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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 owing to natural habitats and indicates 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 mid-century, 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 is already 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 the production of fisheries[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 defence mechanisms lag behind those for hardening shorelines[15].

Prioritizing ecosystems for conservation or restoration in service of natural hazard reduction requires knowledge of where habitats are most likely to reduce exposure to erosion and flooding from storms and future sea levels, and protect vulnerable people and property (see Supplementary Information for definitions of vulnerability and so on). 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 United States 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 US shoreline at a 1 km^2 scale (Supplementary Fig. S1). We compiled a nationwide map of the main 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] (see 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 modelled the number of people and total value of property highly exposed to hazards with and without habitats. By quantifying where and to what extent habitats reduce the 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 on a national scale.

We assessed coastal vulnerability now and in the future by estimating the hazard index on 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 US National Climate Assessment scenarios of rise[24] both with and without habitat; see Methods, Supplementary Information and Supplementary Fig. S2). From the frequency distribution of 1,007,020 (ranging from 1.05 to 4.84), we identified the upper quartile ('high hazard') as greater than 3.36 (Supplementary Fig. S3). Today 16% of the US coastline comprises

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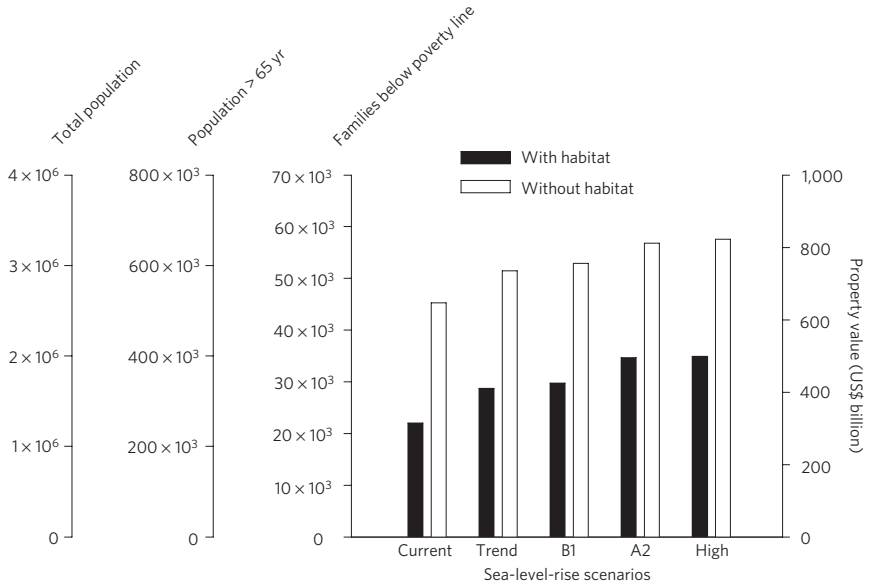

Figure 1 | Coastal habitats reduce by approximately 50% the proportion of people and property along the US coastline that are most exposed to storms and sea-level rise. We estimate people and property exposed to hazards with (black bars) and without (white bars) habitats using four metrics: total population, elderly people, poor families (three left *y* axes) and residential property values (right *y* axis). Results are represented using the same set of bars for all metrics because on 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).

'high hazard' areas, harbouring 1.3 million people, 250,000 elderly, 30,000 families below the poverty line and US$300 billion in residential property value (Fig. 1).

A key question that arises with an index of modelled hazard is whether observed and predicted spatial variation in damages are correlated. To compare our coastal hazard index with findings from empirical studies, we synthesized data from the Spatial Hazards Events and Losses Database for the United States (ref. 25). Using state-level data from 1995 to 2010, we found a highly significant positive relationship between our modelled 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 = 1,270, total coastal hazard-related fatalities =527; see 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 (ref. 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 modelled 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 US$400 to US$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 probably underestimates the number of people and value of property expected to be in harm's way by 2100. Because our analysis includes the value of only 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 United States: coastal forests (for example, 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 (see Supplementary Fig. S4). We modelled the complete loss of habitat to identify where habitats reduce the exposure of people and property to hazards. At present, habitats protect 67% of the coastline, as hazard increases in two-thirds of all segments in the scenario without habitat. Habitat loss would double the extent of coastline highly exposed to storms and sea-level rise (hazard index >3.36), making an additional 1.4 million people now living within 1 km of the coast vulnerable. 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. S5), 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 (for example, beaches, deltas), higher rates of sea-level rise and potential for storm surge (Supplementary Figs S7 and S8). Large expanses of coastal forests and wetlands, oyster and coral reefs, dunes and seagrass beds (Supplementary Fig. S4) are critical for protecting the eastern seaboard and Gulf of Mexico from storms and sea-level rise (compare Supplementary Figs S5 and S6). At the state level, habitats protect the greatest extent of coastline in Florida, North Carolina and Alaska (shown for A2 in Supplementary Table S7). 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 (see difference between 'with habitat' and 'without habitat' in Fig. 2b and Supplementary Table S7 for other metrics).

To determine where habitats are likely to be critical for protecting the most valuable coastline now and under future

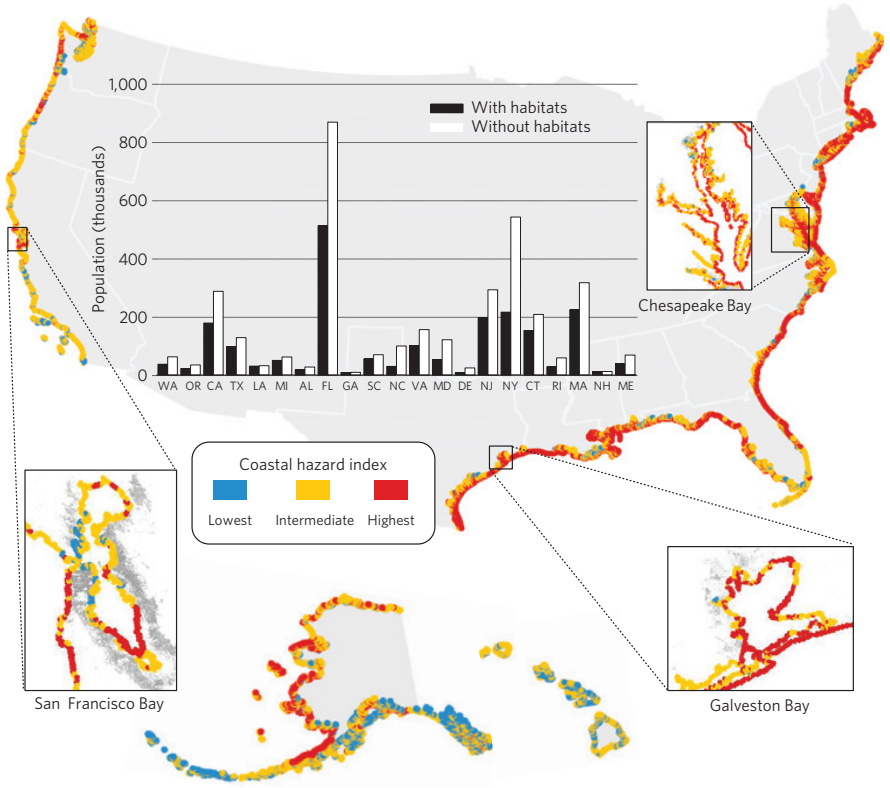

Figure 2 | Exposure of the US coastline and coastal population to sea-level rise in 2100 (A2 scenario) and storms. Warmer colours indicate regions with more exposure to coastal hazards (index >3.36). The bar graph shows the population living in areas most exposed to hazards (red 1 km^2 coastal segments in the map) with protection provided by habitats (black bars) and the increase in population exposed to hazards if habitats were lost owing to climate change or human impacts (white bars). Letters on the *x* axis represent US state abbreviations. Data depicted in the inset maps are magnified views of the nationwide analysis.

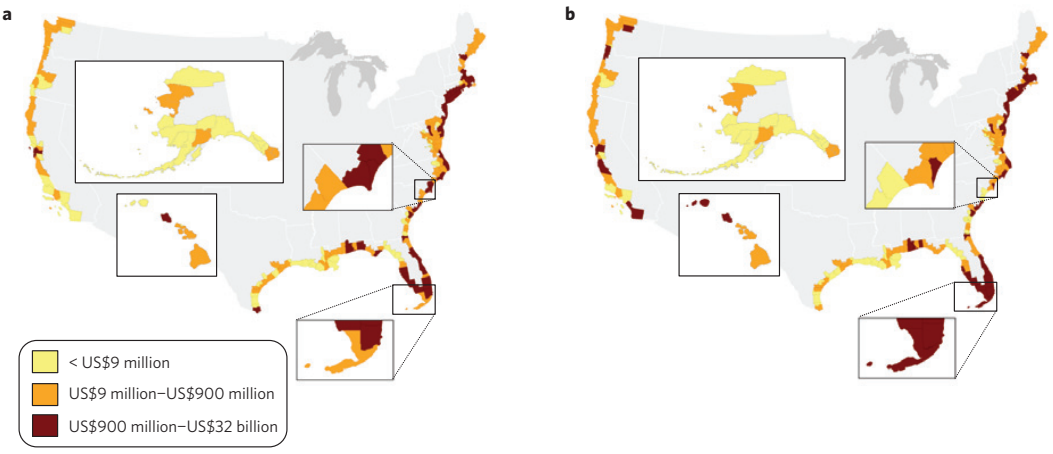

Figure 3 | Nature's shield for total residential property value. a,**b**, Total property value for which habitats reduce exposure to storms and sea-level rise in each coastal county of the United States for the current (**a**) and future A2 (**b**) sea-level-rise scenarios. Insets show Monroe County in Florida, Georgetown and Horry counties in South Carolina and Brunswick and Pender counties in North Carolina. 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.

climate scenarios, we estimated the difference in total property value exposed to coastal hazards, with and without habitats, on a county scale. Variation among counties in the value of property now protected by coastal habitats is substantial, ranging from US$0 (for example, Jefferson, Florida), to more than US$20 billion in Suffolk and Kings, New York (Fig. 3a). There are also differences

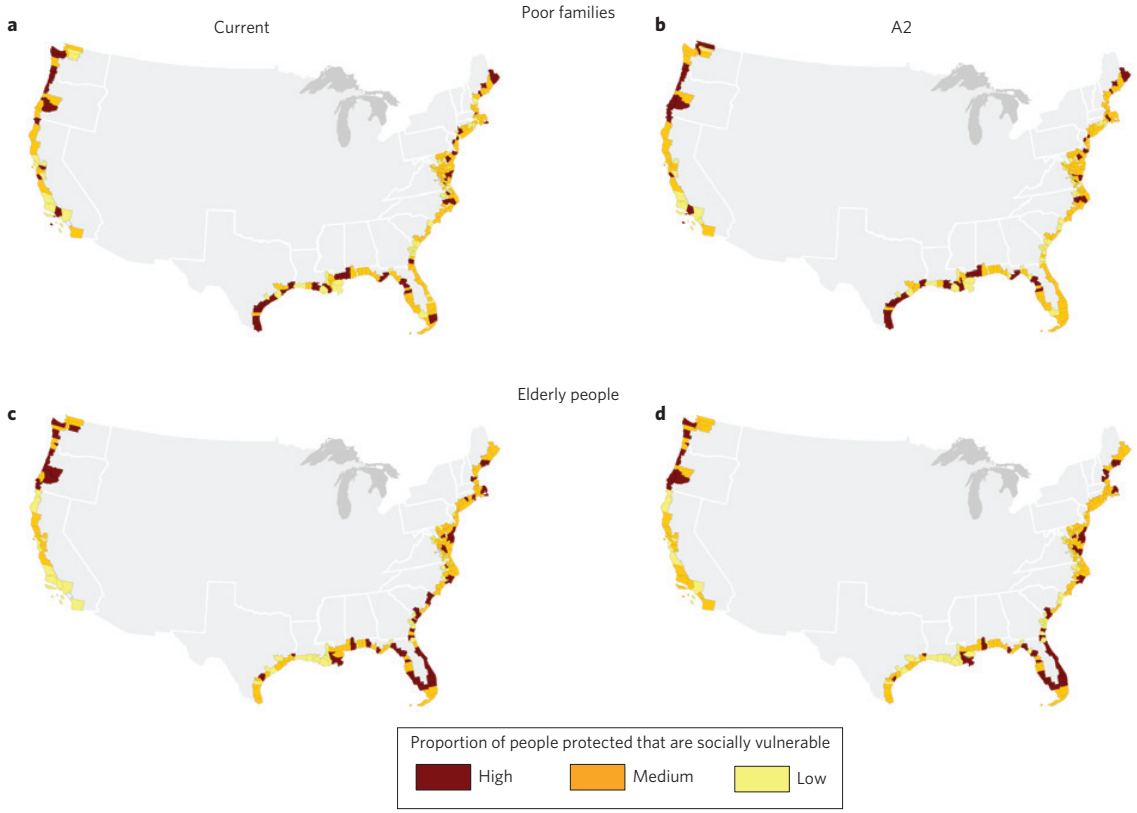

Figure 4 | Nature's shield for socially vulnerable counties. a–d, Proportion of poor families (**a**,**b**) and elderly people (**c**,**d**), relative to the total population in each country that are protected by habitats from exposure to current (**a**,**c**) and future A2 (**b**,**d**) sea-level rise and storms. Cut-offs for high (upper 25%), medium (centre 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.

in the potential importance of habitats for protection as sea levels rise. For example, if the extensive coral, mangrove and seagrass ecosystems that line Florida at present persist in the face of development and climate change, our analysis predicts these habitats will reduce exposure of nearly US$4 billion worth of 2010 home property values within 1 km of the coastline by 2100—up from US$0.7 billion at present (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 to 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 and 4c,d). Thus, on 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 United States, coastal defence 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 probably be emulated by other regions. Our results suggest that the extent to which natural defence mechanisms operate depends on the relative location of the hazard (for example, sea-level rise hotspots)[5], habitats, vulnerable populations and properties. Questions about the adaptation (or lack thereof) of habitats to climate change (for example, wetlands migrating with sea-level rise) and how numerous habitats (for example, 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. Owing to data limitations on a national scale, we combined physical structures and geomorphology into a single variable, which precludes comparisons of green and grey solutions (see Supplementary Information). A full cost-benefit analysis of alternatives will be most useful on 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, USA and Belize.

The index we developed is most useful on national and regional scales for prioritizing habitats for coastal defence. Our analysis illuminates that loss of existing ecosystems will result in greater damage to people and property or will require massive investments in engineered defences. 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 US using long-term tide-gauge data and guidance from the 2013 US National Climate Assessment: '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 Emissions Scenarios[27] and 'high' incorporates glacier and ice-sheet contributions[24] (see Supplementary Fig. S1). To calculate local estimates of sea-level rise for each scenario we assigned each 1 km^2 segment to the closest tide gauge[28]. 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[28]. Predicted outcomes for the four future scenarios were global rise for 2100 predicted by the National Climate Assessment (0.2, 0.5, 1.2, 2 m; ref. 24), multiplied by a scaling factor (the ratio of the historical local rate to the historical global rate (1.8 mm yr^{-1}); refs 24,28).

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. S4). '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 US 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[29] 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). Owing to uncertainty among models and studies about the relationship between waves and climate change[30], 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 the National Oceanographic and Atmospheric Administration WAVEWATCH III model hindcast reanalysis results for 2005–2010 (ref. 29). We followed the National Oceanographic and Atmospheric Administration's environmental sensitivity index shoreline classification scheme and assumed that seawalls have the same rank as rocky coastlines and cliffs (Supplementary Table S1). This simplification, which in effect combines structures and geomorphology into shoreline type, is an artefact of the limitations of the nationwide data set and analysis, and should be addressed in future research.

Using observed and modelled 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 (see Supplementary Table S1).

$$\text{Hazard Index} = (R_{\text{Habitats}} R_{\text{ShorelineType}} R_{\text{Relief}} R_{\text{SLR}} R_{\text{Wind}} R_{\text{Waves}} R_{\text{SurgePorential}})^{1/7}$$

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 with all other segments nationwide and across the ten habitat-by-climate scenarios (see Supplementary Fig. S2). To map hazard we classified the distribution of results for all segments and scenarios (ranging from one to five) 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%, see Supplementary Fig. S2).

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[23], which is the median market value of residential properties in each US 2010 census block group and five years (2006–2010) of the Census Bureau's American Community Survey 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[31] 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 coastal hazard risk. To assess the ability of the hazard index to capture risk, we compared our estimates for population exposed to highest hazard with the observed number of coastal hazard-related fatalities per state from the Spatial Hazards Events and Losses Database for the United States (ref. 25).

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Author contributions

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

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.K.A.

Competing financial interests

The authors declare no competing financial interests.