Coastal habitats shield people and property from sea-level rise and storms

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Extreme weather, sea-level rise and degraded coastal ecosystems are placing people and property at greater risk of damage from coastal hazards[1–5]. The likelihood and magnitude of losses may be reduced by intact reefs and coastal vegetation[1], especially when those habitats fringe vulnerable communities and infrastructure. Using five sea-level rise scenarios, we calculate a hazard index for every 1 km^2 of the United States coastline. We use this index to identify the most vulnerable people and property as indicated by being in the upper quartile of hazard for the nation's coastline. The number of people, poor families, elderly, and total value of residential property that are most exposed to hazards can be reduced by half if existing coastal habitats remain fully intact. Coastal habitats defend the greatest number of people and total property value in Florida, New York, and California. Our analyses deliver the first national map of risk-reduction due to natural habitats and in so doing, indicate where conservation and restoration of reefs and vegetation have the greatest potential to protect coastal communities.

Globally, coastal flooding and sea level are expected to increase significantly by midcentury, with potentially severe consequences for coastal populations around the world[6]. In the United States--where 23 of the nation's 25 most densely populated counties are coastal--the combination of storms and rising seas already is putting valuable property and large numbers of people in harm's way[1-5]. The traditional approach to protecting towns and cities has been to "harden" shorelines. Although engineered solutions are necessary and desirable in some contexts, they can be expensive to build and maintain[7,8], and construction may impair recreation, enhance erosion, degrade water quality, and reduce fisheries production[9,10]. Over the past decade, efforts to protect people and property have broadened[11] to consider conservation and restoration of marshes, seagrass beds, coastal and kelp forests, and oyster and coral reefs that buffer coastlines from waves and storm surge[12–14] and provide collateral benefits to people[15]. But approaches and tools for evaluating the potential role of natural defense mechanisms lag behind those for hardening shorelines[15].

Prioritizing ecosystems for conservation or restoration in service of natural hazard reduction, requires knowing where habitats are most likely to (1) reduce exposure to erosion and flooding from storms and future sea levels, and (2) protect vulnerable people and property (see Supplement definitions of vulnerability etc.). Previous efforts have mapped physical vulnerability of coastal areas using data and forecasts for sea-level rise and storm surge [16,17] and used social metrics of vulnerability[18] to identify where consequences of physical hazards will be greatest for people [2,19]. Missing, however, is a synthesis of hazard models, climate scenarios, demographic information, and ecological data to identify where habitats may contribute to protection from coastal hazards. Events such as Hurricane Sandy, which devastated the northeast U.S. in October 2012, demonstrate the desperate need for such an analysis to inform planning and yield coastal regions more resilient to the expected effects of climate change[20].

To identify the stretches of shoreline where habitats have the greatest potential to defend coastal communities against storms and sea-level rise, we created a hazard index that incorporates the protective role of ecosystems for the shoreline of the U.S. at a 1-km^2 scale (Supplementary Fig. 1). We compiled a nationwide map of the major coastal habitats, designed two habitat scenarios (with and without habitat) and five scenarios of current and future sea level, and identified areas with the highest exposure to inundation and erosion using physical data and models[16,17,21] (Methods and Supplementary Information). Next, we converted hazard to imperiled human life and property by mapping exposure of the people, poor families, elderly populations[22], and residential property values[23] in each 1-km^2 segment of the coastline. To determine the reduction in risk of damages provided by habitats to current storm intensities and the five scenarios of current and future sea level[24], we modeled the numbers of people and total value of property highly exposed to hazards with and without habitats. By quantifying where and to what extent habitats reduce exposure of vulnerable populations and property, our analyses are, to the best of our knowledge, the first to target where conservation and restoration of coastal habitats are most critical for protecting lives and property at a national scale.

We assessed coastal vulnerability now and in the future by estimating the hazard index at a 1-km^2 scale for the entire coastline across ten scenarios varying in sea-level rise and presence of habitats (no rise, and four U.S. National Climate Assessment scenarios of rise[24] both with and without habitat; Methods, Supplementary Information, Supplementary Fig. 2). From the frequency distribution of 1,007,020 (ranging from 1.05-4.84), we identified the upper quartile (‘high hazard)’ as greater than 3.36 (Supplementary Fig. 3). Today 16% of the U.S. coastline are ‘high hazard’ areas, harboring 1.3 million people, 250,000 elderly, 30,000 families below the poverty line, and $300 billion in residential property value (Fig. 1).

A key question that arises with an index of modeled hazard is whether observed and predicted spatial variation in damages are correlated. To compare our coastal hazard index to findings from empirical studies, we synthesized data from the Spatial Hazards Events and Losses Database for the U.S. (SHELDUS[25]). Using state-level data from 1995-2010, we found a highly significant positive relationship between our modeled estimates of total population exposed to the greatest coastal hazard (current scenario only; upper quartile > 3.14) and the observed number of coastal hazard-related fatalities ($N=21$ states, $R^2=0.70$, $P<0.0001$, total coastal hazards=1270, total coastal hazard-related fatalities=527, Supplementary Information).

To assess future vulnerability, we examined results from the hazard index and estimated risk to people and property under four sea-level rise scenarios for the year 2100[24]. Across all future scenarios, our results suggest that more coastal segments will be highly exposed to hazards, and that the amount of highly threatened people and property will increase by 30-60% over the current scenario (Fig. 1). Given modeled sea-level rise and observed storm characteristics, 1.7 to 2.1 million of today's population will live in areas exposed to the highest hazard (Fig. 1). Between 30,000 and 40,000 families below the poverty line and $400 to $500 billion of residential property will be most exposed to future hazards (Fig. 1). Of course, both property values and populations along the coast are expected to grow; thus, our study likely underestimates the number of people and value of property expected to be in harm's way by 2100. Because our analysis includes only the value of residential units, not commercial properties, it underestimates the total value of property exposed to damage from coastal hazards.

To determine the extent to which habitats provide protection, we compared estimates of risk for the five sea-level rise scenarios with and without the presence of nine habitats that fringe the U.S.: coastal forests (e.g., mangroves and other coastal trees and shrubs), coral reefs, emergent marsh, oyster reefs, high and low dunes, seagrass beds, kelp forests, and additional intertidal aquatic vegetation (Supplementary Fig. 4). We modeled the complete loss of habitat to identify where habitats reduce the exposure of people and property to hazards. Habitats currently protect 67% of the coastline, as hazard increases in two-thirds of all segments in the without habitat scenario. Habitat loss would double the extent of coastline highly exposed to storms and sea-level rise (hazard index > 3.36), making vulnerable an additional 1.4 million people currently living within 1 km of the coast. The number of poor families, elderly people, and total property value highly exposed to hazards would also double if protective habitats were lost (Fig. 1).

Vulnerability to coastal hazards and the importance of natural habitats vary across the United States. For all climate scenarios (Supplementary Fig. 5), the east and gulf coasts are more physically vulnerable to sea-level rise and storms than the west coast (shown for A2 in Fig. 2). Regions with greater exposure to hazards have a greater percentage of low-relief coastal areas with softer substrates (e.g., beaches, deltas), higher rates of sea-level rise, and potential for storm surge (Supplementary Figs. 7,8). Large expanses of coastal forests and wetlands, oyster and coral reefs, dunes, and seagrass beds (Supplementary Fig. 4) are critical for protecting the eastern seaboard and Gulf of Mexico from storms and sea-level rise (compare Supplementary Figs. 5 to 6). At the state level, habitats protect the greatest extent of coastline in Florida, North Carolina and Alaska (shown for A2 in Supplementary Table 7). Although coastal ecosystems are most important for reducing exposure to hazards in the aforementioned states, they provide protection for the greatest number of people, socially vulnerable populations, and property in Florida, New York and California (difference between "with habitat" and "without habitat" Fig. 2B, Supplementary Table 7 for other metrics).

To determine where habitats are likely to be critical for protecting the most valuable coastline now and under future climate scenarios, we estimated the difference in total property value exposed to coastal hazards, with and without habitats, at a county scale. Variation among counties in the value of property currently protected by coastal habitats is substantial, ranging from $0 (e.g., Jefferson, Florida), to over $20 billion in Suffolk and Kings, New York (Fig. 3A). There are also differences in the potential importance of habitats for protection as sea levels rise. For example, if the extensive coral, mangrove, and seagrass ecosystems that currently line Florida persist in the face of development and climate change, our analysis predicts these habitats will reduce exposure of nearly $4 billion 2010 USD in home property values within 1 km of the coastline by 2100 – up from $0.7 billion currently (Fig. 3A,B insets). In other counties sea-level rise will overwhelm coastal habitats, reducing property protection (Fig. 3 insets).

Focusing solely on property value may cause decision-makers and planners to overlook ecosystems that provide disproportionate protection of vulnerable populations. For example, habitats protect more poor families relative to the total population in Texas (Fig. 4A,B) and more elderly and total property value in Florida (Figs. 3, 4C, 4D). Thus, at the county scale, the greatest hazard protection from habitats for poor families along the Gulf coast occurs where there are disproportionately fewer elderly and lower total property value. These findings reflect the co-location of high property value and vulnerable people in some regions and their independence in other regions.

Around the world and the U.S., coastal defense planning is beginning to incorporate ecosystems alongside physical structures. In the aftermath of Hurricane Sandy, calls for enhancing the resilience of New York City have included restoration of oyster and wetland habitats[26]. Louisiana's 2012 Master Plan to combine natural and engineered strategies for protection[11], is exemplary of such efforts.

These pioneering initiatives will likely be emulated by other regions. Our results suggest that the extent to which natural defense mechanisms operate depends on relative location of the hazard (e.g., sea-level rise hotspots)[5], habitats, and vulnerable populations and properties. Questions about the adaptation (or lack thereof) of habitats to climate change (e.g., wetlands migrating with sea-level rise) and how multiple habitats (e.g., oysters and marshes) function together to reduce exposure[26], deserve further attention.

More work is needed to identify where combining ecosystem-based and engineered approaches will be most effective for reducing damages. Because of data limitations at a national scale, we combined physical structures and geomorphology into a single variable, which precludes comparisons of green and grey solutions (Supplementary Information). A full cost-benefit analysis of alternatives will be most useful at local scales and require quantitative ecological, surge, and wave models combined with valuation of a suite of ecosystem services. The authors are engaged in such work in Texas, U.S. and Belize.

The index we developed is most useful at national and regional scales for prioritizing habitats for coastal defense. Our analysis illuminates that loss of existing ecosystems will result in greater damage to people and property or will require massive investments in engineered defenses. Identifying the best locations to target for ecosystem-based strategies depends on where habitats effectively reduce hazards and where people benefit the most, both now and under future climate.

Methods:

Design of sea-level rise scenarios. We developed one current and four future sea-level rise scenarios for 2100 for the coast of the United States using long-term tide gauge data and guidance from the 2013 National Climate Assessment (NCA): “current” is based on observed rates of sea-level rise, “trend” represents the projection of the observed rise to 2100, “B1” and “A2” are based in part on the Special Report on Emission Scenarios, and “high” incorporates glacier and ice sheet contributions[24] (Supplementary Fig. 1). To calculate local estimates of sea-level rise for each scenario we assigned each 1-km^2 segment to the closest tide gauge[27]. We estimated the current sea-level rise scenario as the increase in water elevation from 1992 to 2006 using the long-term observed rate for each tide gauge[27]. Predicted outcomes for the four future scenarios were global rise for 2100 predicted by the NCA (0.2, 0.5, 1.2, 2 m)[24], multiplied by a scaling factor (the ratio of the historical local rate to the historical global rate (1.8 mm yr^{-1}))[24,27].

Design of habitat scenarios. To evaluate the role of coastal ecosystems in reducing exposure to sea-level rise and storms, we developed two habitat scenarios. “With habitat” includes nine habitats in the hazard index (Supplementary Fig. 4). “Without habitat” assumes those habitats no longer provide protection. The habitat scenario is assumed to be the current state of the system. The “without habitat” scenario is not intended to be a plausible reflection of the future. Instead, we used it to evaluate where and to what extent habitats play a significant role in protecting people and property, and to determine where their loss would affect risk from coastal hazards.

Calculating coastal hazard. To estimate the relative exposure of each 1-km^2 segment of the U.S. coastline in 2100 and today with and without habitats (for a total of 1,007,020 segments), we calculated an index for coastal erosion and inundation using the coastal vulnerability model in InVEST, an open-source tool available at www.naturalcapitalproject.org. The tool builds on previous approaches[16,17] by specifically including the role of habitats in providing protection. The index also includes the effect of storms on exposure by incorporating observed data on wind, waves[28], and surge potential, as well as data and models for four other key variables: habitat type, shoreline type, relief, and sea-level rise (Supplementary Information). Because of uncertainty among models and studies about the relationship between waves and climate change[29], we made the simplifying assumption that storm intensity and frequency in 2100 will be the same as the current scenario. We estimated current wave and wind exposure based on six years of NOAA WAVEWATCH III model hindcast re-analysis results for 2005-2010[28]. We followed NOAA's ESI shoreline classification scheme, and assumed that seawalls have the same rank as rocky coastlines and cliffs (Supplementary Table 1). This simplification, which in effect combines structures and geomorphology into shoreline type, is an artifact of the limitations of the nationwide dataset and analysis, and should be addressed in future research.

Using observed and modeled data, we generated absolute values for each variable for each 1-km^2 segment of coastline. We then ranked each variable for each segment from low (Rank=1) to high (Rank=5) exposure (Supplementary Table 1).

$$HazardIndex = (R_{Habitats} R_{GeomorphologyORstructures} R_{\mathrm{Relief}} R_{SLR} R_{Wind} R_{Waves} R_{SurgePorential})^{\frac{1}{7}}$$

We weighted all variables equally, after several other coastal vulnerability indices[16,17]. The results are the relative exposure to coastal hazard of each 1-km^2 segment compared to all other segments nation-wide and across the ten habitat by climate scenarios (Supplementary Fig. 2). To map hazard we classified the distribution of results for all segments and scenarios (ranging from 1-5) into quartiles that demarcate areas of highest (>3.36=upper 25%), intermediate (2.36-3.36=central 50%) and lowest hazard (<2.36=lower 25%, Supplementary Fig. 2).

Quantifying risk. To convert hazard to imperiled property and human life we combined it with mapped data on demographics[22] and property values[23] in each 1-km^2 segment of the entire coastline. We used Zillow's Home Value Index (ZHVI)[23], which is the median market value of residential properties in each U.S. 2010 Census block group and five years (2006-2010) of the Census Bureau's American Community Survey (ACS) data[22]. We distributed data for people and properties throughout the census block group at a resolution of 30 m with a dasymetric mapping approach[30] that uses land-use, land-cover and land stewardship data (indicating uninhabited public lands) to identify where people are most likely to live. We then estimated the total population, number of people older than 65 years, number of families below the poverty line, and median value of properties in 1-km^2 segments classified as highest hazard.

Validation of current costal hazard risk. To assess the ability of the hazard index to capture risk, we compared our estimates for population exposed to highest hazard to the observed number of coastal hazard-related fatalities per state from the Spatial Hazards Events and Losses Database for the United States (SHELDUS[25]).

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Acknowledgments: We thank the Gordon and Betty Moore Foundation for financial support and for hosting the National Climate Assessment Biodiversity, Ecosystems and Ecosystem Services Technical Chapter working group. We thank the many individuals and institutions that provided data (see SI for full details). We also thank Jen Burke, Guy Gelfenbaum, Rob Griffin, CK Kim, Josh Lawler, Mark Plummer, Peter Ruggiero, Jameal Samhouri, Heather Tallis, Jodie Toft, and Guy Ziv for helpful discussions during this research. Links for downloading the coastal hazard index and visualizing results are available at www.naturalcapitalproject.org. Data are available from the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.[NNNN]

Author contributions:

P.K., M.R., K.A., G.G., A.G., S.W., G.V. conceived the research. G.G. and G.V. developed the coastal hazard index. K.A., G.V., S.W. performed analyses. K.A., G.G., G.V., S.W. collected the data. M.L. and J.S. helped with data collection and analyses. K.A. wrote the paper with contributions from A.G., G.G, P.K., M.R., J.S., G.V., S.W.

Competing Financial Interests: The authors declare no competing financial interests.

Figure legends:

Figure 1. Coastal habitats reduce by approximately 50% the proportion of people and property along the United States coastline that are most exposed to storms and sea-level rise. We estimate people and property exposed to hazards with (■) and without (□) habitats using four metrics: total population, elderly people, poor families (three left axes), and residential property values (right axis). Results are represented using the same set of bars for all metrics because at the national scale these variables are highly correlated. The correlation breaks down on more local scales (Figs. 3, 4). Data are for highest hazard segments (index > 3.36).

Figure 2. Exposure of the United States coastline and coastal population to sea-level rise in 2100 (A2 scenario) and storms. Warmer colors indicate regions with more exposure to coastal hazards (index > 3.36). The bar graph shows the population living in areas most exposed to hazards (red 1-km^2 coastal segments in the map) with protection provided by habitats (■), and the increase in population exposed to hazards if habitats were lost due to climate change or human impacts (□). Data depicted in the inset maps are zoomed-in views of the nationwide analysis.

Figure 3. Total property value for which habitats reduce exposure to storms and sea-level rise in each coastal county of the United States for the A) current and B) future A2 sea-level rise scenarios. Insets show Monroe County, FL, Georgetown and Horry counties in SC, and Brunswick and Pender counties in NC. Reduction in the total value of property exposed to coastal hazards is the difference in the total value of property exposed to coastal hazards with and without habitats included in the hazard index.

Estimates for each 1-km^2 segment in the highest hazard category (index > 3.36) are summed by county.

Figure 4. Nature's shield for socially vulnerable counties. Proportion of poor families (A, B) and elderly people (C, D), relative to the total population in each country, that are protected by habitats from exposure to current (A, C) and future A2 (B, D) sea-level rise and storms. Cut-offs for high (🟫 = upper 25%), medium (🟧 = center 50%) and low (🟨 = lower 25%) proportions are based on the quantiles of the two distributions (ratio of poor or elderly to total population) across the two sea-level rise scenarios.

Figure 1

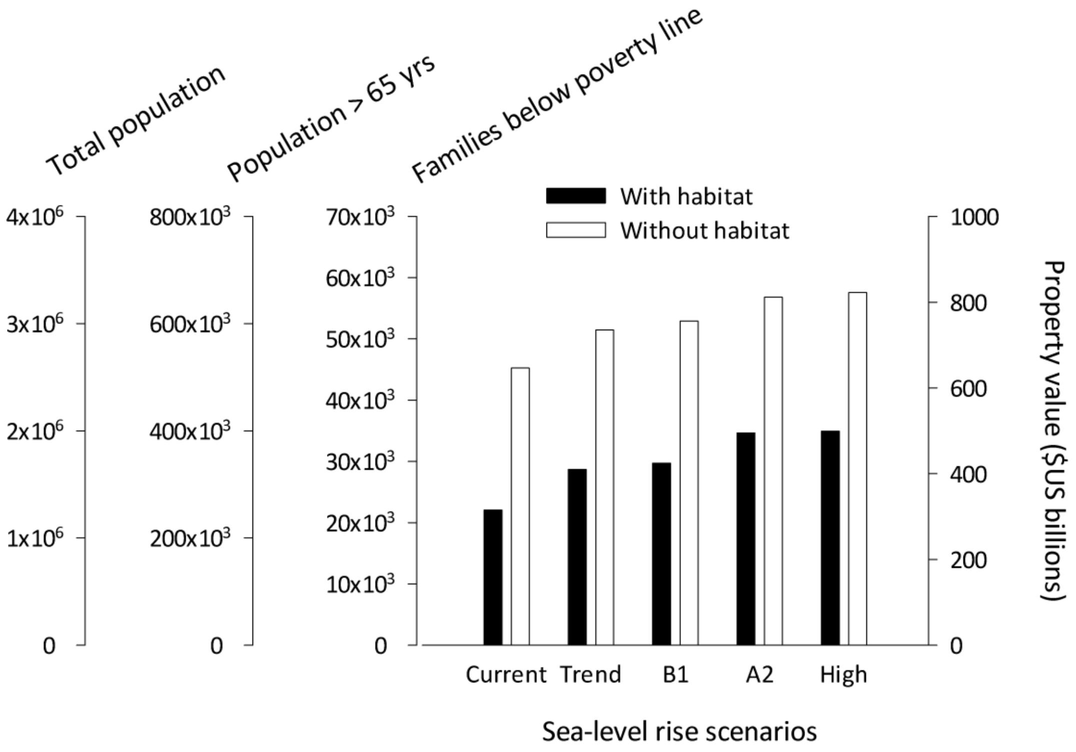

Total population
Population > 65 yrs
Families below poverty line
With habitat
Without habitat
4x10^6
3x10^6
2x10^6
1x10^6
0
800x10^3
600x10^3
400x10^3
200x10^3
0
70x10^3
60x10^3
50x10^3
40x10^3
30x10^3
20x10^3
10x10^3
0
1000
800
600
400
200
0
Property value ($US billions)
Current
Trend
B1
A2
High
Sea-level rise scenarios

Figure 2

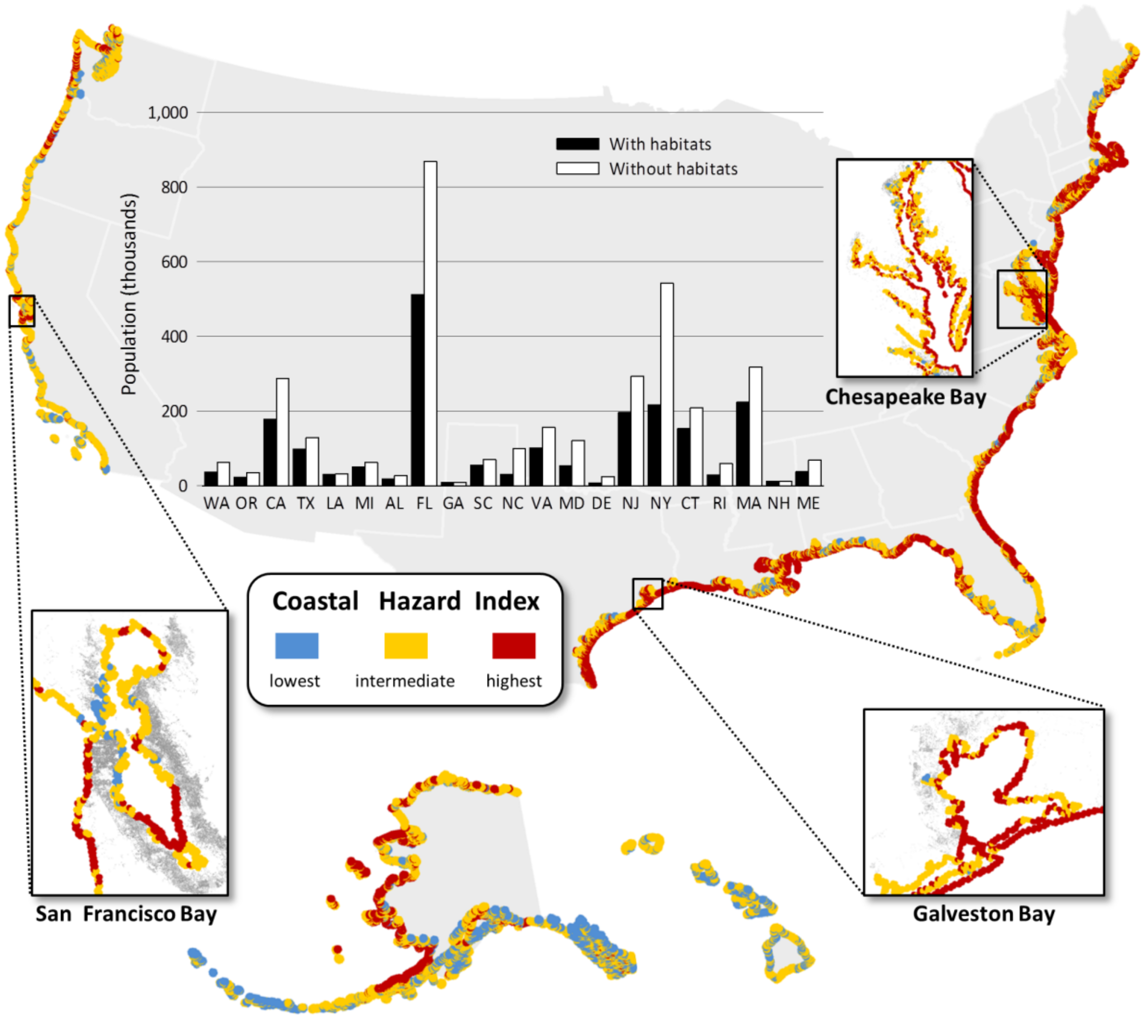

1,000
800
600
400
200
0
Population (thousands)
With habitats
Without habitats
WA OR CA TX LA MI AL FL GA SC NC VA MD DE NJ NY CT RI MA NH ME
Chesapeake Bay
Coastal Hazard Index
lowest
intermediate
highest
San Francisco Bay
Galveston Bay

Figure 3

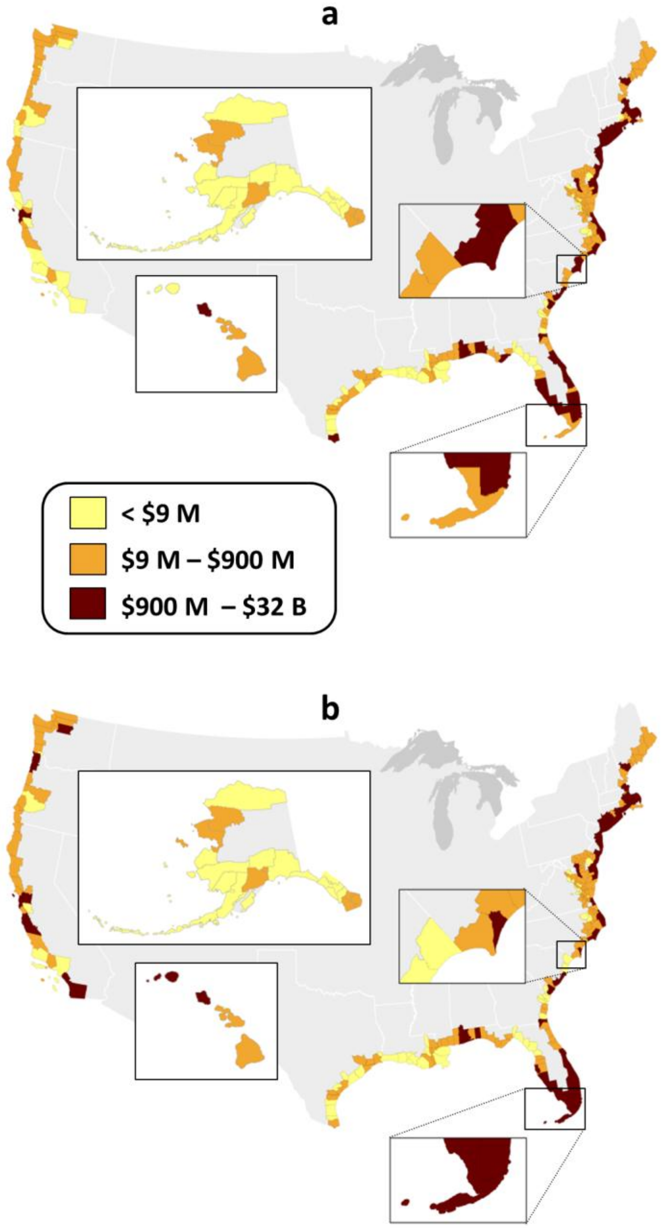
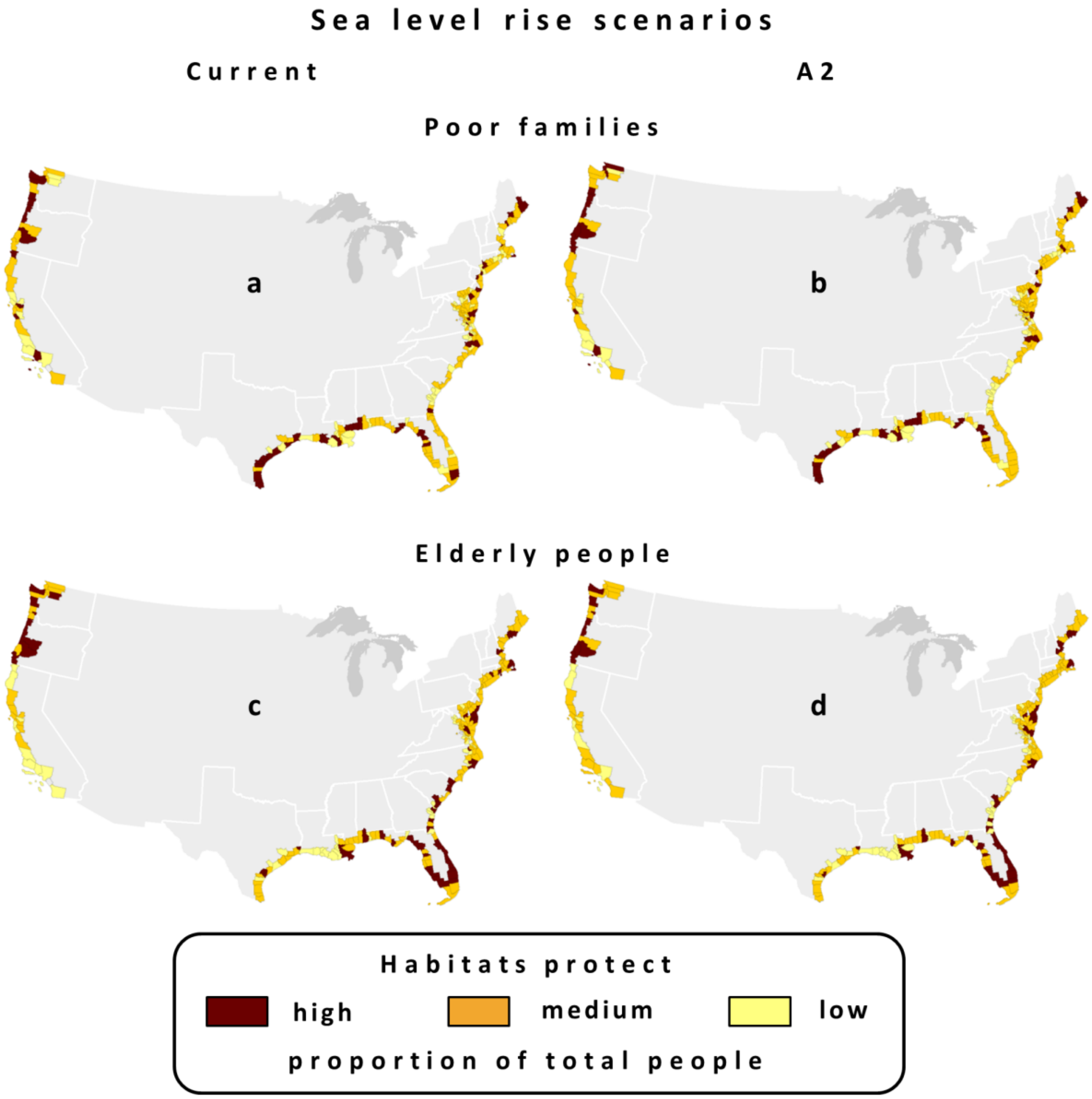


Figure 4


Sea level rise scenarios
Current
A2
Poor families
a
b
Elderly people
c
d
Habitats protect
high
medium
low
proportion of total people