RPA, 2013; Entergy, 2010). Gulf Coast communities are already incurring substantial losses from relative sea level rise (SLR) and hurricanes on the order of billions of dollars annually (Carter et al., 2014; Entergy, 2010). The destruction from Hurricanes Katrina and Sandy across the Gulf Coast and Northeast megaregions, respectively, has made coastal resilience a national priority.

The resilience of human and ecological communities to climate change is inherently linked. Coastal habitats that provide vital nesting, resting, and feeding areas for threatened birds and other wildlife also provide societal benefits through ecosystem services. For example, beaches, mangroves, marshes, shellfish beds, and barrier islands offer increased flood protection and storm defenses, carbon sequestration, erosion control, natural water filtration, recreation, and increased quality of life, among other benefits. The value that U.S. coastal wetlands alone provide in protection against coastal storms has been estimated at $23.2 billion per year (in 2008 dollars) (Costanza et al., 2008). Ensuring the integrity and proper functioning of these ecosystems will enhance both the ecological and societal resilience of our coasts.

1.1. The need for ecological threshold information

The need for identifying ecological thresholds related to climate change impacts is well documented (e.g., Needelman et al., 2012; NRC, 2010; CCSP, 2009a; Burkett et al., 2005), but large gaps remain in understanding what tipping points are, as well as when and where they will occur. In 2009, the U.S. Global Change Research Program (USGCRP) released a 'state of knowledge' report on the scientific understanding of thresholds for ecosystems in response to climate change, which found that the capacity to predict and manage threshold crossings that could trigger large-scale, abrupt changes in ecosystems and/or the services they provide was limited (CCSP, 2009a).

Threshold data provide information about critical tipping points beyond which a population is no longer viable or management options are no longer available. We adopted the Intergovernmental Panel on Climate Change's (IPCC, 2014) definition of ecological threshold for a species as any abrupt or nonlinear change or disruption to a species' population, productivity, reproduction, or habitat in response to a threat. For our thresholds assessment, we focused on SLR and coastal storms as the focal climate change related threats. While we use the term 'threshold' frequently, tipping point, ecosystem shift, and abrupt or nonlinear change are interchangeable with this term.

Natural resource managers and conservation scientists need quantitative data to most effectively manage natural resources and prepare for the consequences of crossing tipping points. Moreover, methods for assessing a species' vulnerability to climate change, defined as a function of a system's sensitivity and exposure to climate change as well as its capacity to adapt to those changes (IPCC, 2007), often rely, at least partly, on qualitative data and expert judgment (e.g., Hare et al., 2016; Watson et al., 2015b). Threshold data provide truly quantitative values about how a species will likely respond to a particular threat, thereby generating greater confidence in species rankings and vulnerability assessments.

Further, future storms and accelerating rates of SLR are expected to exacerbate and compound other climate change threats, such as changing precipitation regimes (Osland et al., 2016), and non-climatic threats like urbanization and pollution. Such compound effects could lead to a species reaching a critical threshold level more quickly. Of particular concern is the potential for a keystone species' threshold response to cascade and impact other species, leading to "wholesale ecosystem collapse" (NRC, 2013). For example, the absence of sea otter populations in coastal waters of the North Pacific resulted in abundant sea urchin populations and loss of kelp forests that had indirect effects on dozens of other coastal species (Soulé et al., 2003). Generating more information on thresholds for keystone species is a priority if resource managers are to be prepared for the possibility of abrupt, irreversible system changes (CCSP, 2009a).

The impacts of climate change on species and habitats will be largely determined by their adaptive capacity, which includes the ability of a species or population to cope with climatic change through a combination of phenotypic plasticity, dispersal ability, and genetic diversity (Beever et al., 2016). Thus, there are inherent factors that contribute to a species' fundamental adaptive capacity as well as extrinsic factors that constrain or affect its ability to endure myriad threats (e.g., climate change, land use change, pollution, etc.); management also plays an important role to mitigate extrinsic effects and ensure species-level adaptive capacity is

maximized and not compromised (Beever et al., 2016).

1.2. Objectives of this work

To better understand the current 'state of science' on species thresholds and how these data can inform management practices, we synthesized existing data related to SLR and coastal storm thresholds of viability for 45 fish, wildlife, and plant species along the Atlantic and Gulf Coasts and Caribbean. This was accomplished through a comprehensive literature review and extensive expert elicitation. Species were selected based on their ecological (i.e., foundation or representative species), economic, and cultural importance and have been previously identified as focal species and/or species of conservation concern.

Our results assess recent advances and identify information gaps that when filled will increase the efficiency of managing for climate change impacts in the coastal zone. We further summarize climate change adaptation strategies being used to delay or pre-empt substantial population declines, help sustain and recover listed species, and maintain economically important populations sensitive to SLR and coastal storms. This synthesis is intended to help direct future research, guide strategic program investments, and inform coastal ecosystem management focal areas.

2. Sea level rise and storm projections

Global mean sea levels are projected to rise between 0.3 and 1.2 m by 2100 (Melillo et al., 2014), though more recent projections that consider the melting of land ice (e.g., Antarctica) and unabated emissions are for nearly 2 m of SLR by 2100 (DeConto and Pollard, 2016). The U.S. Atlantic and Gulf Coasts are already experiencing higher-than-average rates of SLR in many locations that will likely continue due to land subsidence (Horton et al., 2014; Carter et al., 2014). Portions of the Gulf Coast are experiencing some of the highest rates of relative SLR in the world, which have exceeded 9 mm per year in parts of Louisiana and 6 mm per year in parts of Texas (NOAA Tides and Currents, 2013). Rates of SLR along the Atlantic Coast are variable with the greatest rates in the mid-Atlantic states of Virginia, Maryland, Delaware, and New Jersey, where they can exceed 5 mm per year (NWF and Manomet, 2014; NOAA Tides and Currents, 2013). Much of the Northeast and Mid-Atlantic regions could have between 0.5 and 1.8 m of SLR, or more, by 2100 (Horton et al., 2015). In Rincón, Puerto Rico, the coastline is eroding at a rate of 1 m per year as a result of relative SLR and poor shoreline management practices (PRCCC, 2013).

Projections of storm intensity and frequency are less certain. For the United States in general, Melillo et al. (2014) reported a slight decrease in the number of tropical cyclones per year by late this century but an increase in the number of the strongest hurricanes (category 4 and 5), as well as greater rates of rainfall associated with hurricanes. Northern coastal states may experience an increase in Atlantic landfalling hurricanes as storm tracks shift poleward (Yin, 2005), and storm surge will likely become more destructive due to rising sea levels (NWF and Manomet, 2014). Winter storms (e.g., nor'easters) that affect the North Atlantic coast are not expected to change much over the next few decades; however, by 2100, 5%—15% more late winter storms are projected under a high emissions scenario (Frumhoff et al., 2007), with the greatest risk to the northernmost parts of the North Atlantic coast (Colle et al., 2010).

3. Species selection and synthesis approach

Our selection of the 45 coastal species included in this review was based primarily on ongoing efforts by regional partners along the Atlantic and Gulf Coasts: six Landscape Conservation Cooperatives (LCCs) - North Atlantic, South Atlantic, Peninsular Florida, Gulf Coast Prairie, Gulf Coastal Plains and Ozarks, and Caribbean; and three Climate Science Centers (CSCs) - Northeast, Southeast, and South Central. An initial list of 107 coastal species was compiled from existing efforts, such as State Wildlife Action Plans developed by each state's fish and wildlife agency, and the Gulf Coast Vulnerability Assessment, which was initiated by the four LCCs in the Gulf of Mexico. In addition, the project core team consisting of 15 representatives from the six coastal LCCs and three CSCs was asked to review and modify the list by adding, removing, or substituting species based on their expert knowledge of priority species in their regions.

This initial list of species was reduced to a more manageable number using critical attribute information for each species. Ten attributes were considered (Table 1); information for each attribute was gathered through a literature review and expert elicitation (N = 15 experts). Experts ranked the attributes with scales from 1-5 based on species-specific knowledge and professional judgment. The species rankings and attribute list were used to finalize the selection by assigning the highest priority to three criteria: 1) species previously identified as vulnerable to SLR or storms, 2) being a representative or foundation species,[3] and 3) whether a species was listed as a species of greatest conservation need (SGCN) (see Supplementary material). We selected species with at least a 4 or 5 ranking for one of these first two criteria and/or were listed as a SGCN in many state wildlife action plans (SWAPs). Further prioritization using the criteria in Table 1 included: 4) federal status (prioritizing endangered or threatened species), 5) geographic distribution across the Atlantic and Gulf Coasts, 6) responses to management, and 7) if it was considered a priority species among federal agencies. Based on this prioritization scheme and a final review by the experts consulted, 45 species were selected that include a diversity of bird, fish, reptile, amphibian, plant, and invertebrate taxa. We acknowledge that there are many other important species in our study area that may have established thresholds related to SLR and storms. However, the prioritization of broadly representative and foundational species means that the threshold data compiled here should be applicable to other important and potentially vulnerable species.

Quantitative thresholds related to SLR and storms were compiled and synthesized for each of these 45 species based on an assessment of both grey and peer-reviewed literature using Web of Science and Google Scholar. Supplemental web searches using other search engines were also used if information was difficult to obtain for a particular species. The following three search terms were used sequentially: species' scientific and common names plus "climate change," "sea level rise," and "storms." Studies found using "climate change," were scanned for "sea level rise" and "storms" and then relevant threshold data. For "sea level rise" and "storms" results, abstracts and full text were scanned for relevant threshold information and searched for the terms "threshold" and "tipping point." We only included results with specific quantitative thresholds related to SLR or storms and only papers relevant to this geography or that were universally relevant. In addition to the literature review, we elicited, via direct communication, supplemental input and information from 26 species experts (see Supplementary material).

This review focuses strictly on SLR and coastal storm thresholds. Numeric thresholds related to other threats may be established for

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Table 1
List of attributes and criteria used for selection of the 45 focal species.

Attribute	Description	Scale
Sensitivity to Sea Level Rise	How sensitive the species is to changes in sea levels and related effects, including resulting habitat loss, inundation, erosion, saltwater intrusion, etc.	1 = not sensitive to 5 = extremely sensitive
Sensitivity to Storm Impacts	How sensitive the species is to major storms, hurricanes and tropical storms, including associated impacts like overwash; erosion; storm surge; sediment transport; temporary, rapid changes in salinity; etc.	1 = not sensitive to 5 = extremely sensitive
Foundational Species	Species' importance to the health and function of the ecosystem	1 = very poor to 5 = very well
Representative Species	How well the species represents other related species in the ecosystem	1 = very poor to 5 = very well
State Wildlife Action Plans (SWAPs)	Whether species is listed as a SGCN within study geography	yes/no
Number of SWAPs	The total number of SWAPs the species is listed in as a SGCN	List total number of states where species is listed
Federal Status	The species' listing status under the Endangered Species Act	E = Endangered T = Threatened C=Candidate UR=Under Review NL=Not Listed
Distribution	Species' geographic distribution within the study region	1 = very limited range to 5 = broad range, not limited
Response to Management	If the species has been shown to respond to management techniques, such as through its population extent, geographic extent, timing of response, etc.	1 = does not respond to 5 = very responsive
Considered a Priority Species to Federal Agencies	Whether the species is considered a priority or focal species by LCCs, CSCs, and/or NOAA	yes/no

some of these species but are not included in this review. Examples of thresholds related to other stressors could include extreme precipitation and temperature shifts that may affect timing of reproductive activities and increased energy expenditures to reach forage areas from changing prey distributions and/or abundance.

The synthesis results reflect a range of threshold estimates related to SLR and coastal storms. While some are quantitative threshold metrics (e.g., salinity tolerance of 9 parts per thousand (ppt) or below), many reflect habitat loss or gain represented as percentages related to certain levels of SLR (e.g., 20% loss of habitat with a 1 m SLR). These different thresholds require some computation to translate the threshold responses (e.g., percentage of habitat loss under a given scenario of SLR) to another location (e.g., a specific refuge or management unit). However, percentages may actually represent more robust estimates of a response or impact, as specific metrics are location specific (depending on habitat characteristics or resource availability) and may be less transferable. In lieu of a specific metric threshold, percentages still allow managers to take action under uncertainty.

4. Review of species thresholds related to sea level rise and storm projections

Table 2 summarizes the number of species by major taxa with

Table 2
Summary of the total number of species per major taxonomic group with and without quantitative threshold data related to SLR and coastal storms. See Supplementary material for a full list of species in each taxa, listed according to their most frequently used common name along with the scientific name.

Taxonomic Groups	No. of Species with (✓) and without (X) Threshold Data	
	✓	X
Shore/Wading Birds	11	10
Plants	5	3
Reptiles	3	2
Fishes	2	3
Invertebrates/Chelicerata	2	0
Mollusk	1	0
Mammals	1	1
Amphibians	0	1
Total	**25**	**20**

threshold data available. All 45 species are considered highly sensitive to the impacts from SLR and storms. Some of the commonly identified threats include: limited marsh migration; coastal squeeze and development; physical damage or death from storm surge; and reduced productivity with increasing inundation regimes. We first provide a brief overview of how these threats are affecting the coastal species and habitats included in this review.

Marsh plants are undergoing changes as a consequence of SLR and increased flooding. Blackgrass growth and reproduction is optimized at elevations well above mean high water (MHW) (Watson et al., 2015a), while smooth cordgrass shows signs of reduced productivity due to flooding stress (Watson et al., 2014). Although marsh elevation has kept up with relative SLR rates in some areas, the high marsh habitats once dominated by salt-meadow cordgrass are converting to smooth cordgrass in areas stressed by SLR and flooding, particularly where marshes cannot migrate inland (Smith et al., 2012; Erwin et al., 2006). Tidal marsh specialists, such as seaside and saltmarsh sparrows as well as king and clapper rails, are particularly vulnerable to marsh loss and fragmentation in areas where high marsh habitat loss is extensive (Correll et al., 2016; Hodgman et al., 2015) and marsh migration is prevented or limited by adjacent development, hardened infrastructure, or drastic changes in the slope of the landscape.

Seabirds and shorebirds are considered important indicator species for ecosystem change (Galbraith et al., 2014; Sydeman et al., 2012; Piatt and Sydeman, 2007) because of nesting and foraging habitat requirements. Seabirds on our list, including the brown pelican, gull-billed tern, and roseate tern, are among the most vulnerable taxonomic groups to climate change (Sydeman et al., 2012). Many federally threatened and endangered birds are currently showing steep declines, or their recovery is threatened by future climate change, such as red knots and piping and snowy plovers (van Gils et al., 2016; USFWS, 2014; Seavey et al., 2011a; Aiello-Lammens et al., 2011). Shorebirds that breed, nest, migrate, or winter in low-lying beaches and barrier islands face increased inundation and coastal squeezing in places bounded by development or land cover that is not suitable for migration (Hare et al., 2016; Galbraith et al., 2014; Wiest et al., 2014; Sydeman et al., 2012). These bird species may be pushed into areas with increased predation and disturbance and must find new sources of food and refuge or risk local extirpation. Some bird species, such as plovers, could initially benefit from the influence of storms on

coastal areas through the temporary creation of open, unvegetated habitat (Gieder et al., 2014); however, most birds will likely be negatively impacted over the long term by higher sea levels and increased storm intensity or frequency. Natural geophysical beach processes such as dune building may also have critical thresholds under projections of SLR and storms that, if crossed, could affect their functioning and persistence and the species that use them.

Increased erosion and coastal squeezing threaten many species on this list, including the horseshoe crab that is losing optimal spawning beach habitat (USFWS, 2014; Titus et al., 2009); the eastern beach tiger beetle that requires undisturbed, wide, open beach habitats (Massachusetts Climate Adaptation Partnership, 2015; Knisley, 2011; Fenster et al., 2006); the Alabama beach mouse, where SLR and development are reducing connectivity among adequate dune habitat (Chen et al., 2014); and sea turtles that are experiencing increased nest flooding on eroded and storm-impacted beaches (Rivas et al., 2016; Pike and Stiner, 2007). All sea turtles are federally listed and vulnerable to the impacts of climate change (Rivas et al., 2016; Watson et al., 2015b; Mazaris et al., 2012; Hays, 2008; Fish et al., 2008, 2005). Further, physical damage from strong storm surge can break up oyster reefs (Seavey et al., 2011b) and cause rapid sediment erosion or deposition in supralittoral zones that only rarely experience saltwater spray. Finally, these 45 species rely primarily on coastal habitats that are vulnerable to the impacts from SLR and storms, including tidal marshes (e.g., Watson et al., 2015c; Carter et al., 2014; Couvillion and Beck, 2013; Kirwan et al., 2010), beaches and barrier islands (e.g., de Winter and Ruessink, 2017; Gutierrez et al., 2007; Horton et al., 2014; Feagin et al., 2005), mangroves (e.g., Gilman et al., 2008; McLeod and Salm, 2006), and shellfish beds (e.g., Seavey et al., 2011b; Dekshenieks et al., 2000).

For many species, the information synthesized here shows a preliminary continuum of vulnerability that when combined with SLR scenarios can be used to prioritize actions based on time to tipping points and species-specific sensitivities (Fig. 1). For example, the saltmarsh sparrow was identified as relatively more vulnerable to SLR compared to some other marsh species like the willet. Fig. 1 includes only species with quantitative threshold metrics related to projected amounts of SLR, which included 19 species with this type of data available as well as black and white mangroves based on qualitative studies described in McLeod and Salm (2006). The figure excludes 6 species with threshold data related to coastal storms, salinity, or inundation regimes that are not associated with a particular SLR scenario. Quantitative threshold results from the literature review and expert elicitation are presented below.

4.1. Thresholds for bird species

Numeric thresholds of viability related to SLR and coastal storm projections have been quantified for 11 of the 21 bird species on our list, including: red knot, whooping crane, willet, piping and snowy plovers, clapper and black rails, saltmarsh and seaside sparrows, mottled duck, and American oystercatcher (Table 3). Thresholds were not currently available for American black duck; however, decision support tools are helping to predict future abundance along the Atlantic Coast based on the proportion of energetic carrying capacity provided by coastal wetlands and changes due to SLR (Jones et al., 2016), which could be used to estimate potential thresholds in the future.

Numeric threshold data were unavailable for mangrove cuckoo, king rail, black skimmer, brown pelican, gull-billed, least, and roseate terns, Wilson's plover, and Nelson's sparrow. However, insights on their vulnerability could be made based on related research:

- Pickens and King (2014) found that for the king rail and other marsh birds in Louisiana and Texas, water depth is a better predictor than marsh type or current management practices. Furthermore, Hodgman et al. (2015) emphasize that declining populations of certain marsh birds will likely lead to their extinction, such as the Nelson's sparrow which is declining at 4.2% annually and the saltmarsh sparrow which is declining at 9% annually in New England tidal marshes (Correll et al., 2016; Hodgman et al., 2015).
- Habitat fragmentation threatens black skimmer populations across their range along the Gulf Coast, and storm surge may create additional risk to nesting success leading to colony failure. Biotic interactions with prey and limited space and resources due to SLR and climate change are still largely uncertain but are likely to negatively affect skimmers (Watson et al., 2015b).
- Wilson's plovers occupy very narrow beaches that are threatened by SLR, development, and climate change and, as such, may experience increased competition for limited nesting space in the future (Watson et al., 2015b).

Nearly all of the 21 bird species in this review are experiencing population declines. Population trend analyses provide indications of when and where species may cross thresholds of viability by identifying critical abundance levels needed for a species to recover and/or persist in the face of climate change and other threats. Despite the perceived wealth of monitoring programs for birds, a lack of consistently collected long-term monitoring data has hindered development of robust population assessments for this comparatively well-studied group. The Saltmarsh Habitat and Avian Research Program (SHARP) has completed statewide population studies for tidal marsh birds in the Mid and North Atlantic regions. Their work shows that some of the species in this review may already be beyond viable levels to sustain or recover populations. In particular, the saltmarsh sparrow is expected to decline by 92% over the next 50 years and may be unable to breed successfully without intervention by 2050 given current rates of SLR and marsh elevation conditions (Correll et al., 2016; Hodgman et al., 2015; USFWS, 2015b). Kern and Shriver (2014) estimated that marsh losses of 15% and 33% over the next 50 years in the Chesapeake Bay, Maryland, resulted in a 19% and 50% probability, respectively, of reaching the quasi-extinction threshold for seaside sparrows.

For many of these avian species, information is limited by: 1) few studies, 2) number and range of SLR scenarios or storm levels considered, and 3) the spatial scales considered (such as a single site or location versus across a species' distribution). For example, only one study measuring threshold values for the willet was found for Chesapeake Bay (Wilson and Watts, 2009), compared to multiple studies conducted on seaside sparrow populations and habitats in Chesapeake Bay (Wilson and Watts, 2009), Connecticut (Hodgman et al., 2015; Shriver and Gibbs, 2004), Texas (Smith et al., 2014), and Florida (Frank et al., 2015). Spatial scales also varied from site-specific to statewide and regional studies (e.g., for the seaside sparrow - Table 3). However, while local rates of relative SLR can vary substantially along the Atlantic and Gulf Coasts (NOAA Tides and Currents, 2013), findings based on a single site or area may be transferrable to other similar areas as precautionary indicators of how SLR will affect local habitats and wildlife populations.

4.2. Thresholds for plant species

Plant species represent the 2nd best studied group in this review, with quantitative thresholds found for 5 out of 8 species (Table 4). Accelerating rates of SLR and associated accretion deficits
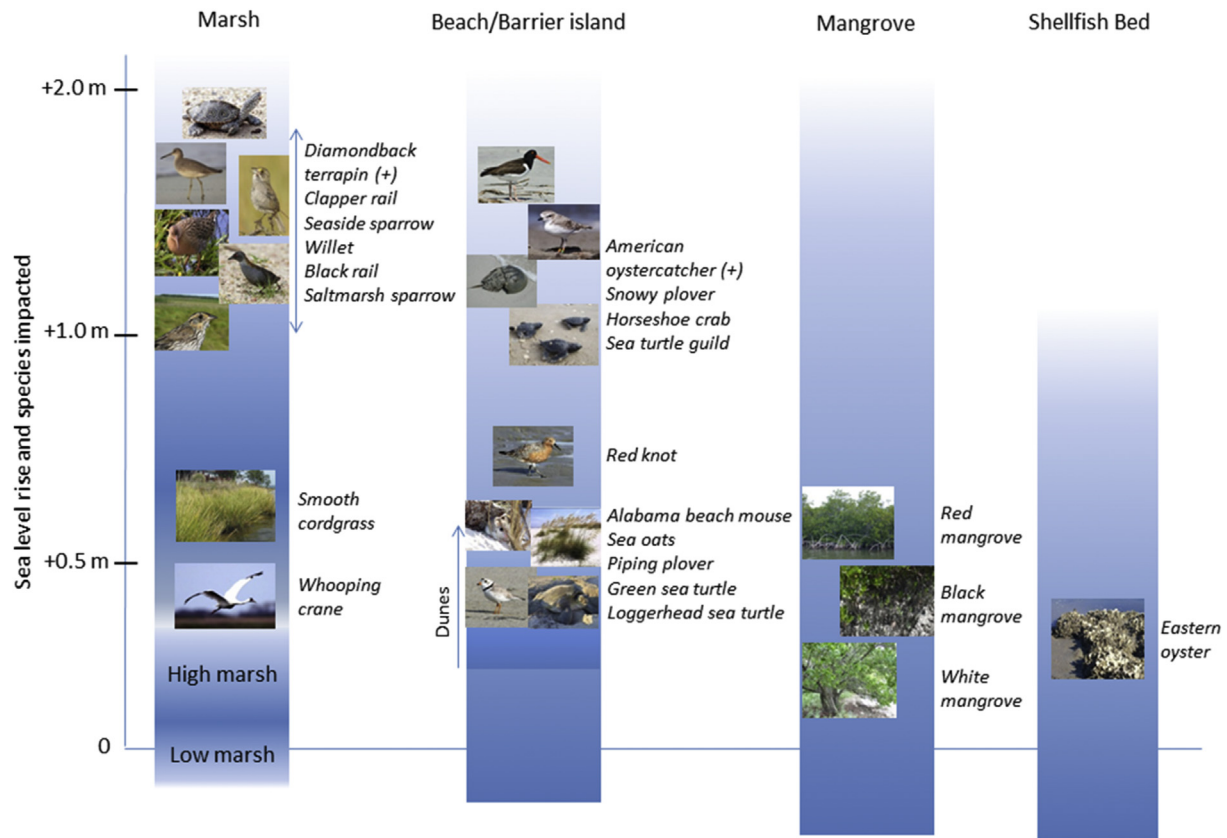
Fig. 1. Species' relative vulnerability to SLR within marsh, beach/barrier island, mangrove, and shellfish bed habitats based on a literature review of species thresholds. Locations of the species/guilds along the vertical axis represent approximate levels of SLR at which species are expected to be impacted according to the citations associated with each species in Tables 3–7. Species are listed as being relatively more (bottom) to less (top) vulnerable within each group. Two species may experience habitat gains associated with SLR, denoted by a "+", and may be most resilient to SLR.

threaten saltmarsh and beach plant species that are intolerant to frequent inundation and/or higher submersion time periods, including blackgrass, sea oats, saltmeadow cordgrass, and spikegrass. Thresholds for these plants generally focus on water level ranges relative to MHW or the marsh surface. As SLR accelerates, the low marsh species smooth cordgrass is moving to higher elevations within marshes and replacing the high marsh species saltmeadow cordgrass (e.g., Donnelly and Bertness, 2001). Spikegrass can tolerate submergence for up to one hour on some coastlines (Lonard et al., 2013), which suggests possible tolerance thresholds related to SLR and storm surge levels. Marsh communities may keep pace with an increase in the rate of SLR in areas with adequate sediment supply, such as where increases in water depth and inundation lead to increased plant growth of flood-tolerant species and, in turn, increased sedimentation rates (Osland et al., 2016; Nyman et al., 2006). Alternatively, these habitats may keep pace with SLR by transgression and expansion into adjacent uplands, such as where saltwater intrusion has triggered forest dieback (Kirwan et al., 2016). The only dune plant in this review is the sea oat, which shows sensitivity to moderate levels of SLR (Feagin et al., 2005).

Similar to tidal marshes, sediment availability combined with local rates of relative SLR make mangrove responses to SLR highly variable and localized. Like marsh plant species, mangroves that cannot accrete sediment at a rate to keep pace with SLR will suffer from increased frequency of inundation. Although out of the geographical range of this study, but as a point of comparison, in coastal north-central Brazil, mangroves may not be able to adapt to

a SLR rate greater than 0.76 cm per year, which could occur under a 1 m SLR scenario within this century (Muehe, 2010; CCSP, 2009b). Additionally, in the Pacific islands, which have a tidal range of less than 1 m, mangrove ecosystems could be disrupted by a more moderate rate of SLR of 0.3 m and are expected to retreat inland with a SLR of 1 m; while low and high island mangroves may keep pace with a SLR of up to 0.12 m and 0.45 m, respectively (Ellison, 2000).

Limited quantitative tolerance data exist for red, black, and white mangroves. McLeod and Salm (2006) found that red mangroves generally have a high peat accumulation (5.3 mm per year) and may be better able to keep pace with increasing rates of SLR compared to other mangrove species (thus their relative placement in Fig. 1). In addition, Harrington and Harrington (1982) observed that flooding for four months to a depth of 30–45 cm in an impoundment at India River in East Florida resulted in death of black and red mangroves. Coastal storms can have contrasting effects on mangrove viability. They can lead to large-scale destruction of mangrove forests, peat collapse, and loss of elevation (McLeod and Salm, 2006), but surge and overwash can also deposit significant amounts of sediment in mangrove forests, acting to increase local accretion (Smoak et al., 2013). Thresholds related to other climate drivers, such as minimum winter temperature extremes and changing rainfall regimes, could lead to the replacement of salt marshes by mangrove forests in the Gulf Coast, which could further impact populations (e.g., whooping crane) that rely on marshes for food and habitat (Osland et al., 2016).

Table 3
Summary of existing quantitative threshold information under projections of sea level rise and coastal storms for 11 (out of 21) bird species.

Common Name (Scientific Name)	Habitat				Thresholds Related to Projections of Sea Level Rise and Storms
	Tidal Marsh	Beaches/ Barrier Islands	Mangroves	Shellfish Beds	
Black rail (Laterallus jamaicensis)	X				• Could lose up to 100% of population with a 1–2 m SLR by 2100 in Chesapeake Bay region (Wilson and Watts, 2009). • Projected to lose up to 58% of current habitat with a 1 m SLR and as much as 96% with a 2.5 m SLR within the Matanzas Basin of FL (Frank et al., 2015).
Clapper rail (Rallus longirostris)	X				• Could lose 70–80% of population with a 1–2 m SLR by 2100 in Chesapeake Bay (Wilson and Watts, 2009).
American oystercatcher (Haematopus palliates)	X	X		X	• Could have a large gain in habitat of 167% with a 1 m SLR within the Matanzas Basin of Florida (Frank et al., 2015).
Mottled duck (Anas fulvigula)	X				• Salinities > 9 ppt negatively affect survival of the mottled duck (Moorman et al., 1991).
Red knot (Calidris canutus)	X	X			• 0.6 m relative SLR could reduce foraging areas by 57% or more by 2100 in Delaware Bay (Titus et al., 2009). • 1–2 m SLR leads to a major loss of coastal wintering habitat for shorebirds in North America, particularly in areas with land subsidence such as the northern Gulf Coast (Galbraith et al., 2014).
Saltmarsh sparrow (Ammodramus caudacutus)	X				• Could lose up to 100% of population with a 1–2 m SLR by 2100 in Chesapeake Bay (Wilson and Watts, 2009). • Maximum tide height experienced by successful nests without being flooded was just 6 cm higher than for failed nests, and the odds of nest failure due to flooding rose by 8% for every 1-cm increase in maximum tide (Wigand et al., 2015).
Seaside sparrow (Ammodramus maritimus)	X				• Could lose 70–80% of population with a 1–2 m SLR by 2100 in Chesapeake Bay (Wilson and Watts, 2009). • 1 m SLR by 2100 could cause a 50% loss of tidal marsh habitat in Connecticut resulting in a 50% chance of population decline, but persistence may be unlikely even under a moderate SLR of 0.5 m (Shriver and Gibbs, 2004). • 1 m SLR by 2100 could decrease primary habitat along the Texas coast by as much as 68% (Smith et al., 2014). • Loss of habitat within the Matanzas Basin of the Guana Tolomato Matanzas Research Reserve in Florida is projected to be 43% under a 1 m SLR and 83% for a 2.5 m SLR (Frank et al., 2015).
Willet (Tringa semipalmata)	X	X			• Could lose nearly 80% of population with a 1–2 m SLR by 2100 in Chesapeake Bay (Wilson and Watts, 2009).
Piping plover (Charadrius melodus)		X			• When development was not considered, a 0.5 m SLR decreased habitat area by as much as 41% for barrier islands in Suffolk County, New York if they respond statically to SLR; • Habitat area was predicted to increase by as much as 15% if they respond dynamically, but development (e.g. buildings, roads, jetties and groins) stymies this potential gain and results in a 5–12% reduction of migrating habitat; • A 1.5 m SLR resulted in 52% less habitat with a static compared to a dynamic response on these barrier islands (Seavey et al., 2011a). • Compounded effects of SLR and storms suggest that storm surge from a major hurricane under a 1.5 m SLR could flood over 95% of habitat (Seavey et al., 2011a).
Snowy plover (Charadrius nivosus)		X			• With 1 m SLR, the risk of extinction was 1.9% more than the baseline risk of about 7%; the risk of decline to 20 birds was 6.3% more; and it reduced predicted population size by at least 20 individuals over a 90-year time period. With 2 m of SLR, the risk of extinction was 3.7% more than the baseline risk; the risk of decline to 20 birds was 7.6% more; and it reduced predicted population size by at least 27 individuals over a 90-year time period (Aiello-Lammens et al., 2011). • The risk of extinction in the next 90 years increases from about 7% to 9% for 1 m of SLR and up to 11% for 2 m of SLR (Aiello-Lammens et al., 2011).
Whooping crane (Grus americana)	X				• A1B mean scenario of 0.39 m SLR by 2100 is projected to decrease primary habitat in coastal Texas by 12% by 2075 and 23% by 2100; • Under the A1B maximum scenario of 0.69 m SLR by 2100, primary habitat coverage decreases by 36% by 2075 and by 52% by 2100, with the greatest losses along back barrier marshes; • A 1 m SLR led to a 50% loss of primary habitat by 2075 and 54% loss by 2100; • A 2 m SLR led to a 52% decrease in primary habitat by 2075 but some areas could partially recover by 2100 with a 2 m SLR (Smith et al., 2014). • 0.43 m SLR over the next 100 years on the Texas coast could reduce suitability of salt marsh and open water areas by making them too deep for use (CWS and USFWS, 2007).

4.3. Thresholds for reptile species

Quantitative thresholds were found for 3 out of the 5 reptile

species in this review (Table 5). Erosion and SLR degrade or remove sea turtle nesting habitat (Rivas et al., 2016), and some studies have linked numeric SLR thresholds to sea turtle nesting habitat

Table 4
Summary of existing quantitative threshold information under projections of sea level rise and coastal storms for 5 (out of 8) plant species.

Common Name	Habitat				Thresholds Related to Projections of Sea Level Rise and Storms
	Tidal Marsh	Beaches/ Barrier Islands	Mangroves	Shellfish Beds	
A subset of mangrove species (*Rhizophora mangle*)			X		• Mangroves on low limestone islands can keep pace with a SLR of 8–9 cm per 100 years, are under stress at 9–12 cm per 100 years, and cannot persist over 12 cm per 100 years, based on calibrations of Holocene stratigraphic records from around the world (Ellison and Stoddart, 1990).
Sea oats (*Uniola paniculata*)		X			• A moderate SLR scenario of 0.48 m by 2100 shows that dune plants on Galveston Island do not grow in lower sections of a beach–sand dune gradient due to high stress levels. A high SLR scenario of 0.88 m by 2100 shows a complete breakdown of successional processes with only colonizers randomly distributed in the upper section of the dune (Feagin et al., 2005).
Salt meadow Cordgrass (*Spartina patens*)	X				• Inundation frequency of twice daily to a depth of 5 cm reduced aboveground biomass by 70% and tiller density by 54% based on experimental plantings and simulated semidiurnal tides (Watson et al., 2015c). • Salinities between 30 and 40 ppt will stress *S. patens*, but not cause mortality; they can survive salinities upwards of 60–93 ppt, but the combination of elevated salinity and flooding frequency (more frequent high tides with longer inundation periods) may be the key abiotic stress in high marsh (Smith et al., 2012).
Smooth cordgrass (*Spartina alterniflora*)	X				• A rate of relative SLR to achieve an equilibrium elevation and optimal depth of tidal flooding for plant growth was predicted to be 1.2 cm/year for marsh with high sediment loading such as along the southeast coast; at higher rates of relative SLR the plant community cannot sustain elevations within its range of tolerance (Morris et al., 2002). • *S. alterniflora* zones expand with increasing tidal amplitude. Maximum mean tidal range is 2.88 m. The maximum upper limit relative to mean high water (MHW) is +0.70 m, while the zone of highest abundance relative to MHW is +0.17 m (McKee and Patrick, 1988). • Migration of cordgrass upslope in southern New England coincides with an increase in the rate of SLR from 1 to 2.4 mm/year from a New York City tide gauge. Projections that local SLR rates could increase to 6 mm/year or more in the next 100 years is expected to drown cordgrass communities (Donnelly and Bertness, 2001).
Spikegrass or salt grass (*Distichlis spicata*)	X				• Dieback in Louisiana has been attributed to excessive submergence, but it can tolerate tidal amplitudes ranging from 1.36-1.74 m for 1 h on some coastlines (Lonard et al., 2013). • Elevational distribution is restricted to water level ranges from 10-15 cm below to 5 cm above the marsh surface (MHW) in mid-Atlantic and Connecticut coastal marshes (Lonard et al., 2013). • High inundation (2× daily to a depth of 5 cm) reduced aboveground biomass by 65%, tiller density by 41%, and rhizome biomass by 65%, based on experimental plantings and simulated semidiurnal tides (Watson et al., 2015c).

availability (e.g., Frank et al., 2015; Vargas et al., 2013; Fuentes et al., 2010; Fish et al., 2008, 2005; Daniels et al., 1993). For example, up to half of sea turtle nesting areas could be lost with a global SLR of 0.5 m or more in the next 100 years in areas of the world where coastal squeezing is occurring or no retreat options exist (Fish et al., 2008, 2005). In the Matanzas Basin of northeastern coastal Florida, habitat for sea turtles could be reduced by 64% with 1 m of SLR by 2100 and with a future urban development scenario for 2060 (Frank et al., 2015). In contrast, the diamondback terrapin, which uses both brackish and salt marshes, could benefit from habitat changes associated with a 1 m SLR scenario, perhaps due to the projected conversion of some forested freshwater wetlands or other land types to estuarine habitat (Frank et al., 2015).

Sea turtles with nesting periods that overlap with the hurricane season are the most vulnerable to coastal storms. Storm-related threshold research for sea turtles has focused on surge levels that can destroy nests and reduce hatching success rates. For instance, Milton et al. (1994) found that Hurricane Andrew impacted sea turtle nests in south Florida within 40 miles of the eye of Andrew, while nests located at least 90 miles from the eye were unaffected. Green sea turtles, in particular, nest during peak hurricane season, making nests and developing eggs highly vulnerable to storm surge

Table 5
Summary of existing quantitative threshold information under projections of sea level rise and coastal storms for 3 (out of 5) reptile species.

Common Name (*Scientific Name*)	Habitat				Thresholds Related to Projections of Sea Level Rise and Storms
	Tidal Marsh	Beaches/ Barrier Islands	Mangroves	Shellfish Beds	
Diamondback terrapin (*Malaclemys terrapin*)	X				• Could have increases in habitat associated with a 1 and 2.5 m SLR of 36% and 40%, respectively, in the Matanzas Basin of Florida due to dependence on brackish and saline marshes (Frank et al., 2015).
Green sea turtle (*Chelonia mydas*)		X			• A 0.59 m SLR would inundate 28% of the total nesting area for green sea turtles, with the extent of inundation for individual beaches ranging from 11% to 36% (Fuentes et al., 2010). • 63% of nests that occurred within 45 miles from the eye of Hurricane Andrew were lost or destroyed due to inundation from a 1.8 m surge (Milton et al., 1994).
Loggerhead sea turtle (*Caretta caretta*)		X			• Relative SLR of 0.53 m along South Carolina's coast (SLR scenario of 31 cm along with subsidence of 22 cm) could reduce nesting area by 51% on Cape Romain (Daniels et al., 1993). • 25% of nests within a 45-mile radius from the eye of Hurricane Andrew were lost or destroyed due to inundation from a 1.8 m surge (Milton et al., 1994).

Table 6
Summary of existing quantitative threshold information under projections of sea level rise and coastal storms for 2 (out of 5) fish species.

Common Name (Scientific Name)	Habitat				Thresholds Related to Projections of Sea Level Rise and Storms
	Tidal Marsh	Beaches/ Barrier Islands	Mangroves	Shellfish Beds	
Shortnose sturgeon (*Acipenser brevirostrum*)		X			• Saltwater intrusion will threaten optimal salinity ranges, which are between 1.75 and 3 ppt during the breeding season, up to 8 ppt during early life stages, and up to 20 ppt for older life stages (Jager et al., 2013).
Gulf sturgeon (*Acipenser oxyrinchus desotoi*)		X			• Exposure to waters with salinity of 10 ppt for a 24-hr period resulted in 100% mortality for 71-day old larvae (Randall et al., 2013).

and inundation (Pike and Stiner, 2007). While no numeric threshold data were found specifically for the Kemp's Ridley sea turtle, this species is believed to be highly vulnerable to SLR as it exhibits low phenotypic plasticity and nests almost exclusively on barrier islands across the Gulf Coast that are highly susceptible to habitat degradation and loss (Watson et al., 2015b).

4.4. Thresholds for fish species

Numeric threshold data specific to SLR and coastal storm stressors were scarce for fishes, with quantitative information only available for 2 out of the 5 species (Table 6). SLR and storm impacts are generally of only moderate concern to fisheries managers, ranking below other climate stressors like water temperature and ocean acidification (Gregg et al., 2016). Thus, only a small subset of fishes was selected that are highly dependent on salt marsh, mangrove, and similar land-based coastal habitats. However, research suggests that some fish species are sensitive to changing salinities and likely to be impacted by SLR in low-lying coastal areas through saltwater intrusion into freshwater areas or by changes in submerged aquatic vegetation (SAV) or other preferred habitat. Diamond killifish in Louisiana tend to use high marsh (*Distichlis spicata*) when it is available (Rozas and Reed, 1993). More intense storms could lead to declines in high marsh plants, losses in SAV, as well as losses of mangrove forests that diamond killifish and other

fish rely on for food and protection from predators, leading to population declines (Gilman et al., 2008; Field, 1995; Nordlie, 1987). Further, long-term salinity increases following hurricanes, which occurred at three sites in southwest Louisiana following the 2008 hurricane season, combined with reduced SAV habitat, may negatively affect diamond killifish abundance (La Peyre and Gordon, 2012). Rainwater killifish prefer structurally complex beds of tapegrass and other SAV, but elevated salinity levels can preclude the colonization and growth of these relatively sensitive SAV-dependent species (Jordan, 2002).

More frequent storms could negatively impact fish that exhibit slow recovery and growth rates, such as gulf sturgeon. Coastal storms usually make landfall in summer when the majority of the gulf sturgeon population is residing in the lower reaches of rivers and are more vulnerable to flooding. If a major landfalling storm reduces a population significantly, it could take decades before population numbers become detectibly higher or rebound to pre-storm levels (Adam Kaeser, U.S. Fish and Wildlife Service, pers. comm., April 2016).

4.5. Thresholds for other taxonomic groups

Quantitative thresholds were found for some of the remaining coastal species, which included invertebrates (2 out of 2), an amphibian (0 out of 1), a mollusk (1 out of 1), and a coastal mammal

Table 7
Summary of existing quantitative threshold information under projections of sea level rise and coastal storms for 2 invertebrates (out of 2), 1 mollusk (out of 1), and 1 coastal mammal (out of 1) species. No thresholds were found for the single amphibian species.

Common Name (Scientific Name)	Habitat				Thresholds Related to Projections of Sea Level Rise and Storms
	Tidal Marsh	Beaches/ Barrier Islands	Mangroves	Shellfish Beds	
Horseshoe crab (*Limulus polyphemus*)	X	X			• SLR and erosion can reduce beach habitat and affect spawning, as they rarely spawn unless sand is at least 10 cm deep (Titus et al., 2009). • Hurricane Sandy is largely responsible for a 70% decrease in optimal spawning habitat that occurred on the New Jersey side of Delaware Bay (Niles et al., 2013).
Eastern oyster (*Crassostrea virginica*)				X	• A SLR rate of 3.6 mm/year over the next 70 years could increase submergence greatly and accelerate oyster reef decline in Florida's Big Bend Coast (Seavey et al., 2011b). • A storm surge level of 2.5 m in Florida's Waccassassa Bay was implicated as a threshold event that broke up several stressed offshore reefs (Seavey et al., 2011b). • Reducing salinity by 3 ppt led to a 168–200% reduction in the number of total oysters, adult oysters, abundance of spawn, recruits, and larvae relative to reference simulations in Galveston Bay (Dekshenieks et al., 2000). • Following hurricane Irene and tropical storm Lee, monthly mortality of 10% and 55% on upper bay beds in Delaware Bay exceeded long-term averages at those locations and were associated with a continuous low salinity (<7) exposure for more than 20 days (Munroe et al., 2013).
Eastern beach tiger beetle		X			• Exhibits preference for beaches that are at least 6 m wide and 100 m long (Fenster et al., 2006); barrier island beach widths are a geomorphic characteristic in SLR and storm vulnerability modeling (e.g., Gutierrez et al., 2015).
Alabama beach mouse (*Peromyscus polionotus ammobates*)		X			• A 100-year storm event would flood more than 82% of their habitat, and when coupled with a SLR of 0.5 m would flood 86% of their habitat (Chen et al., 2014).

(1 out of 2) (Table 7). The eastern oyster is relatively well studied and exhibits optimal submersion times and salinity levels that, if changed, could result in large declines in abundance. The eastern oyster will need to migrate upslope or recruit oysters upward at a pace that maintains preferred submersion times relative to changing rates of SLR (Solomon et al., 2014). Storm-related salinity declines, such as simulated for Galveston Bay, Texas and the Gulf of Mexico, showed that a 3 ppt drop could lead to substantial reductions in larval and adult oysters (Dekshenieks et al., 2000). During record rainfall events throughout the Mississippi River Basin in 2011 that triggered the opening of water control structures, freshwater inputs into the Mississippi Sound lowered salinities to less than 5 ppt for several weeks, substantially diminishing oyster stocks (LA DWF, 2011). Turner (2006) further found that eastern oyster landings were inversely related to freshwater flows in five major estuaries of the Gulf Coast. In addition, winds associated with increased storm activity can increase suspended sediment loads and lead to complete burial and decreased recruitment success of oyster larvae (Solomon et al., 2014; Livingston et al., 1999). Sediment loads of 8 g/L have resulted in significant reductions of oyster settlement (Boudreaux et al., 2009).

In many areas where inland migration is restricted, beach narrowing and other physical changes to beach habitat were found to indirectly impact the horseshoe crab, eastern beach tiger beetle, and the eastern oyster. Loss of beach habitat due to erosion from SLR can lead to large changes in available nesting and spawning habitat for the horseshoe crab (Titus et al., 2009). The eastern beach tiger beetle also exhibits specific habitat requirements that are threatened by erosion and SLR (see Table 7); however, numeric thresholds of SLR and storm levels have not been measured to indicate whether habitat changes will threaten the viability of the eastern beach tiger beetle. For the endangered Alabama beach mouse, limited threshold research suggests that the synergistic effects of storms and SLR could have detrimental impacts on their habitat (Chen et al., 2014). Finally, the eastern oyster is the only species in our review to have a quantitative threshold related to storm surge, which was recorded as part of an extreme event that broke up reefs in a Florida bay (see Table 7).

4.6. Discussion

Nearly all of the species reviewed here exhibit sensitivity to the impacts from SLR and coastal storms, and the majority show predictions of diminished abundance. The oystercatcher and diamondback terrapin were exceptions to this result. For these potentially resilient species, however, we found only one study containing quantitative predictions of SLR or storm-related effects that could lead to increased habitat availability. Overall, thirteen species (29%) are projected to lose at least 50% of their population or habitat (e.g. foraging, nesting, spawning, or resting habitat) in certain areas with a 0.5 m or greater rise in sea levels by 2100. Quantitative tolerance thresholds related to coastal storms are extremely limited, representing a critical knowledge gap.

The 20 species which lack specific numeric threshold data related to SLR or coastal storms include the following:

• American black duck	• Gull-billed tern	• Perdido Key beach mouse
• Black mangrove	• Kemp Ridley's sea turtle	• Rainwater killifish
• Black skimmer	• King rail	• Roseate tern
• Blackgrass	• Least tern	• Spadefoot toad
• Brown pelican	• Leatherback sea turtle	• White mangrove
• Common snook	• Mangrove cuckoo	• Wilson's plover
• Diamond killifish	• Nelson's sparrow	

Our results suggest that research on quantitative thresholds is still in its infancy. Limited quantitative threshold information hinders our ability to know when and where to take actions that can delay or prevent rapid population declines, extirpation, or extinction. Improved knowledge of quantitative thresholds would provide needed benchmarks to guide and support climate-smart management actions and decision making in the coastal zone.

5. Restoration and management alternatives for increasing persistence and resilience of vulnerable species

Despite limited species-specific threshold metrics, an expanding focus on coastal habitat responses to the effects of SLR and coastal storms are helping to inform how species are likely to be impacted. There is a growing body of research on how salt marshes may respond to SLR and coastal storms (e.g., Lentz et al., 2016; Kirwan et al., 2016; Osland et al., 2016; Watson et al., 2015b; Fagherazzi et al., 2013; Morris et al., 2002). Further, research has shown that barrier islands along the Atlantic and Gulf Coasts are susceptible to instability and exhibit diagnostic characteristics that indicate they could cross geomorphic tipping points in response to future SLR (Gutierrez et al., 2007 and references within).

Coastal resource and conservation managers can use habitat tolerance information to bolster planning for species and habitat management under local rates of SLR, changing storm activity, and related vulnerabilities. For instance, Caribbean islands are projected to lose up to 38% of small beaches with a SLR of 0.5 m, which was estimated to reduce sea turtle nesting habitat by one-third (Fish et al., 2005). Given the difficulty in identifying species-specific thresholds, assessing the vulnerability and response of sensitive habitats will continue to be an important area of research for advancing threshold-related science and the interactive effects of SLR and coastal storms.

The following climate change adaptation strategies are currently being employed throughout the Atlantic and Gulf coasts as well as the Caribbean to conserve and manage vulnerable coastal habitats. We present these approaches to disseminate the concept of how threshold data could be used to increase the persistence and resilience of dependent coastal species in a changing climate.

- **Restoration of tidal marsh restrictions** (e.g., manmade hydrologic restrictions and impounded freshwater areas) to restore natural tidal flows, increase the transport of necessary sediment subsidies, and build elevation (such as through sediment diversions). This strategy was used at Prime Hook National Wildlife Refuge, Delaware Bay to restore impounded freshwater areas back to brackish and salt marsh habitats to enhance marsh development, reverse subsidence, and support the recolonization and domination of *Spartina* species. Research has suggested that a SLR rate of 12 mm per year or less in areas with high sediment loading will allow smooth cordgrass growth to sustain an equilibrium elevation and optimal depth of tidal flooding (USFWS, 2015a). The restoration project is incorporating research and monitoring to further identify thresholds or guidelines to mitigate future habitat loss and benefit local species, such as the saltmarsh sparrow, American oystercatcher, and red knot.
- **Sediment augmentation** (e.g., thin-layer deposition) as a salt marsh restoration technique that, when used in conjunction with plantings of native species, builds critical elevation in areas where marsh accretion rates are insufficient to keep pace with local SLR. Sediment augmentation is also used for mangrove systems. Thresholds for marsh plant species like saltmeadow cordgrass, smooth cordgrass, and blackgrass can help identify specific target elevations for thin-layer deposition techniques to

support plant growth and persistence. This will further support other coastal species that rely on salt marsh and mangroves for nesting and reproduction, such as willets and saltmarsh sparrows (USFWS, 2015b).

- **Coastal response modeling** to identify timelines, thresholds, uncertainties, and opportunities for further management and conservation actions (Lentz et al., 2016). This method assesses the ability of habitats to respond dynamically (i.e., migrate inland or build elevation) or statically (i.e., inundate) in response to SLR and coastal storms. Identifying where dynamic responses are more likely is important for planning and decision making related to land acquisition that facilitates upslope or inland migration of beach and barrier island habitats and dependent species including terns, plovers, sea turtles, the eastern beach tiger beetle, and sea oats. Quantitative thresholds can take this further by providing planning time horizons that indicate when and where actions will be most effective and have the greatest confidence levels for successful conservation.

- **Conservation of high biodiversity areas** through acquisitions and easements (e.g., advancement zones, rolling easements, land acquisitions) within a landscape conservation design that prioritizes areas to mitigate habitat losses, maximize movement corridors, and buffer high quality habitat from SLR and storms (Hodgman et al., 2015; Wiest et al., 2014). For example, the Guana Tolomato Matanzas National Estuarine Research Reserve in Florida estimated percent changes in species' habitats and areas of high biodiversity under low and high SLR scenarios to identify vulnerable areas and prioritize conservation lands outside the reserve as an adaptation strategy (Hoctor et al., 2015). This is expected to benefit many wildlife species including black rail; seaside sparrow; least tern; black skimmer; piping plover; and the loggerhead, green, Kemp's Ridley, and leatherback sea turtles.

- **Modeling and monitoring of beach/barrier island geomorphological change** after large coastal storms to improve data and predictions of habitat persistence, barrier island dynamics, and declining or listed species that use these systems. For example, habitat response models have helped identify and quantify highly vulnerable piping plover habitat due to the interactive effects of SLR, storm surge, and development for barrier islands in Suffolk County, New York (Seavey et al., 2011a). Thresholds derived from these modeling and monitoring activities will benefit all beach and barrier island dependent species.

- **Facilitated expansion and assisted migration of coastal habitats** using land-use planning, rolling easements, or zoning rules to identify and acquire areas for plant and animal species to move into as future habitat (Gilman et al., 2008). For example, quantitative thresholds for mangrove species related to SLR would provide timelines to help plan and manage transitional areas in the near and long term. Based on the findings from Ellison and Stoddart (1990) (Table 4), local rates of relative SLR that approach 9 cm per year could trigger action to identify and secure future habitat areas for the long-term persistence and resilience of local red mangrove species in the face of continued SLR.

- **Performance metrics and monitoring** to track and detect possible ecological threshold crossings across multiple scales. Combine threshold-based adaptive management with other decision support tools, such as scenario planning, adaptive resource management, and structured decision-making (Staudinger et al., 2015; Caves et al., 2013) to make informed and iterative adjustments to management decisions as new information on thresholds is obtained. For instance, quantitative ecological performance metrics such as number of nests present, wildlife population, and reproductive success rates can be tracked and evaluated over time for any focal species in a particular management unit or jurisdiction. Monitoring at the community level is ideal to detect and track changes in species interactions and assemblages driven by shifts in habitat use in response to coastal stressors (Stein et al., 2014).

- **Managing ecological shifts at landscape scales**. In particular, climate refugia will become an increasingly important strategy to enhance the persistence of vulnerable species long term (Morelli et al., 2016; Stein et al., 2014, 2013). This includes identifying areas where coastal habitats are able to migrate inland and predicting where range shifts are likely to occur due to changes in temperature or salinity, for instance, that could force species into new areas less exposed to SLR and storm impacts. Mangrove ecosystems (red, white, and black mangroves) and coastal species that use these habitats (e.g., the brown pelican) would especially benefit from management actions that incorporate threshold metrics for a range of stressors (e.g., SLR, temperature, precipitation), as well as across seasons and latitudinal gradients.

- **Beach nourishment** to enhance beach and barrier island habitat, such as through the beneficial use of dredged material for restoration. Quantitative thresholds can guide beach nourishment projects to ensure any adverse impacts to shorebirds, invertebrates, sea turtles, or other beach-dependent species are minimized. For instance, beach nourishment that takes into account thresholds of SLR and coastal storms can better ensure that suitable sand depths for horseshoe crab spawning (Titus et al., 2009) or sea turtle nesting (Rivas et al., 2016) are maintained following storm events.

- **Living shorelines** as a shoreline management technique to protect the natural land-water continuum, reduce flooding and erosion, and provide habitat for coastal species (Currin et al., 2010). Quantitative threshold metrics related to SLR or coastal storms for species that are often part of a living shoreline approach (e.g., smooth cordgrass and eastern oysters) can inform site selection and design to ensure they are used in the most appropriate places and provide the greatest ecological and human community benefits. For instance, identifying inundation thresholds for eastern oysters can inform the construction and ongoing maintenance of oyster reefs in a living shoreline project to ensure optimal oyster submersion times relative to changing rates of SLR (Solomon et al., 2014).

These climate change adaptation strategies represent some of the ways coastal managers and decision makers are effectively increasing the persistence and resilience of vulnerable habitats and species to SLR and coastal storms. Threshold metrics enhance these strategies and build on decision support tools by informing monitoring and decision making, thus increasing our understanding of ecosystem responses to threats and enabling more informed actions (Foley et al., 2015). Further, quantitative thresholds provide resource managers greater confidence in their decisions — even when coupled with the high uncertainties associated with climate and SLR projections.

6. Conclusions

This review of 45 coastal species of conservation concern found quantitative thresholds for 25 species; of these, at least 29% are expected to lose roughly 50% or more of their population or habitat under a moderate rate of SLR of 0.5 m or greater by 2100. Taxa with the greatest amount of threshold data include coastal birds, plants, and reptiles. Less information exists for mangroves, fishes, amphibians, and coastal mammals, suggesting there is insufficient

information to understand and predict when and where these species will cross critical tipping points that could lead to irreversible changes in abundance, productivity, reproduction, or habitat. Threshold metrics for coastal storms were scarce for all species, with only one metric found for strength of storm surge (eastern oyster in Waccassassa Bay, FL (Seavey et al., 2011b)). Despite this, there is a growing body of research and rapid development of decision support tools addressing future impacts of SLR and coastal storms that facilitate decision making and action under high uncertainty. For example, scenario planning (e.g., Rowland et al., 2014), structured decision-making (e.g., Gregory et al., 2012), and adaptive management (e.g., Allen et al., 2011) are helping to connect diverse partners and planning efforts across landscape scales to begin making general decisions with qualitative scenarios, and integrate threshold data when they become available. Two such examples in this geography are Nature's Network: Sustaining lands and waters for wildlife and people – from Maine to Virginia (naturesnetwork.org), and the Southeast Conservation Adaptation Strategy effort (http://secassoutheast.org/).

We conclude that significant gaps in quantitative thresholds and tipping points remain; therefore, it is imperative that research, monitoring, and modeling efforts prioritize critical deficiencies in knowledge. While decisions and actions can still be made with qualitative climate change adaptation tools, quantitative thresholds strengthen decision making and enhance the effectiveness of coastal management approaches seeking to increase the resilience and adaptive capacity of at-risk species and habitats. For instance, quantitative threshold data can be used to modify qualitative risk categories typically used in climate change vulnerability assessments (e.g., extremely, highly, moderately, or not vulnerable) based on how SLR or storms are projected to impact a species or climate-sensitive habitat (Fig. 1). In this way, thresholds provide truly quantitative benchmarks or management targets for vulnerable species and habitats that can inform more definitive planning horizons and prioritize specific actions at a local scale.

The thresholds synthesized in this review are transferrable to other similar areas as precautionary indicators of how SLR will affect local habitats and wildlife populations. However, we urge caution when only a single threshold is available for a specific species or location, as this represents higher uncertainty in its transferability. Ideally, two or more threshold metrics across a species' life stage and/or across latitudinal gradients would support robust decision making and management strategies that are effectively honed. More research quantifying tolerance thresholds across multiple scales for representative species and climate-sensitive habitats under multiple projections of SLR and storm levels is clearly needed at local and regional scales. Lastly, increased guidance on how to incorporate threshold data into coastal management and decision making can ensure that this type of information is useful to managers and can immediately influence coastal restoration and adaptation outcomes.

Acknowledgements

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ocecoaman.2017.07.012.

References

Aiello-Lammens, M.E., Librada Chu-Agor, M.A., Convertino, M., Fischer, R.A., Linkov, I., Akcakaya, H.R., 2011. The impact of sea-level rise on snowy plovers in Florida: integrating geomorphological, habitat, and metapopulation models. Glob. Change Biol. http://dx.doi.org/10.1111/j.1365-2486.2011.02497.

Allen, C.R., Fontaine, J.J., Pope, K.L., Garmestani, A.S., 2011. Adaptive management for a turbulent future. J. Environ. Manag. 92, 1339–1345.

Beever, E.A., O'Leary, J., Mengelt, C., West, J.M., Julius, S., Green, N., Magness, D., Petes, L., Stein, B., Nicotra, A.B., Hellmann, J.J., Robertson, A.L., Staudinger, M.D., Rosenberg, A.A., Babij, E., Brennan, J., Schuurman, G.W., Hofmann, G.E., 2016. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conserv. Lett. 9 (2), 131–137.

Boudreaux, M.L., Walters, L.J., Rittschof, D., 2009. Interactions between native barnacles, non-native barnacles, and the eastern oyster Crassostrea virginica. Bull. Mar. Sci. 84 (1), 43–57.

Bracken, M.E.S., Bracken, B.E., Rogers-Bennett, L., 2007. Species diversity and foundation species: potential indicators of fisheries yields and marine ecosystem functioning. CalCOFI, Rep. 48, 82. UC Davis: Retrieved from: http://escholarship.org/uc/item/1wk4k66d.

Burkett, V.A., Wilcox, D.A., Stottlemyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone, G., Doyle, T., 2005. Nonlinear dynamics in ecosystem response to climatic change: case studies and policy implications. Ecol. Complex. 2, 357–394. http://dx.doi.org/10.1016/j.ecocom.2005.04.010.

Carter, L.M., Jones, J.W., Berry, L., Burkett, V., Murley, J.F., Obeysekera, J., Schramm, P.J., Wear, D., 2014. In: Melillo, J.M., Richmond, Terese (T.C.), Yohe, G.W. (Eds.), Ch. 17: Southeast and the Caribbean. Climate Change Impacts in the United States: the Third National Climate Assessment. U.S. Global Change Research Program, pp. 396–417. http://dx.doi.org/10.7930/J0NP22CB.

Caves, J.K., Bodner, G.S., Simms, K., Fisher, L.A., Robertson, T., 2013. Integrating collaboration, adaptive management, and scenario-planning: experiences at las cienegas national conservation area. Ecol. Soc. 18 (3), 43.

U.S. Climate Change Science Program [CCSP], 2009a. Thresholds of climate change in ecosystems. In: Fagre, D.B., Charles, C.W., Allen, C.D., Birkeland, Charles, Chapin III, F.S., Groffman, P.M., Guntenspergen, G.R., Knapp, A.K., McGuire, A.D., Mulholland, P.J., Peters, D.P.C., Roby, D.D., Sugihara, George (Eds.), A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, 86 pp.

U.S. Climate Change Science Program [CCSP], 2009b. Coastal Sensitivity to Sea-level Rise: a Focus on the Mid-Atlantic Region. U.S. Climate Change Science Program Synthesis and Assessment Product 4.1. U.S. Geological Survey, Reston, VA.

Chen, Q., Wang, H., Wang, L., Tawes, R., Rollman, D., 2014. Predicting impacts of tropical cyclones and sea-level rise on beach mouse habitat. J. Coast. Res. 68, 12–19.

Colle, B.A., Rojowsky, K., Buonaito, F., 2010. New York city storm surges: climatology and an analysis of the wind and cyclone evolution. J. Appl. Meteorol. Climatol. 49, 85–100.

Correll, M.D., Wiest, W.A., Hodgman, T.P., Shriver, W.G., Elphick, C.S., McGill, B.J., O'Brien, K.M., Olsen, B.J., 2016. Predictors of specialist avifaunal decline in coastal marshes. Conserv. Biol. http://dx.doi.org/10.1111/cobi.12797.

Costanza, R., Perez-Maqueo, O., Martinez, M.L., Sutton, P., Anderson, S.J., Mulder, K., 2008. The value of coastal wetlands for hurricane protection. Ambio 37 (4), 241–248.

Couvillion, B.R., Beck, H., 2013. Marsh collapse thresholds for coastal Louisiana estimated using elevation and vegetation index data. In: Brock, J.C., Barras, J.A., Williams, S.J. (Eds.), Understanding and Predicting Change in the Coastal Ecosystems of the Northern Gulf of Mexico, pp. 58–67. http://dx.doi.org/10.2112/SI63-006.1. Journal of Coastal Research, Special Issue No. 63.

Currin, C.A., Chappell, W.S., Deaton, A., 2010. Developing alternative shoreline armoring strategies: the living shoreline approach in North Carolina. In: Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., Dinicola, R.S. (Eds.), 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, pp. 91–102.

Canadian Wildlife Service [CWS] and U.S. Fish and Wildlife Service [USFWS], 2007. International Recovery Plan for the Whooping Crane. Ottawa: Recovery of Nationally Endangered Wildlife (RENEW), and U.S. Fish and Wildlife Service, Albuquerque, New Mexico, 162 pp.

Dalton, M.S., Jones, comps, S.A., 2010. Southeast Regional Assessment Project [SERAP] for the National Climate Change and Wildlife Science Center. U.S. Geological Survey: U.S. Geological Survey Open-File Report 2010–1213, 38 pp.

Daniels, R.C., White, T.W., Chapman, K.K., 1993. Sea-level rise: destruction of threatened and endangered species habitat in South Carolina. Environ. Manag. 17 (3), 373–385.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597. http://dx.doi.org/10.1038/nature17145.

Dekshenieks, M.M., Hofmann, E.E., Powell, E.N., 2000. Quantifying the effects of environmental change on an oyster population: a modeling study. Estuaries 23 (5), 593–610.

Donnelly, J.P., Bertness, M.D., 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. PNAS 98 (25), 14218–14223.

Ellison, J., 2000. How South Pacific mangroves may respond to predicted climate change and sea level rise. In: Gillespie, A., Burns, W.C.G. (Eds.), Climate Change in the South Pacific: Impacts and Responses in Australia, New Zealand, and Small Islands States. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 289–301. Chapter 15.

Ellison, J.C., Stoddart, D.R., 1990. Mangrove ecosystem collapse during predicted sea-level rise: holocene analogues and implications. J. Coast. Res. 7 (1), 151–165.

Entergy, 2010. Building a Resilient Energy Gulf Coast: Executive Report. Entergy Corporation, America's Wetland Foundation, and America's Energy Coast, 11 pp. Available online at: http://www.entergy.com/content/our_community/environment/GulfCoastAdaptation/Building_a_Resilient_Gulf_Coast.pdf.

Erwin, R.M., Sanders, G.M., Prosser, D.J., Cahoon, D.R., 2006. In: Greenberg, R., Maldonado, J.E., Droege, S., Mcdonald, M.V. (Eds.), High Tides and Rising Seas: Potential Effects on Estuarine Waterbirds. Studies in Avian Biology, No. 32, 214–228. Found in Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation.

Fagherazzi, S., Mariotti, G., Wiberg, P.L., McGlathery, K.J., 2013. Marsh collapse does not require sea level rise. Oceanography 26 (3), 70–77. http://dx.doi.org/10.5670/oceanog.2013.47.

Feagin, R.A., Sherman, D.J., Grant, W.E., 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. Front. Ecol. Environ. 3 (7), 359–364.

Fenster, M.S., Knisley, C.B., Reed, C.T., 2006. Habitat preference and the effects of beach nourishment on the federally threatened northeastern beach tiger beetle, *Cicindela dorsalis dorsalis*: western shore, Chesapeake bay, Virginia. J. Coast. Res. 22 (5), 1133–1144.

Field, C.D., 1995. Impact of expected climate change on mangroves. Hydrobiologia 295, 75–81.

Fish, M.R., Cote, I.M., Gill, J.A., Jones, A.P., Renshoff, S., Watkinson, A.R., 2005. Predicting the impact of sea-level rise on Caribbean sea turtle nesting habitat. Conserv. Biol. 19 (2), 482–491.

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

Foley, M.M., Martone, R.G., Fox, M.D., Kappel, C.V., Mease, L.A., Erickson, A.L., Halpern, B.S., Selkoe, K.A., Taylor, P., Scarborough, C., 2015. Using ecological thresholds to inform resource management: current options and future possibilities. Front. Mar. Sci. 2 (95) http://dx.doi.org/10.3389/fmars.2015.00095.

Frank, K., Volk, M., Jourdan, D., 2015. Planning for Sea Level Rise in the Matanzas Basin: Opportunities for Adaptation. Appendix D: Conservation Impacts and Priorities in the Matanzas Basin. University of Florida and the National Estuarine Research Reserve System, 304 pp.

Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.C., Wuebbles, D.J., 2007. Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions. Synthesis Report of the Northeast Climate Impacts Assessment (NECIA). Union of Concerned Scientists (UCS), Cambridge, MA, 160 pp.

Fuentes, M.M.P.B., Limpus, C.J., Hamann, M., Dawson, J., 2010. Potential impacts of projected sea-level rise on sea turtle rookeries. Aquat. Conserv. Mar. Freshw. Ecosyst. 20, 132–139.

Galbraith, H., DesRochers, D.W., Brown, S., Reed, J.M., 2014. Predicting vulnerabilities of North American shorebirds to climate change. PLoS ONE 9 (9), e108899. http://dx.doi.org/10.1371/journal.pone.0108899.

Gieder, K.D., Karpanty, S.M., Fraser, J.D., Catlin, D.H., Gutierrez, B.T., Plant, N.G., Turecek, A.M., Thieler, E.R., 2014. A Bayesian network approach to predicting nest presence of the federally-threatened piping plover (*Charadrius melodus*) using barrier island features. Ecol. Model. 276, 38–50.

Gilman, E.L., Ellison, J., Duke, N.C., Field, C., 2008. Threats to mangroves from climate change and adaptation options. Aquat. Bot. 89, 237–250.

van Gils, J.A., Lisovski, S., Lok, T., Meissner, W., Ozarowska, A., de Fouw, J., Rakhimberdiev, E., Soloviev, M.Y., Piersma, T., Klaassen, M., 2016. Body shrinkage due to Arctic warming reduces red knot fitness in tropical wintering range. Science 352 (6287), 819–821. http://dx.doi.org/10.1126/science.aad6351.

Gregg, R.M., Score, A., Pietri, D., 2016. The State of Climate Adaptation in U.S. Marine Fisheries Management. EcoAdapt, Bainbridge Island, WA, 120 pp.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., Ohlson, D., 2012. Structuring environmental management choices. In: Structured Decision Making: a Practical Guide to Environmental Management Choices. John Wiley & Sons, Ltd, Chichester, UK.

Gutierrez, B.T., Williams, S.J., Thieler, E.R., 2007. Potential for Shoreline Changes Due to Sea-level Rise along the U.S. Mid-Atlantic Region: U.S. Geological Survey Open-file Report 2007-1278. Web only, available at: http://pubs.usgs.gov/of/2007/1278.

Gutierrez, B.T., Plant, N.G., Thieler, E.R., Turecek, A., 2015. Using a Bayesian network to predict barrier island geomorphologic characteristics. J. Geophys. Res. Earth Surf. 120, 2452–2475. http://dx.doi.org/10.1002/2015JF003671.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., et al., 2016. A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental shelf. PLoS ONE 11 (2), e0146756. http://dx.doi.org/10.1371/journal.pone.0146756.

Harrington, R.W., Harrington, E.S., 1982. Effects on fishes and their forage organisms of impounding a Florida salt marsh to prevent breeding by salt marsh mosquitos. Bull. Mar. Sci. 32, 523–531.

Hays, G.C., 2008. Sea turtles: a review of some key recent discoveries and remaining questions. J. Exp. Mar. Biol. Ecol. 356, 1–7.

Hoctor, T., Volk, M., Zhu, M., 2015. Planning for Sea Level Rise in the Matanzas Basin, Appendix D: Conservation Impacts and Priorities in the Matanzas Basin. University of Florida, 205 pp.

Hodgman, T.P., Elphick, C.S., Olsen, B.J., Shriver, W.G., 2015. The Conservation of Tidal Marsh Birds: Guiding Action at the Intersection of Our Changing Land and Seascapes. Saltmarsh Habitat & Avian Research Program (SHARP), 161 pp.

Horton, R., Yohe, G., Easterling, W., Kates, R., Ruth, M., Sussman, E., Whelchel, A., Wolfe, D., Lipschultz, F., 2014. In: Melillo, J.M., Richmond, Terese (T.C.), Yohe, G.W. (Eds.), Ch. 16: Northeast. Climate Change Impacts in the United States: the Third National Climate Assessment. U.S. Global Change Research Program, pp. 371–395.

Horton, R., Little, C., Gornitz, V., Bader, D., Oppenheimer, M., 2015. Chapter 2: Sea Level Rise and Coastal Storms. New York City Panel on Climate Change 2015 Report. Annals of the New York Academy of Sciences, New York, NY, pp. 36–44.

Intergovernmental Panel on Climate Change [IPCC], 2007. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change [IPCC], 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part a: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 32 pp.

Jager, H.I., Peterson, D.L., Farrae, D., Bevelhimer, M.S., 2013. A population model to assess influences on the viability of the shortnose sturgeon population in the ogeechee river, Georgia. Trans. Am. Fish. Soc. 142, 731–746.

Jones, M.T., Luke, K., Coluccy, J., Devers, P., 2016. Development of a Decision Support Tool to Inform Black Duck Habitat Delivery Goals Considering Current and Future Landscape Conditions. Final Performance Report Submitted to Chesapeake Bay Trust. 33 pp. Online at: https://acjv.org/ABDU/abdu_cbt_finalreport_15dec2016_v5.pdf.

Jordan, F., 2002. Field and laboratory evaluation of habitat use by rainwater killifish (*Lucania parva*) in the st. Johns river estuary, Florida. Estuaries 25 (2), 288–295.

Kern, R.A., Shriver, W.G., 2014. Sea level rise and prescribed fire management: implications for seaside sparrow population viability. Biol. Conserv. 173, 24–31.

Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophys. Res. Lett. 37, L23401. http://dx.doi.org/10.1029/2010GL045489.

Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. Nat. Clim. Change 6, 253–260. http://dx.doi.org/10.1038/NCLIMATE2909.

Knisley, C.B., 2011. Anthropogenic disturbances and rare tiger beetle habitats: benefits, risks, and implications for conservation. Terr. Arthropod Rev. 4, 41–61.

Louisiana Department of Wildlife and Fisheries [LA DWF], 2011. Oyster Stock Assessment Report of the Public Oyster Areas in Louisiana Seed Grounds and Seed Reservations. Office of Fisheries, Oyster Data Report Series No. 17, 92 pp.

Lentz, E.E., Thieler, E.R., Plant, N.G., Stippa, S.R., Horton, R.M., Gesch, D.B., 2016. Evaluation of Dynamic Coastal Response to Sea-level Rise Modifies Inundation Likelihood. Nature Climate Change, Letters. http://dx.doi.org/10.1038/NCLIMATE2957.

Livingston, R.J., Howell IV, R.L., Niu, X., Lewis III, F.G., Woodsum, G.C., 1999. Recovery of oyster reefs (*Crassostrea virginica*) in a gulf estuary following disturbance by two hurricanes. Bull. Mar. Sci. 64 (3), 465–483.

Lonard, R.I., Judd, F.W., Stalter, R., 2013. The biological flora of coastal dunes and wetlands: *Distichlis spicata* (C. Linnaeus) E. Greene. J. Coast. Res. 29 (1), 105–117.

Massachusetts Climate Adaptation Partnership, 2015. Ecology and Vulnerability of Northeastern Beach Tiger Beetle. Massachusetts Wildlife Climate Action Tool. Online at: https://climateactiontool.org/species/northeastern-beach-tiger-beetle. (Accessed March 2016).

Mazaris, A.D., Kallimanis, A.S., Pantis, J.D., Hays, G.C., 2012. Phenological response of sea turtles to environmental variation across a species' northern range. Proc. R. Soc. B 280, 20122397.

McKee, K.L., Patrick Jr., W.H., 1988. The relationship of smooth cordgrass (Spartina alterniflora) to tidal datums: a review. Estuaries 11 (3), 143–151.

McLeod, E., Salm, R.V., 2006. Managing Mangroves for Resilience to Climate Change. International Union for Conservation of Nature [IUCN] Resilience Science Group Working Paper Series No. 2, Gland, Switzerland. 64pp.

Melillo, J.M., Richmond, Terese (T.C.), Yohe, G.W. (Eds.), 2014. Climate Change Impacts in the United States: the Third National Climate Assessment. U.S. Global

Change Research Program. http://dx.doi.org/10.7930/J0Z31WJ2, 841 pp.

Milton, S.L., Leone-Kabler, S., Schulman, A.A., Lutz, P.L., 1994. Effects of Hurricane Andrew on the sea turtle nesting beaches of South Florida. Bull. Mar. Sci. 54 (3), 974–981.

Moorman, A.M., Moorman, T.E., Baldassarre, G.A., Richard, D.M., 1991. Effects of saline water on growth and survival of mottled duck ducklings in Louisiana. J. Wildl. Manag. 55, 471–476.

Morelli, T.L., Daly, C., Dobrowski, S.Z., Dulen, D.M., Ebersole, J.L., Jackson, S.T., Lundquist, J.D., Millar, C.I., Maher, S.P., Monahan, W.B., Nydick, K.R., Redmond, K.T., et al., 2016. Managing climate change refugia for climate adaptation. PLoS ONE 11 (8), e0159909. http://dx.doi.org/10.1371/journal.pone.0159909.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea levels. Ecology 83 (10), 2869–2877.

Muehe, D., 2010. Brazilian coastal vulnerability to climate change. Pan Am. J. Aquat. Sci. 5 (2), 173–183.

Munroe, D., Tabatabai, A., Burt, I., Bushek, D., Powell, E.N., Wilkin, J., 2013. Oyster mortality in Delaware bay: impacts and recovery from hurricane irene and tropical storm lee. Estuar. Coast. Shelf Sci. 135, 209–219.

Needelman, B.A., Crooks, S., Shumway, C.A., Titus, J.G., Takacs, R., Hawkes, J.E., 2012. In: Needelman, B.A., Benoit, J., Bosak, S., Lyons, C. (Eds.), Restore-adapt-mitigate: Responding to Climate Change through Coastal Habitat Restoration. Restore America's Estuaries, Washington D.C., 63 pp.

Niles, L.J., Smith, J.A.M., Daly, D.F., Shadel, W., Dillingham, T., Dey, A.D., Danihel, M.S., Hafner, S., Wheeler, D., 2013. Restoration of Horseshoe Crab and Migratory Shorebird Habitat on Five Delaware Bay Beaches Damaged by Superstorm Sandy, 22 pp. Online at: http://arubewithaview.com/wordpress/wp-content/uploads/2012/12/RestorationReport_112213.pdf.

National Oceanic and Atmospheric Administration [NOAA] Tides and Currents, 2013. Sea Level Trends. National Oceanic and Atmospheric Administration. Center for Operational Oceanographic Products and Services. https://tidesandcurrents.noaa.gov. (Accessed May 2016).

Nordlie, F.G., 1987. Salinity tolerance and osmotic regulation in the diamond killifish, Adinia xenica. Environ. Biol. Fishes 20, 229. http://dx.doi.org/10.1007/BF00004957.

National Research Council [NRC], 2010. Advancing the Science of Climate Change. National Research Council of The National Academies Press, Washington, DC, 527 pp.

National Research Council [NRC], 2013. Abrupt Impacts of Climate Change: Anticipating Surprises. National Research Council of The National Academies Press, Washington, D.C., 223 pp.

National Wildlife Federation [NWF] and Manomet, 2014. The Vulnerabilities of Northeastern Fish and Wildlife Habitats to Sea Level Rise. A Report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. National Wildlife Federation and Manomet Center for Conservation Sciences, Manomet, Plymouth, MA, 55 pp.

Nyman, J.A., Walters, R.J., Delaune, R.D., Patrick Jr., W.H., 2006. Marsh vertical accretion via vegetative growth. Estuar. Coast. Shelf Sci. 69, 370–380.

Osland, M.J., Enwright, N.M., Day, R.H., Gabler, C.A., Stagg, C.L., Grace, J.B., 2016. Beyond just sea-level rise: considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. Glob. Change Biol. 22, 1–11. http://dx.doi.org/10.1111/gcb.13084.

La Peyre, M.K., Gordon, J., 2012. Nekton density patterns and hurricane recovery in submerged aquatic vegetation, and along non-vegetated natural and created edge habitats. Estuar. Coast. Shelf Sci. 98, 108–118.

Piatt, J.F., Sydeman, W.J., 2007. Theme Section: seabirds as indicators of marine ecosystems. Mar. Ecol. Prog. Ser. 352, 199–309.

Pickens, B.A., King, S.L., 2014. Multiscale habitat selection of wetland birds in the northern gulf coast. Estuaries Coasts 37, 1301–1311.

Pike, D.A., Stiner, J.C., 2007. Sea turtle species vary in their susceptibility to tropical cyclones. Glob. Change Conserv. 153, 471–478.

Puerto Rico Climate Change Council [PRCCC], 2013. State of Puerto Rico's Climate 2010-2013 Executive Summary. Assessing Puerto Rico's Social-ecological Vulnerabilities in a Changing Climate. Puerto Rico Coastal Zone Management Program. Department of Natural and Environmental Resources, Office of Ocean and Coastal Resource Management (NOAA-OCRM), San Juan, PR, 27 pp.

Randall, M., Price, M., Gillett, B., Sulak, K.J., Brownell, P., 2013. Gulf Sturgeon (Acipenser Oxyrinchus Desotoi) Categorical Habitat Attribute Acceptability Tool (CHAAT). Report, April 18, 2013. 82 pg.

Rivas, M.L., Tomillo, P.S., Dieguez-Uribeondo, J., Marco, A., 2016. Potential effects of dune scarps caused by beach erosion on the nesting behavior of leatherback turtles. Mar. Ecol. Prog. Ser. 551, 239–248.

Rowland, E.L., Cross, M.S., Hartmann, H., 2014. Considering Multiple Futures: Scenario Planning to Address Uncertainty in Natural Resource Conservation. US Fish and Wildlife Service, Washington, DC.

Rozas, L.P., Reed, D.J., 1993. Nekton use of marsh-surface habitats in Louisiana (USA) deltaic salt marshes undergoing submergence. Mar. Ecol. Prog. Ser. 96, 147–157.

Regional Plan Association [RPA], 2013. Megaregions. America2050. Regional Plan Association. Online at: http://www.america2050.org/content/megaregions.html. (Accessed May 2016).

Seavey, J.R., Gilmer, B., McGarigal, K.M., 2011a. Effect of sea-level rise on piping plover (Charadrius melodus) breeding habitat. Biol. Conserv. 144 (1), 393–401.

Seavey, J.R., Pine III, W.E., Frederick, P., Sturmer, L., Berrigan, M., 2011b. Decadal changes in oyster reefs in the big bend of Florida's gulf coast. Ecosphere 2 (10), 114. http://dx.doi.org/10.1890/ES11-00205.1.

Shriver, W.G., Gibbs, J.P., 2004. Seaside sparrows (Ammodramus maritimus) in Connecticut: projected effects of sea-level rise. In: Akcakaya, R.H., Burgman, M.A., Kindvall, O., et al. (Eds.), Species Conservation and Management Case Studies. Oxford University Press, Oxford, pp. 397–409.

Smith, S.M., Medeiros, K.C., Tyrrell, M.C., 2012. Hydrology, herbivory, and the decline of Spartina patens (aiton) muhl. In outer cape cod salt marshes (Massachusetts, USA). J. Coast. Res. 28 (3), 602–612.

Smith, E.H., Chavez-Ramirez, F., Lumb, L., Gibeaut, J., 2014. Employing the Conservation Design Approach on Sea-level Rise Impacts on Coastal Avian Habitats along the Central Texas Coast. Report Submitted to the Gulf Coast Prairie Landscape Conservation Cooperative. 140 pp.

Smoak, J.M., Breithaupt, J.L., Smith III, T.J., Sanders, C.J., 2013. Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park. Catena 104, 58–66.

Solomon, J.A., Donnelly, M.J., Walters, L.J., 2014. Effects of sea level rise on the intertidal oyster Crassostrea virginica by field experiments. J. Coast. Res. SI 68, 57–64.

Soulé, M.E., Estes, J.A., Berger, J., del Rio, C.M., 2003. Ecological effectiveness: conservation goals for interactive species. Conserv. Biol. 17 (5), 1238–1250.

Staudinger, M.D., Morelli, T.L., Bryan, A.M., 2015. Integrating Climate Change into Northeast and Midwest State Wildlife Action Plans. DOI Northeast Climate Science Center Report, Amherst, Massachusetts.

Stein, B.A., Staudt, A., Cross, M.S., Dubois, N.S., Enquist, C., Griffis, R., Hansen, L.J., Hellmann, J.J., Lawler, J.J., Nelson, E.J., Pairis, A., 2013. Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Front. Ecol. Environ. 11 (9), 502–510. http://dx.doi.org/10.1890/120277.

Stein, B.A., Glick, P., Edelson, N., Staudt, A. (Eds.), 2014. Climate-smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C., 272 pp.

Sydeman, W.J., Thompson, S.A., Kitaysky, A., 2012. Seabirds and climate change: roadmap for the future. Mar. Ecol. Prog. Ser. 454, 107–117.

Titus, J.G., Anderson, K.E., Cahoon, K.R., Gesch, D.B., Gill, S.K., Gutierrez, B.T., Thieler, E.R., Williams, S.J., 2009. Coastal Sensitivity to Sea-level Rise: a Focus on the Mid-Atlantic Region. U.S. Climate Change Science Program, Synthesis and Assessment Product 4.1. 320 pp.

Turner, R.E., 2006. Will lowering estuarine salinity increase Gulf of Mexico oyster landings? Estuaries Coasts 29 (3), 345–352.

U.S. Fish and Wildlife Service [USFWS], 2014. Rufa Red Knot Background Information and Threats Assessment. Supplement to: Endangered and Threatened Wildlife and Plants; Final Threatened Status for the Rufa Red Knot (Calidris canutus Rufa). U.S. Fish and Wildlife Service. Northeast Region, 383 pp.

U.S. Fish and Wildlife Service [USFWS], 2015a. Draft Environmental Assessment Prime Hook National Wildlife Refuge for Recovery and Ecosystem Restoration, 131 pp.

U.S. Fish and Wildlife Service [USFWS], 2015b. Maidford Salt Marsh Restoration Draft Project Description. U.S. Fish and Wildlife Service and Rhode Island National Wildlife Refuge Complex, 75 pp.

Vargas, J.C., Flaxman, M., Chu, C., 2013. KeysMAP: Florida Keys, Florida. Keys Marine Adaptation Planning. GeoAdaptive LLC for Florida Fish and Wildlife Conservation Commission – Fish and Wildlife Research Institute (FWC-FWRI), Marathon, FL.

Watson, E.B., Oczkowski, A.J., Wigand, C., Hanson, A.R., Davey, E.W., Crosby, S.C., Johnson, R.L., Andrews, H.M., 2014. Nutrient enrichment and precipitation changes do not enhance resiliency of salt marshes to sea level rise in the Northeastern U.S. Clim. Change 125, 501–509.

Watson, E.B., Wigand, C., Cencer, M., Blount, K., 2015a. Inundation and precipitation effects on growth and flowering of the high marsh species Juncus gerardii. Aquat. Bot. 121, 52–56.

Watson, A., Reece, J., Tirpak, B.E., Edwards, C.K., Geselbracht, L., Woodrey, M., LaPeyre, M., Dalyander, P.S., 2015b. The Gulf Coast Vulnerability Assessment: Mangrove, Tidal Emergent Marsh, Barrier Islands, and Oyster Reef, 132 pp. Available from: http://gulfcoastprairielcc.org/science/scienceprojects/gulf-coast-vulnerability-assessment.

Watson, E.B., Andrews, H.M., Fischer, A., Cencer, M., Coiro, L., Kelley, S., Wigand, C., 2015c. Growth and photosynthesis responses of two co-occurring marsh grasses to inundation and varied nutrients. Botany 93, 671–683.

Wiest, W.A., Shriver, W.G., Messer, K.D., 2014. Incorporating climate change with conservation planning: a case study for tidal marsh bird conservation in Delaware, USA. J. Conserv. Plan. 10, 25–42.

Wigand, C., Ardito, T., Chaffee, C., Ferguson, W., Paton, S., Raposa, K., Vandemoer, C., Watson, E., 2015. A climate change adaptation strategy for management of coastal marsh systems. Estuaries Coasts. http://dx.doi.org/10.1007/s12237-015-0003-y.

Wilson, M., Watts, B., 2009. Impacts of Sea Level Rise on Marsh Birds. The Center for Conservation Biology. May 1, 2009. Online at: http://www.ccbbirds.org/2009/05/01/impacts-of-sea-level-rise-on-marsh-birds. (Accessed May 2016).

de Winter, R.C., Ruessink, B.G., 2017. Sensitivity analysis of climate change impacts on dune erosion: case study for the Dutch Holland coast. Clim. Change 141, 685–701. http://dx.doi.org/10.1007/s10584-017-1922-3.

Yin, J.H., 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophys. Res. Lett. 32, L18701.