ARTICLE IN PRESS

Biological Conservation xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat

Jennifer R. Seavey [a,*], Ben Gilmer [b], Kevin M. McGarigal [c]

[a] *Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, FL 32601, United States*
[b] *Global Marine Initiative, The Nature Conservancy, Seattle, WA 98101, United States*
[c] *Department of Natural Resources Conservation, University of Massachusetts, Amherst, MA 01003, United States*

ARTICLE INFO

Article history:
Received 3 January 2010
Received in revised form 10 September 2010
Accepted 13 September 2010
Available online xxxx

Keywords:
Barrier islands
Climate change
Shorebirds

ABSTRACT

Climate change is raising sea levels, threatening many low-lying coastal areas and associated wildlife. We assessed the threat of sea-level rise (SLR) to the breeding habitat of the federally threatened piping plover on the barrier islands of Suffolk County, New York. We determined the extent of habitat change over the next 100 years under several SLR estimates, as well as the interactive effects of coastal development and storm surge. We found that if plover habitat cannot migrate, SLR is likely to reduce breeding areas. However, if habitat is able to migrate upslope and inland, breeding areas could actually increase with SLR. Unfortunately, this potential habitat gain is stymied by human development, which we found to reduce migrating habitat by 5–12%, depending on SLR estimates. We also found that the spatial configuration of developed areas mattered more than intensity of development in blocking the migration of potential habitat area. Our results raise concern over the likelihood of increased conflict between plover habitat protection and human recreation as habitat is likely to become a larger proportion of the barrier islands in the future. Finally, our results highlight risk from the synergism between SLR and coastal storms, as we estimate that a large hurricane could flood up to 95% of plover habitat. To assure the future of plover habitat on these barrier islands, management needs to promote natural overwash and habitat migration, while minimizing development adjacent to future breeding habitat.

1. Introduction

Habitat loss, a leading threat to wildlife, is expected to escalate under global climate change resulting in the extinction of many species (Jetz et al., 2007; Mac Nally et al., 2009; Sekercioglu et al., 2008; Thomas et al., 2004; Wilcove et al., 2000). Habitat loss is predicted to be particularly high among low-lying coastal systems because of their vulnerability to sea-level rise (Farbotko, 2010; Nicholls et al., 2007). Coastal land loss will escalate extinction risk for associated wildlife species, especially those imperiled under current climate conditions (Baker et al., 2006; Daniels et al., 1993; Fish et al., 2008; LaFever et al., 2007; Markham, 1996).

Melting ice and thermal expansion are expected to increase sea levels between 0.18 m and 2 m over the next 100 years (Rahmstorf, 2010; Grinsted et al., 2009; Richardson et al., 2009; IPCC, 2007). The consequences of these rising sea levels on coastal systems include inundation of low-lying areas, as well as increased erosion and storm flooding (IPCC, 2007; Klein and Nicholls, 1999; Titus and Richman, 2001). For example, inundation from a 1.5 m rise is expected to result in the loss of 6 million hectares of coastal land along the eastern shores of the United States (Titus and Richman, 2001). The mid-Atlantic shoreline, from New York to North Carolina, is especially vulnerable due to higher than the global average rates of sea-level rise (Titus et al., 2009). In addition, the northeast coast of the United States is expected to experience changes to the Atlantic meridional overturning circulation as a result of global climate change, which will also lead to increased sea-level rise in this region (Yin et al., 2009).

Negative impacts from sea-level rise (SLR) are expected to be especially acute on barrier islands because of their abundance of low elevations in combination with the process of island migration (Davis and Fitzgerald, 2004; FitzGerald et al., 2008; Hayes, 2005). Island migration is the mechanism by which barrier islands have historically absorbed SLR (Titus et al., 2009). This absorption process is driven by waves and storm surges that push ocean water over islands, carrying sediment from the ocean side to the leeside. This movement of sediment causes a shift of the landform, which ultimately maintains the island system. The concern among many scientists is that the rate of SLR under climate change will outpace the migration process (Titus et al., 2009; FitzGerald et al., 2008; Hayes, 2005; Zhang et al., 2004). If the migration process is overwhelmed by rising waters, erosion and flooding are expected and will lead to the inundation and loss of many barrier islands (Titus et al., 2009; Zhang et al., 2004).

Aggravating this threat to migration dynamics is the prevalence of coastal development. Human development alters barrier island

---

* Corresponding author. Tel.: +1 413 237 7733.
E-mail address: jseavey@ufl.edu (J.R. Seavey).

0006-3207/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biocon.2010.09.017

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

migration by blocking and altering the movement of wind, sand, and water (Feagin et al., 2005; FitzGerald et al., 2008; Hartig et al., 2002; IPCC, 2007; Titus, 1989; Zhang et al., 2004). Further, coastal development can squeeze barrier island habitats between the ocean and hardened surfaces such as walls, jetties, roads, and buildings (French, 2001), causing a rearrangement of landscape patterns and change in habitat connectivity (Feagin et al., 2005; Galbraith et al., 2002).

Habitat loss associated with SLR threatens all barrier island organisms, including shorebirds. Worldwide, scientists estimate that many shorebirds are currently in decline and will suffer further reduction from habitat loss brought about by climate change (Galbraith et al., 2002; Le V. dit Durell et al., 2006; Warnock et al., 2002). The decline of the piping plover (*Charadrius melodus*), federally listed in 1986, is blamed primarily on habitat loss and degradation resulting from human development (USFWS, 1996). Habitat degradation is expressed as increased disturbance and predation on plover populations (USFWS, 1996). Though conservation management over the past 20 years has led to a steady increase in the plover population, recovery goals have not been met and concern is increasing over climate change impacts, especially from rising sea levels (USFWS, 2009).

In addition to direct habitat loss, SLR is expected to act synergistically with global changes in storms to increase coastal flooding that will likely increase the risk of negative impacts on plover nesting habitat. Higher sea-surface temperatures in the tropics that are expected from global climate change are predicted to increase the frequency and intensity of storm events in the future (Bender et al., 2010; Frumhoff et al., 2007). These storms are expected to have increased wind speeds, heavier precipitation, larger and more frequent tidal surges, and wind-driven waves, all of which will increase flooding along the Atlantic Coast during the breeding season (Frumhoff et al., 2007). Increased flooding of plover nesting habitat is expected to amplify nest abandonment and bird (especially eggs and chick) mortality (USFWS, 2009).

New York's piping plover population, second only to Massachusetts in terms of both population size and recovery (USFWS, 2009), is reliant on low-lying barrier island habitat as it provides the majority of the state's breeding habitat (Seavey, 2009). These islands provide plover habitat primarily through the process of barrier island migration (Cohen, 2005; Cohen et al., 2009; Elias-Gerken, 1994; Seavey, 2009). However, if migration is overwhelmed by SLR, island land area (Hayes, 2005; Zhang et al., 2004) and plover habitat could be lost. The assessment of risk from rising sea levels to the piping plovers of New York's barrier islands is critical to plover recovery planning. In this study, we examined potential changes to piping plover breeding habitat from rising sea levels under several SLR estimates over the next 100 years. In addition, since the methodology for modeling SLR is currently debated and rapidly changing (FitzGerald et al., 2008; Thieler and Hammar-Klose, 2000), we explored different models to examine uncertainty in our predictions. Further, we investigated the influence of human development in altering SLR impacts and flooding risk from storms. With these analyses, our aim was to quantify potential SLR impacts to piping plover habitat in an important region of the current breeding range and highlight management concerns.

2. Material and methods

2.1. Study Site

Our study area encompassed the barrier island system of Suffolk County, which spans 93 km of barrier island and peninsula shoreline along the southern coast of Long Island, New York, USA (Fig. 1). Multiple inlets break this barrier system into four segments (from west to east): Jones Beach Island, Fire Island, Westhampton Island, and Southampton Beach. The current dimensions of the islands are approximately 6 km by 0.1 km for the smallest and 50 km by 2.6 km for the largest. These dimensions are not stable, as island profiles are shifting and dynamic (McCormick et al., 1984). The elevation of these islands is almost entirely below 3.5 m, especially along Westhampton Island, where most of the island is below 1.5 m (Titus and Richman, 2001). This barrier island system is considered sand limited and has historically been subject to frequent storm erosion due to its low topography and sandy soils (Schwab et al., 2000). Human development within the system is highly variable, ranging from large, day-use public recreation facilities along Jones Beach and Fire Island to low-density (195.3 units per km^2) summer homes along Westhampton Island and Southampton Beach (USCB, 2003).

2.2. Habitat and landform response models

We modeled two possible responses of plover habitat to SLR: static and dynamic. In the static habitat response, we assumed that SLR would occur at a rate that outpaces the migration of habitat and the islands themselves. In this model, the spatial distribution of habitat was fixed and the rising sea level simply submerged land and existing habitat, resulting in a new spatial configuration of remaining habitat. A static habitat response is expected if the rate of SLR outpaces the ability of flora and fauna to migrate upslope and/or if development blocks movement of the landform (Bush et al., 2004; Feagin et al., 2005). There are two reasons this habitat response model is plausible in our study area. First, human development in our study system has been shown to restrict land movement (McCormick et al., 1984). Second, the likelihood of a static response is also deemed higher in a sand-limited system such as ours where a lack of substrate limits island movement (Fallon and Mushsacke, 1996; Hartig et al., 2002; Schwab et al., 2000; Zhang et al., 2004). This static response represents the most liberal habitat loss scenario that we considered and has been widely adapted for modeling sea-level rise impacts (Bush et al., 2004; Cooper and McKenna, 2008; Demirkesen et al., 2008; Feagin et al., 2005; LaFever et al., 2007; Titus and Richman, 2001; Weiss and Overpeck, 2006).

The second response model allowed for a dynamic habitat response wherein habitat could shift upslope and inland, redistributing itself based on the underlying landform. Our initial run of this model was conducted without the restriction of habitat movement by development (see below for a description of our development modeling). Documented movement of flora both inland and upslope with historic SLR in many coastal systems validates this as a plausible response model (Clark and Patterson, 1985; French, 2001; Gilman et al., 2006; Michener et al., 1997; Moorhead and Brinson, 1995).

We purposefully did not incorporate a dynamic landform response. This response, which would include the movement of both habitat and island landforms, is based on historic observation of barrier island dynamics (Leatherman, 1979, 1985; Zhang et al., 2004). A dynamic landform response is more likely in areas with minimum development and abundant sediment (Zhang et al., 2004). Because of the widespread extent of beach stabilization structures (Hecht and Melvin, 2009), and lack of sediment (Hartig et al., 2002) in our study area, we expect that landform dynamics are severely constrained and unrealistic, and thus we did not considered it in our analysis.

2.3. Habitat modeling

We modeled habitat response to SLR based on a plover breeding habitat map created during May through July of the 2005 breeding

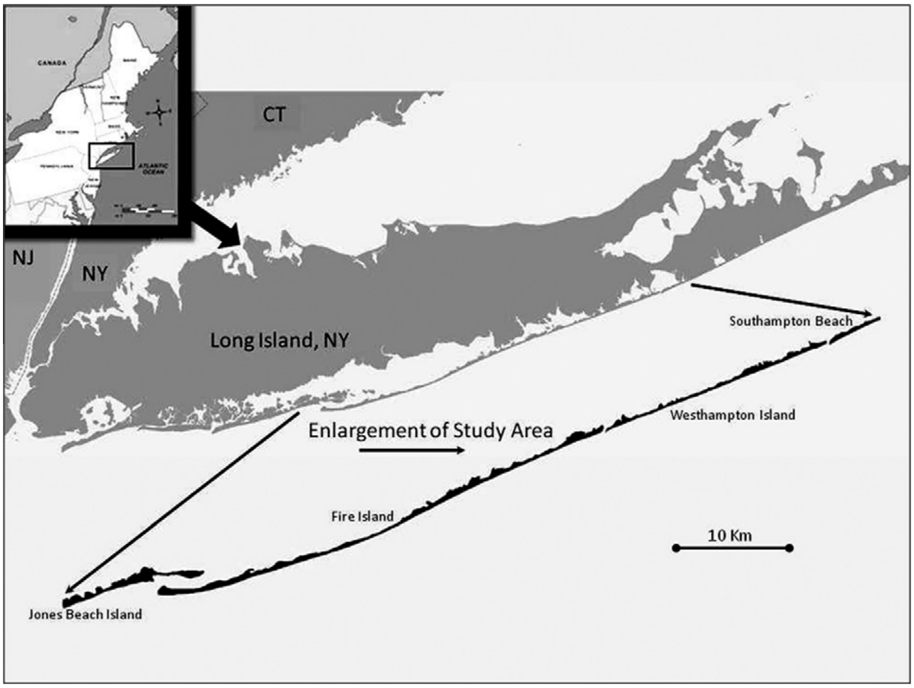

Fig. 1. The study area, located in Suffolk County on Long Island, New York. The regional context of the study area is in the upper left corner. Our study area is enlarged.

season. Using a global positioning system, we delineated the inland habitat boundary based on the presence of dense vegetation, steeply eroded banks, or human-made structures along the entire barrier island coastline of Suffolk County. We delineated the ocean-side habitat boundary as the high water line, which we considered as a one-day benchmark by which to measure relative habitat width in an otherwise dynamic system. Our mapped habitat area represented true plover breeding habitat as evidenced by the incorporation of 88–97% of the known 142–147 plover nests identified in the study area during the 2003–2005 breeding season in a parallel study (Seavey, 2009). The final format of this habitat map was an ESRI raster grid with 5 m horizontal resolution (ESRI, 1999–2006). This grid served as the base map for the analysis of the static habitat response and the binary response variable in a logistic generalized linear model (GLM) used to predict plover breeding habitat under the dynamic habitat response.

We built the GLM with two explanatory variables that play a key role in determining the movement of water and sand across islands: least-cost distance and elevation (Clark, 1986; Cohen et al., 2008; Davis and Fitzgerald, 2004; Leatherman, 1979; McCormick et al., 1984). The least-cost distance variable represented the accumulative cost distance of water and sand moving from the ocean to each inland grid cell, weighted by the elevation value of each cell. Least-cost distance provided a more realistic terrain-adjusted distance for overwash connectivity than the straight-line Euclidean distance or beach width, neither of which factor in topography and therefore do not account for topographic and hydrologic dynamics that determine the movement of water and sand across a landscape. We created the least-cost distance grid for the entire study area using the Cost Distance function in ArcGIS (ESRI, 1999–2006). We identified ocean cells by extracting and masking all elevation values equal to or less than zero on the ocean side of all barrier islands. The cost grid was calculated by first setting all grid cells to one and then adding the squared elevation value for each cell. Through combining linear distance with the cost grid, the least-cost variable increased exponentially with increasing elevation above sea level and linearly with increased distance from the ocean. Elevation data was provided from a 2005 light detection and ranging (LIDAR) digital elevation model (DEM) with 3.0 m horizontal accuracy and 0.3 m vertical resolution (USACE, 2005).

We built the GLM model from 2000 randomly selected points, evenly split between habitat and non-habitat. The GLM was run using R open-source software (R core team, 2005) with the Stats, Design, and PresenceAbsence packages. We checked the model for over dispersion and validated several measures of model calibration and discrimination with a bootstrapping method, employing 100 resamples (Harrell, 2001). Bootstrapping is particularly good at identifying bias that may have resulted from our use of a single sample of data to create and calibrate our GLM (Guisan and Zimmermann, 2000). We measured model discrimination performance using a receiver operating characteristic curve (ROC). We created binary model output maps using a threshold value that split model output into habitat (0) or non-habitat (1). The threshold value was identified through the ROC analysis and the maximum Kappa value (Freeman and Moisen, 2008). We established further support for the GLM by comparing the C index (Hanley and McNeil, 1982), as well as the omission and commission error rates resulting from the GLM, to a regression tree model (also performed in R using the rpart package). The regression tree was developed using the gini splitting criterion and equal prior probabilities (Breiman et al., 1984), and the appropriate size was obtained using 10-fold cross-validation based on the 1-S.E. rule (De'ath and Fabricius, 2000). We derived a *p*-value for the final tree using a Monte Carlo resampling procedure based on 1000 permutations of the data. We computed the coefficient of determination (R^2) for each permuted tree and calculated the *p*-value as proportion of the permuted R^2 values greater than the R^2 for the original tree.

2.4. Sea-level rise scenarios

We selected four well-supported SLR scenarios upon which to model habitat changes. Each scenario represented a 30-year average SLR prediction, centered on 2080. Thirty-year averages are standard climate modeling time slices aimed at reducing forecast uncertainty (NYPCC, 2009). Three of our four SLR scenarios are

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

based on Intergovernmental Panel on Climate Change (IPCC) and New York City Panel on Climate Change estimates (NYPCC, 2009; IPCC, 2007). The scenarios, referred to here by codes given in the IPCC, 2007 report, are B1 which projects a rise of 0.38 m, A1B which projects a rise of 0.47 m, and A2 which projects a rise of 0.5 m (see IPCC, 2007 for scenario details). Our fourth SLR scenario was higher than IPCC predictions based on recently verified rates of ice sheet loss, not used in IPCC models (Grinsted et al., 2009). Recent SLR estimates that incorporate rapid ice sheet loss currently average around 1.5 m over the next 100 years (Jevrejeva et al., 2010; Richardson et al., 2009; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009). We tailored all four SLR scenarios to our study area DEM by calibrating mean high tide with local data from tidal gauges located at The Battery and Montauk, which are within 40 km east and west of our study area, respectively (NYPCC, 2009). The mean high tide value was 0.44 m, which we subtracted from the original DEM grid before calculating the SLR scenarios.

We applied the four SLR scenarios, plus no SLR, to both the static and dynamic habitat response models. For the static response, we simply inundated the habitat grid by filling the DEM values with each SLR estimate. Under the dynamic habitat model, we predicted new habitat extents for each SLR using the GLM and new scenario-specific DEM and least-cost grids. For example, for the 1.5 m scenario, we subtracted 1.5 m from all original DEM cell values, creating a new DEM, which was then used to create the least-cost distance grid. We submitted these scenario-specific grids to the GLM, generating a binary map of plover breeding habitat under the 1.5 m SLR.

2.5. Development intensity

Development data included buildings, roads, jetties and groins that were digitized at the 1:2000 scale using 2004 natural color photographs with a 0.5 m resolution (NYSGIS, 2004; USGS, 2004). A development intensity surface was created using the kernel procedure found in the Spatial Analysis Kernel Density function in ArcGIS, masked or contained by the footprint of development (ESRI, 1999–2006). Because the starting development map was a binary grid in which each cell had a value of 1 or 0, the kernel procedure created a surface that represented spatial development intensity and not human density. We created three levels of development intensity by evenly dividing the spatial density values into three classes: low, medium, and high. These three classes were highly correlated with human density as observed in the types of development encompassed by each intensity level. Low intensity development included roads and low human density residential housing. Medium intensity development included higher human density residential housing and recreational use areas. There were only two areas of high intensity development: the community of Ocean Beach and the recreational facilities of Smith County Park, both on Fire Island.

We compared the influence of development on the dynamic habitat response models by systematically examining each SLR scenario under each level of development intensity. We created final potential habitat estimates for each SLR/development combination by masking the GLM habitat predictions by each level of development intensity so that habitat could not fall in developed areas.

2.6. Storm surge

We examined the risk of storm-induced plover habitat flooding under the 1.5 m SLR with the addition of development as this represents the most likely combination of our models (Richardson et al., 2009). We flooded this scenario with three types of storms: 5-year storm surge average, category-two hurricanes, and category-three hurricanes. The 5-year storm surge average over the period 1959 through 2007 was 1.65 m, which was derived from flood data recorded at The Battery and Montauk tide gauges. This surge level was applied to the entire study area homogeneously. Conversely, hurricane surges were non-homogenous throughout the study area as derived from National Hurricane Center's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) models. These models were developed by the National Oceanic and Atmospheric Administration's Coastal Services Center and were specifically calibrated for Long Island, New York (Jelesnianski et al., 1992). SLOSH

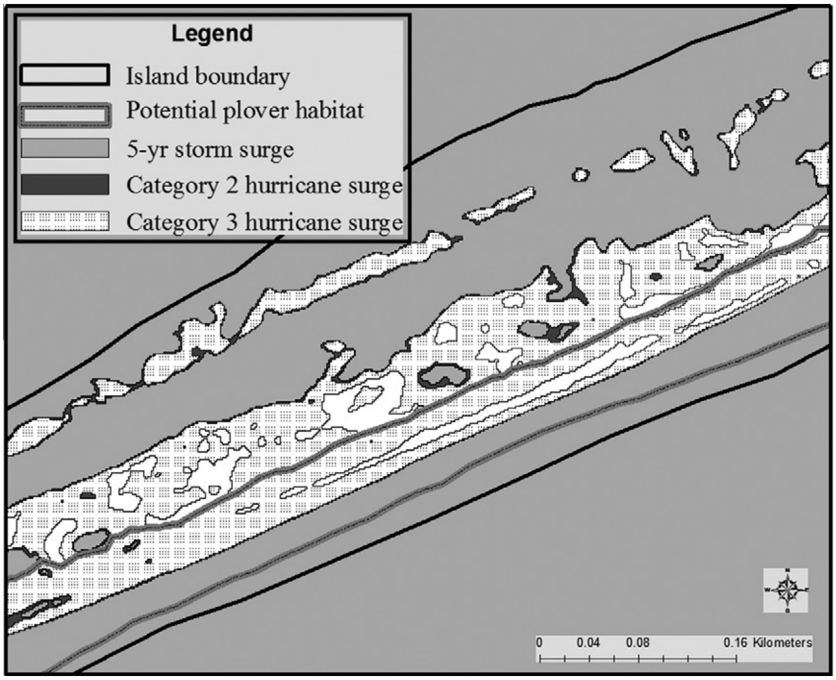

Fig. 2. Example of the overlay of flooding models for 5-year storms, category 2 hurricanes, and category 3 hurricanes, and potential plover habitat under a 1.5 m sea-level rise with development blocking habitat formation. Note the storms and habitat layers are overlaid on top of an aerial photo of Fire Island, New York.

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

models determine storm surge at a 5 m cell resolution via a series of hundreds of hypothetical hurricanes –in each category– with various forward speeds, landfall directions, and landfall locations (Jelesnianski et al., 1992). At the end of each model run, an envelope of water is generated, reflecting the variable maximum surge height obtained in each grid cell (Jelesnianski et al., 1992). We specifically used the Maximum Envelope of Water (MEOW) which represents the maximum surge height in each grid cell for each storm category (Jelesnianski et al., 1992). The MEOW for category-two hurricanes varied between 0 and 2.4 m and category-three hurricanes ranged between 0 and 3.7 m. The amount of plover habitat flooded by each storm type was calculated by clipping the resulting 1.5 m dynamic SLR with development habitat map by each storm flood extent (Fig. 2).

3. Results

The plover habitat model described 79% of the variance in plover breeding habitat occurrence and had a significant model likelihood ratio (Likelihood ratio chi-square = 1797.6, $p < 0.001$). In the process of model building, we observed that elevation had a curvilinear relationship with habitat, so we added a squared term in the GLM equation. We did not observe overdispersion in the 0.48 ratio of residual scaled deviance to residual degrees of freedom, as the ratio is well below 1 (Crawley, 2007). In our validation assessment, bootstrapping revealed very little difference between parameter estimations of the original model versus the resampled data sets (Table 1), showing that our model is robust to our choice of data in model building (Harrell, 2001). The final GLM had a C index of 0.96, indicating strong predictive performance (Elith et al., 2006). A confusion matrix of model predictions showed a commission error of 11% and omission error of 6%. At the maximum Kappa value the threshold value was 0.59, which means that all model predictions at or above that value were classified as habitat. At this Kappa value, the average elevation of habitat was 1.96 m (SE = 1.19) and the average least-cost distance was 888. 87 m (SE = 875.76).

Table 1
Comparison of original and bootstrapped parameter estimates from the plover habitat GLM used to predict habitat changes with sea-level rise scenarios for Suffolk County, New York.

Parameter	Original data	Bootstrap data	Corrected
Somer's D	0.928	0.928	0.928
R^2	0.791	0.791	0.790
Intercept	0.000	0.000	–0.008
Slope	1.000	1.000	0.999

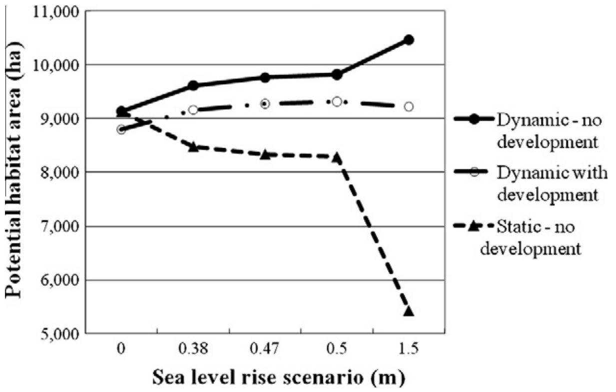

Fig. 3. Estimated amount of potential piping plover habitat (hectares) resulting from five sea-level rise estimates with and without development on the barrier islands of Suffolk County, New York under both static and dynamic habitat response models.

Our regression tree model built on the same sample data resulted in a C index of 0.91 and commission error of 10% and omission error of 8%, based on the least-cost distance variable alone. We selected the GLM for further assessment due to a higher C index and slightly lower omission error compared to the regression tree results.

Without considering the influence of development, the pattern of habitat change under increasing SLR differed greatly between the static and dynamic habitat response models (Fig. 3). Potential piping plover breeding habitat area was reduced by as much as 41% under the static response model. In contrast, in the dynamic model habitat area grew by as much as 15%. Comparing across the models, the static habitat model resulted in as much as 52% less habitat compared to the dynamic model under the 1.5 m SLR.

The habitat response model also influenced the proportion of the study area that was converted to potential plover habitat under each scenario (Fig. 4). The 2005 plover habitat covered 25% of the study area, which under the static habitat response model gradually increased from 25% to 29% with increasing SLR. This increase in relative amount of habitat reflected the steady loss of the barrier island system in this model. For example, under the 1.5 m SLR, less than half of the study area remained above water and 29% of that was habitat. Under the dynamic response, the study area was also lost due to flooding; however, the habitat redistributed itself across the landscape in greater proportion. As the SLR estimate increased, the amount of plover habitat went from 32% to 65% of the total barrier island system.

Development covered 19% (7099 ha) of the study area landscape in 2005. Of this developed area, 7% was low intensity, 10% was medium intensity, and 2% was high intensity. The inclusion of development intensity reduced habitat expansion in the dynamic models (Fig. 3). Including development intensity reduced potential habitat from 5% to 12% compared to models without development, as SLR increased. The results showed that a stable development footprint inhibited potential habitat expansion under the dynamic response model (Fig. 3). Further, though medium intensity development covered a larger percentage of total island area compared to low intensity, low intensity was more frequently adjacent to habitat (Fig. 5). Due to this juxtaposition, low intensity

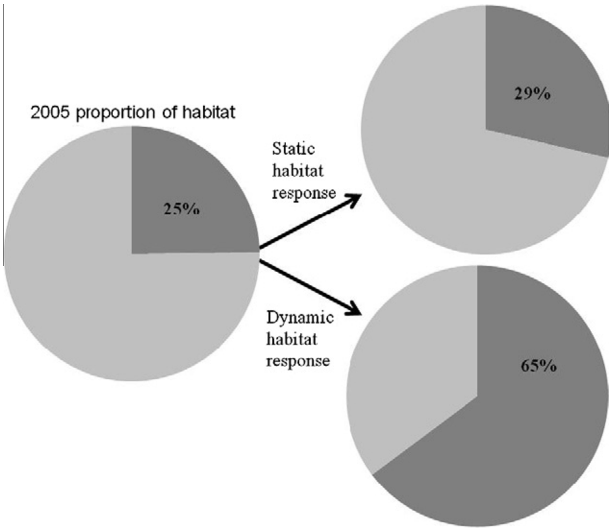

Fig. 4. Proportion of study area islands that is comprised of potential habitat under no change, static and dynamic habitat response models and a 1.5 m sea-level rise without development in Suffolk County, New York.

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

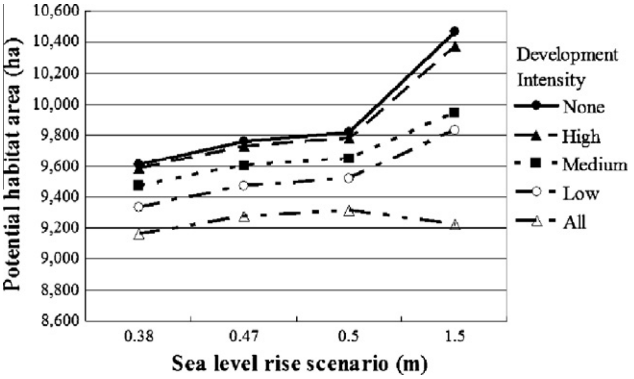

Fig. 5. Estimated amount of potential piping plover habitat (hectares) resulting from four development intensity levels in combination with the SLR scenarios with a dynamic habitat response on the barrier islands of Suffolk County, New York. Development impact is restricted by the extent of each intensity level; of the total 7099 ha (19% of the total study area) of developed land in 2005, 7% was low intensity, 10% was medium intensity, and 2% was high intensity.

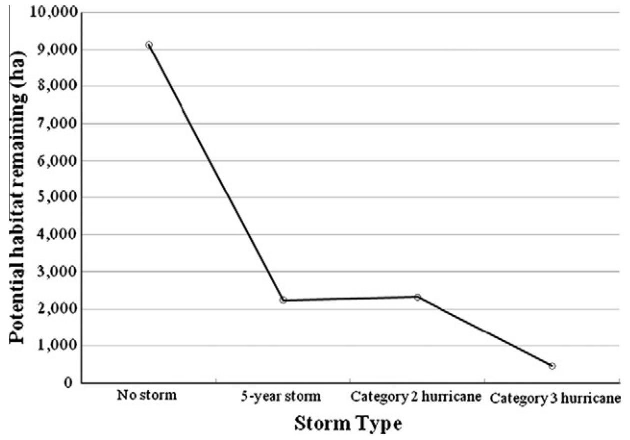

Fig. 6. Potential piping plover habitat remaining under no storm, a 5-year storm event, a category-two hurricane, and a category-three hurricane. Note that flooding was projected on the dynamic 1.5 m sea-level rise scenario with development habitat estimation for Suffolk County, New York.

development resulted in a greater loss in potential habitat compared to medium. However, the influence of medium intensity development increased under higher (1.5 m) SLR because habitat moved inland and into more areas of medium intensity compared to under lower (< 1.5 m) SLR.

Storm surge flooding impacted a large proportion of the projected habitat under the 1.5 m SLR with development scenario (Fig. 6). The 5-year storm and category-two hurricane surge flooded about 75% of potential nesting habitat; whereas a category-three hurricane surge flooded over 95% of the area. Among the piping plover nests found in the study area during the 2003–2005 breeding seasons, 74% of nests would have been flooded by a 5-year storm, 73% by a category-two hurricane, and 97% by a category-three hurricane. The large impact from all storm types stemmed from the relatively low elevation of the barrier island system in Suffolk County. Based on the 1st and 4th quantiles of our DEM data, the island elevation typically falls between 0.3 and 3.3 m, which is well within the range of all storm types (0–3.7 m).

4. Discussion

Low-lying coastal areas are vulnerable to rising sea levels resulting from global climate change (Poulter et al., 2009). However, specific predictions as to how landscapes and organisms will respond to climate change are uncertain due to assumptions and limitations in current methodology, including those used in our study. For example, our models assumed static development levels, and did not account for the likelihood of future development and beach stabilization structures built over the next 100 years (Galbraith et al., 2002; LaFever et al., 2007; Park et al., 1991). The population of Suffolk County, New York is expected to increase 25% over the next 14 years, and while much of this growth is expected on the mainland of Long Island, increased development of the islands is likely (SCPD, 2004). Concurrent with increased development of the barrier islands is an increase in the probability of new beach stabilization projects (CPAD, 2008). The assumptions and limitations of our work call for the heuristic use of our results – to compare predicted impacts of our scenarios and models relative to each other. Our models should not be used as absolute predictions about the future of piping plover habitat in New York.

Despite limitations, our study demonstrates that how barrier island plover habitat responds to SLR (i.e., static versus dynamic response) can make a large difference in predictions of future habitat. In our simulations, habitat migration allowed for an increase in plover habitat with SLR in Suffolk County, New York. This increase resulted from the specific topography of these particular islands, which has more land area at higher elevations and inland compared to the current position of plover habitat. However, the ability of plover habitat to migrate across this particular landscape is uncertain and complex. Despite the historic observation of coastal habitat migration in response to rising seas (Redfield, 1965), many factors such as sediment limitation, flora and fauna response, and development may change future dynamics.

Sediment limitation in the region (Hartig et al., 2002) suggests that a dynamic habitat response may be constrained. Limited sediment increases the likelihood that barrier islands will reach a threshold beyond which migration ability is lost or substantially reduced under SLR (Titus et al., 2009). Once sand resources are exhausted, migration ceases and catastrophic land loss can occur (Sallenger et al., 2007). However, sediment limitation may be highly variable within a region, especially as a result of localized shoreline hardening (Dolan and Lins, 1987). This variance could in turn increase variability in the type of response exhibited by plover breeding habitat under SLR, making predictions of future plover habitat even more challenging.

Dynamic habitat response is also constrained by the degree to which movement of flora and fauna associated with plover habitat can match the timeframe of SLR. For example, if flora and fauna migration can keep pace with SLR, a dynamic response is possible; otherwise, a static response is more likely. The understanding that habitats have migrated upslope over the last 8000 years on the barrier islands of New York (McCormick et al., 1984) provides evidence of a past dynamic response, under which plover habitat may continue to move during periods of increased SLR in the future. However, the past is not always the best predictor of the future. Current projections move SLR rates outside of their known historic range of variation (Titus et al., 2009; IPCC, 2007), which increases the risk that flora and fauna will not be able to keep up with the pace of change. The rapid rate of SLR is already showing evidence of outpacing the migration abilities of many coastal species in salt marsh, coastal forests, and coral reefs (Nicholls et al., 2007; Ross et al., 1994; Williams et al., 1999).

Our results suggest that development can substantially affect the potential for a dynamic habitat response to SLR. In our simulations, development interfered with habitat migration, resulting in dynamic model habitat predictions that were similar to those of the static habitat models. In other words, development promoted a static habitat response to rising sea level. In addition, the dampening impact of development on the habitat response grew with

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

higher SLR estimates because of greater development further inland. Our findings are supported by other studies that have found development to impede overwash and island migration (Feagin et al., 2005; Fish et al., 2005; LaFever et al., 2007). Variance in the spatial configuration and intensity of development along Suffolk County barrier islands will vary the relative influence of development in changing habitat dynamics across the island system. However, as island migration is suppressed by development, a mosaic of inundation vulnerability emerges (Matias et al., 2008). We assert that the future of plover habitat with rising sea levels will be dictated, in large part, by how coastal development is zoned and managed.

Regardless of the migration response, SLR in combination with the predicted increase in storminess due to climate change (Richardson et al., 2009) is likely to increase nest failure. During 1993–2003, storm flooding caused the failure of only 4% of plover nests at one beach within our study area (Cohen, 2005; Houghton, 2005). However, our results suggest that this relatively low failure rate is likely to dramatically rise if storm activity increases. Current estimates predict a 45% chance of a category-three hurricane or greater in the next 50 years in Suffolk County (LHPP, 2010). A single category-three hurricane event during the plover breeding season in combination with high SLR could be catastrophic for that breeding season. While it is uncertain what the loss of one breeding season would mean to the overall plover population, the increased frequency of large storms predicted to accompany global climate change may make nest flooding more frequent (Richardson et al., 2009) and likely to increase population risk.

Our results raise concern over the potential for SLR to increase human–plover conflict. While the static and dynamic habitat response models diverge in their predictions of total plover habitat area under various SLR scenarios (Fig. 3), both habitat response models predict an increase in the proportion of the island areas in potential plover habitat over the next 100 years. This increase would be especially large if the dynamic habitat response is widespread as our results showed that in the next 100 years, more than half of the barrier island system could be plover habitat. The conflict stems from current management actions taken to protect this federally listed species from human disturbance (USFWS, 1996). Currently, on Fire Island alone, an estimated 2.2 million recreationists visit plover beaches annually (NPS, 2009). If the relative amount of plover habitat increases, conflict is likely to arise especially as the human population in the region grows and with it the demand for beach recreation.

The overall decline in the total amount of barrier island land area and plover habitat expected where a static response dominates, is likely to promote the concentration of plover habitat. Spatial concentration is already a concern, especially in New York, where recreation use, development, beach renourishment, and habitat fragmentation have all restricted plover habitat (Cohen et al., 2009; Hecht and Melvin, 2009). Further restricted habitat availability under a static response may lead to increased plover nesting density, which in turn may decrease productivity (Seavey, 2009). Moreover, interspecies competition for nesting space and other resources may increase as plovers, American oystercatchers (*Haematopus palliatus*), least terns (*Sternula antillarum*), common terns (*Sterna hirundo*), and other coastal species are crowded together.

4.1. Conservation application

The conservation of piping plovers on the barrier island system of New York in light of rising sea levels will require active and adaptive management of development. In general, management needs to move away from reactive into proactive measures, such as coastal retreat (Nicholls et al., 2007). To date, coastal protection is the most utilized option for management in coastal ecosystems in our study area and elsewhere along the mid-Atlantic (Titus et al., 2009). Common protection measures such as sea walls, jetties, and groins affect the natural behavior of coastal landforms and disrupt coastal ecosystem processes, such as habitat migration (Titus et al., 2009). Protection measures can lead to erosion (IPCC, 1990), loss of moist sediment habitat (Galbraith et al., 2002), and disrupt barrier island sediment movement (Titus et al., 2009), all of which have negative impacts on piping plover breeding (Cohen, 2005; Seavey, 2009). Further, coastal protection projects can limit future management options by hardening the environment and committing communities to maintenance of projects. Finally, protection measures have been shown to promote coastal development (Titus et al., 2009) which, as our results suggest, will reduce plover habitat over the next 100 years.

Compared to protection measures, coastal retreat, which removes development from coastal zones, offers longer term sustainability of barrier islands and plover habitat. Retreat allows for the continuation of the migration process (Titus et al., 2009), which naturally builds barrier islands higher, above rising sea levels (Matias et al., 2008). The preservation of barrier island elevation above sea level is critical to reducing or stabilizing the risk of storm flooding. In addition, retreat maintains management flexibility by allowing for the possibility of future protection measures as warranted.

Implementation of coastal retreat will require that the identification of a no-development zone incorporate both future sea-level rise and plover habitat needs. Current coastal zone management in New York, uses coastal hazard zones to restrict development along erosion prone ocean beaches. The delineation of coastal erosion zones is currently based on 40-year average erosion rates (6 NYCRR Part 505, Coastal Erosion Management Regulations). These zones do not currently incorporate escalating rates of sea-level rise and are likely not wide enough to incorporate coastal lands could become plover habitat under future SLR (Titus et al., 2009). Further, current policies allow existing development to remain and even be ‘‘minimally enlarged” with in coastal hazard zones (NYS, 2001). New development is also allowed in hazard zones, although required to be ‘‘movable” (NYS, 2001). New York’s coastal zone widths and regulations need to be proactive, explicating incorporating SLR and habitat migration potential.

Habitat loss resulting from SLR, especially along low-lying, developed coastlines, is likely to increase piping plover extinction risk. To avoid the potential loss of plover habitat, management actions must be based on the assumption that coasts are dynamic, highly variable, and will shift with rising sea levels (Titus et al., 2009). Today’s plover nesting habitat is unlikely to be suitable, or even exist, in the near future. Management will need to be adaptive and focus on actions that restrict and even reduce development so that ecological processes, such as overwash and habitat migration, are preserved. Time is of the essence for management actions; management needs to keep pace with rising sea levels. Addressing SLR is required to reduce impacts, and any delay will only make mitigating for habitat loss increasingly difficult (IPCC, 2007).

Acknowledgements

We extend our gratitude to Brad Compton, NOAA’s Coastal Service Center, and Columbia University’s Center for Climate Systems Research for analysis assistance. We are grateful to Elizabeth Cowan, Morgan Theis, Yumi Aikawa, and Lesley Starke for their tireless field work. We thank two anonymous reviewers for their help to improve the manuscript. Finally, we thank The Nature Conservancy, The Krusos Foundation, Smith College, the National Fish and Wildlife Foundation, and Fire Island National Seashore for generous funding and logistical support.

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

References

Baker, J.D., Littnan, C.L., Johnston, D.W., 2006. Potential effects of SLR on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. Endangered Species Research 4, 1–10.

Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T., Held, I.M., 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic Hurricanes. Science 327, 454–458.

Breiman, L., Friedman, J.H., Olsen, R.A., Stone, G.G., 1984. Classification and Regression Trees. Wadsworth International Group, Belmont, California.

Bush, M.B., Silman, M.R., Urrego, D.H., 2004. 48,000 years of climate and forest change in a biodiversity hot spot. Science 303, 827–829.

Clark, J.S., 1986. Dynamism in the barrier-beach vegetation of Great South Beach, New York. Ecological Monographs 56, 97–126.

Clark, J.S., Patterson, W.A., 1985. The development of a tidal marsh: upland and oceanic influences. Ecological Monographs 55, 189–217.

Cohen, J.B., 2005. Factors Limiting Piping Plover Nesting Pair Density and Reproductive Output on Long Island, New York. Dissertation. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Cohen, J.B., Wunker, E.H., Fraser, J.D., 2008. Substrate and vegetation selection by nesting piping plovers. Wilson Journal of Ornithology 120, 404–407.

Cohen, J.B., Houghton, L.M., Fraser, J., 2009. Nesting density and reproductive success of piping plovers in response to storm- and human-created habitat changes. Wildlife Monographs 173, 1–24.

Cooper, J.A.G., McKenna, J., 2008. Social justice in coastal erosion management: the temporal and spatial dimensions. Geoforum 39, 294–306.

Cornell Program on Applied Demographics (CPAD), 2008. New York State Projection Data by County. <http://www.pad.human.cornell.edu/data/projections.cfm> (accessed 09.07.10).

Crawley, M.J., 2007. The R Book. John Wiley and Sons, Hoboken, New Jersey.

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

Davis, R.A., Fitzgerald, D.M., 2004. Beaches and Coasts. Blackwell Publishing, Malden, Massachusetts.

De'ath, G., Fabricius, K.E., 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81, 3178–3192.

Demirkesen, A.C., Evrendilek, F., Berberoglu, S., 2008. Quantifying coastal inundation vulnerability of Turkey to sea-level rise. Environmental Monitoring and Assessment 138, 101–106.

Dolan, R., Lins, H., 1987. Beaches and barrier islands. Scientific American 257, 68.

Elias-Gerken, S.P., 1994. Piping Plover Habitat Suitability on Central Long Island, New York Barrier Islands. Master's Thesis. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Elith, J., Graham, C.H., Anderson, R.P., Dudik, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, J.R., Jin, L., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakazawa, M., Nakazawa, Y., McC. Overton, J., Peterson, A.T., Phillips, S.J., 2006. Novel methods improve prediction of species distributions from occurrence data. Ecography 29, 129–151.

Environmental Systems Research Institute (ESRI), 1999–2006. ArcMAP. Redlands, California.

Fallon, D., Mushsacke, F., 1996. Tidal Wetlands Trends in Shinnecock Bay, New York 1974 to 1995. Division of Fish, Wildlife and Marine Resources, Department of Environmental Conservation, East Setauket, New York.

Farbotko, C., 2010. Wishful sinking: disappearing islands, climate refugees and cosmopolitan experimentation. Asia Pacific Viewpoint 51, 47–60.

Feagin, R.A., Sherman, D.J., Grant, W.E., 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. Frontiers in Ecology and the Environment 3, 359–364.

Fish, M.R., Cote, I.M., Gill, J.A., Jones, A., Renshoff, S., Watkinson, A.R., 2005. Predicting the impact of sea-level rise on Caribbean sea turtle nesting habitat. Conservation Biology 19, 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 and Coastal Management 51, 330–341.

FitzGerald, D.M., Fenster, M.S., Argow, B.A., Buynevich, I.A., 2008. Coastal impacts due to sea-level rise. Annual Review of Earth Planetary Science 36, 601–647.

Freeman, E.A., Moisen, G.G., 2008. A comparison of the performance of threshold criteria for binary classification in terms of predicted prevalence and kappa. Ecological Modeling 217, 48–58.

French, P.W., 2001. Coastal Defenses: Processes, Problems, and Solutions. Routledge, New York, New York.

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, Union of Concerned Scientists, Cambridge, Massachusetts.

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

Gilman, E., Ellison, J., Coleman, R., 2006. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. Environmental Monitoring and Assessment 124, 1–3.

Grinsted, A., Moore, J.C., Jevrejeva, S., 2009. Reconstructing Sea Level from Paleo and Projected Temperatures 200 to 2100. Climate Dynamics Online Publication. <http://www.springerlink.com/content/527178062596k202/> (accessed 09.07.10).

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecological Modeling 135, 147–186.

Hanley, J.A., McNeil, B.J., 1982. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 143, 29–36.

Harrell, F., 2001. Regression Modeling Strategies: with Applications to Linear Models, Logistic Regression, and Survival Analysis. Springer-Verlag, New York, New York.

Hartig, E.K., Gornitz, V., Kolker, A., Mushsacke, F., Fallon, D., 2002. Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City. Wetlands 22, 71–89.

Hayes, M., 2005. Barrier islands. In: Schwartz, M.L. (Ed.), Encyclopedia of Coastal Science. Springer, Dordrecht, The Netherlands, pp. 117–119.

Hecht, A., Melvin, S., 2009. Population trends of Atlantic coast piping plovers, 1986–2006. Waterbirds 32, 64–72.

Houghton, L.M., 2005. Piping Plover Population Dynamics and Effects of Beach Management Practices on Piping Plovers at West Hampton Dunes and Westhampton Beach, New York. Dissertation. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Intergovernmental Panel on Climate Change (IPCC), 1990. Strategies for Adaptation to Sea-Level Rise. United Nations Ministry of Transport, Public Works and Water Management, The Hague, Netherlands.

Jelesnianski, C.P., Chen, J., Shaffer, W.A., 1992. SLOSH: Sea, lake, and overland surges from hurricanes. NOAA Technical Report NWS 48, National Oceanic and Atmospheric Administration, U. S. Department of Commerce.

Jetz, W., Wilcove, D.S., Dobson, A.P., 2007. Projected impacts of climate and land-use change on the global diversity of birds. Public Library of Science Biology 5, 1211–1219. <http://www.biology.plosjournals.org/archive/1545-7885/5/6/pdf/10.1371_journal.pbio.0050157-L.pdf> (accessed 09.07.10).

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

Klein, R.J.T., Nicholls, R.J., 1999. Assessment of coastal vulnerability to climate change. Ambio 28, 182–187.

LaFever, D.H., Lopez, P.R., Feagin, R.A., Silvy, N.J., 2007. Predicting the impacts of future sea-level rise on an endangered. Lagomorph Environmental Management 40, 430–437.

Landfalling Hurricane Probability Project (LHPP), 2010. 2010 Tropical Cyclone Landfall Probabilities for Suffolk County, New York. <http://www.landfalldisplay.geolabvirtualmaps.com/> (accessed 09.07.10).

Le V.dit Durell, S., Stillman, R.A., Caldow, R., McGrorty, S., West, A.D., Humphreys, J., 2006. Modeling the effect of environmental change on shorebirds: a case study on Poole Harbour, UK. Biological Conservation 131, 459–473.

Leatherman, S.P., 1979. Barrier Island Handbook. National Park Service Cooperative Research Unit, University of Massachusetts, Amherst, Massachusetts.

Leatherman, S.P., 1985. Geomorphic and stratigraphic analysis of Fire Island, New York. Marine Geology 63, 173–195.

Mac Nally, R., Bennett, A.F., Thomson, J.R., Radford, J.Q., Unmack, G., Horrocks, G., Vesk, P.A., 2009. Collapse of an avifauna: climate change appears to exacerbate habitat loss and degradation. Diversity and Distributions 15, 720–730.

Markham, A., 1996. Potential impacts of climate change on ecosystems: a review of implications for policymakers and conservation biologists. Climate Research 6, 179–191.

Matias, A., Ferreira, O., Vila-Concejo, A., Garcia, T., Dias, J.A., 2008. Classification of washover dynamics in barrier islands. Geomorphology 97, 655–674.

McCormick, L.R., Pilkey Jr., O.H., Neal, W.J., Pilkey Sr., O.H., 1984. Living with Long Island's South Shore. Duke University Press, Durham, North Carolina.

Michener, W.K., Blood, E.R., Bildstein, K.L., Brinson, M.M., Gardner, L.R., 1997. Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. Ecological Applications 7, 770–801.

Moorhead, K.K., Brinson, M.M., 1995. Response of wetlands to riding sea level in the lower plains of North Carolina. Ecological Applications 5, 261–271.

National Park Service (NPS), 2009. Fire Island National Seashore – Park Statics. <http://www.nps.gov/fiis/parkmgmt/statistics.htm> (accessed 09.07.10).

New York City Panel on Climate Change (NYPCC), 2009. Climate Risk Information. New York, New York. <http://www.nyc.gov/html/om/pdf/2009/NPCC_CRI.pdf> (accessed 09.07.10).

New York State (NYS), 2001. State Coastal Policies. Department of State, Coastal Management Program. <http://www.nyswaterfronts.com/downloads/pdfs/State_Coastal_Policies.pdf> (accessed 10.09.10).

New York State's Office of Cyber Security & Critical Infrastructure Coordination (NYSGIS), 2004. High Resolution Digital Orthoimagery. <http://www.nysgis.state.ny.us/gateway/mg/index.html> (accessed 09.07.10).

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal Systems and Low-lying Areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 315–356. <http://www.ipcc-wg2.org/index.html> (assessed 09.07.10).

Park, R., Lee, J., Mausel, P.W., Howe, R.C., 1991. Using remote sensing for modeling the impacts of sea-level rise. World Resource Review 3, 184–205.

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017

Pfeffer, W.T., Harper, J.T., O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. Science 321, 1340–1343.

Poulter, B., Feldman, R.L., Brinson, M.M., Horton, B.P., Orbach, M.K., Pearsall, S.H., Reyes, E., Riggs, S.R., Whitehead, J.C., 2009. Sea-level rise research and dialogue in North Carolina: creating windows for policy change. Ocean & Coastal Management 52, 147–153.

R Core Team, 2005. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Switzerland. <http://www.r-project.org/> (accessed 09.07.10).

Rahmstorf, S., 2010. A new view on sea level rise. Nature Reports 4, 44–45.

Redfield, A.C., 1965. Ontogeny of a salt marsh estuary. Science 147, 50–55.

Richardson, K., Steffen, W., Schellnhuber, H.J., Alcamo, J., Barker, T., Kammen, D.M., Leemans, R., Liverman, D., Munasinghe, M., Osman-Elasha, B., Stern, N., Waever, O., 2009. Climate change – Global Risks, Challenges, and Decisions. Synthesis Report, Copenhagen 2009. <www.climatecongress.ku.dk> (accessed 09.07.10).

Ross, M.S., O'Brien, J.J., Sternberg, L.D.L., 1994. Sea-level rise and the reduction in pine forests in the Florida Keys. Ecological Applications 4, 144–156.

Sallenger, A.S., Wright, C.W., Lillycrop, J., 2007. Coastal change impacts during Hurricane Katrina: an overview. In: Kraus, N.C., Rosati, J.D. (Eds.), Coastal Sediments. America Society of Civil Engineers, Reston, Virginia, pp. 888–896.

Schwab, W.C., Thieler, E.R., Denny, J.F., Danforth, W.W., 2000. Seafloor Sediment Distribution Off Southern Long Island, New York. US Geological Survey Open-File Report 00-243. <http://www.pubs.usgs.gov/of/2000/of00-243/default.htm> (accessed 09.07.10).

Suffolk County Planning Department (SCPD), 2004. Demographic, Economic and Development Trends. Hauppauge, New York. <http://www.co.suffolk.ny.us/Planning/Overview02_2004.pdf> (accessed 09.07.10).

Seavey, J.R., 2009. Piping Plover (*Charadrius melodus*) Conservation on the Barrier Islands of New York: Habitat Quality and Implications in a Changing Climate. Dissertation. University of Massachusetts, Amherst, Massachusetts.

Sekercioglu, C.H., Schneider, S.H., Fay, J.P., Loarie, S.R., 2008. Climate change, elevational range shifts, and bird extinctions. Conservation Biology 22, 140–150.

Thieler, E.R., Hammar-Klose, E.S., 2000. National Assessment of Coastal Vulnerability to Sea-level Rise. US Gulf of Mexico Coast. Open-File Report 00-179, US Geological Survey Digital Data Series, vol. 68. <http://www.pubs.usgs.gov/dds/dds68/> (accessed 09.07.10).

Thomas, C.D., Cameron, A., Green, R.R., Bakkenes, M., Beaumont, L.J., Hughes, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, F., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L., Williams, S.E., 2004. Extinction risk from climate change. Nature 427, 145–148.

Titus, J., 1989. The Potential Effects of Global Climate Change on the United States. US Environmental Protection Agency, Office of Policy, Planning, and Evaluation (Chapter 7: Sea-Level Rise). <http://www.epa.gov/climatechange/effects/downloads/rtc_sealevelrise.pdf> (accessed 09.07.10).

Titus, J.G., Richman, C., 2001. Maps of lands vulnerable to sea-level rise: modeled elevations along the US Atlantic and Gulf coasts. Climate Research 18, 205–228.

Titus, J., Anderson, K.E., Cahoon, D.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. Final Report, Synthesis and Assessment Product 4.1, US Environmental Protection Agency, Washington, District of Columbia.

United States Army Corps of Engineers (USACE), 2005. National Coastal Mapping Program Topo/Bathy Lidar: Delaware, Maryland, New Jersey, New York, North Carolina, Virginia, and New York. <http://www.csc.noaa.gov/crs/tcm/ldartdat/metatemplate/usace2005_ec_template.html> (accessed 09.07.10).

United States Census Bureau (USCB), 2003. New York 2000: Population and Housing Unit Counts. <http://www.census.gov/prod/cen2000/phc-3-34.pdf> (accessed 09.07.10).

United States Fish and Wildlife Service (USFWS), 2009. Piping Plover (*Charadrius melodus*). 5-Year Review: Summary and Evaluation. Hadley, Massachusetts.

United States Fish and Wildlife Service (USFWS), 1996. Piping Plover (*Charadrius melodus*). Atlantic Coast Population, Revised Recovery Plan. United States Fish and Wildlife Service, Hadley, Massachusetts.

United States Geological Service (USGS), 2004. Digital Orthoimagery. Seamless Data Distribution System. <http://www.seamless.usgs.gov> (accessed 09.07.10).

Vermeer, M., Rahmstorf, S., 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences of the United States of America 106, 21527–21532.

Warnock, N., Elphick, C., Rubega, M.A., 2002. Shorebirds in the marine environment. In: Schreiber, E.A., Burger, J. (Eds.), Biology of Marine Birds. CRC Marine Biology Series, Boca Raton, Florida, pp. 581–615.

Weiss, J., Overpeck, J.T., 2006. Climate Change and Sea Level: Map of Susceptible Areas. Department of Geosciences Environmental Studies Laboratory, University of Arizona, Tucson, Arizona. <http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/sea_level_rise.htm> (accessed 09.07.10).

Wilcove, D.S., Rothstein, D., Dubow, J., 2000. Leading Threats to US Biodiversity: What's Threatening Imperiled Species? Precious Heritage: The Status of Biodiversity in the United States. Oxford University Press, New York, New York.

Williams, K., Ewel, K., Stumpf, R., Putz, F., Workman, T., 1999. Sea-level rise and coastal forest retreat on the west coast of Florida, USA. Ecology 80, 2045–2063.

Yin, J., Schlesinger, M., Stouffer, R., 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. Nature Geoscience 2, 262–266.

Zhang, K., Douglas, B.C., Leatherman, S.P., 2004. Global warming and coastal erosion. Climatic Change 64, 41–58.

Please cite this article in press as: Seavey, J.R., et al. Effect of sea-level rise on piping plover (*Charadrius melodus*) breeding habitat. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.09.017