ENVIRONMENTAL STUDIES

Hybrid coral reef restoration can be a cost-effective nature-based solution to provide protection to vulnerable coastal populations

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Coral reefs can mitigate flood damages by providing protection to tropical coastal communities whose populations are dense, growing fast, and have predominantly lower-middle income. This study provides the first fine-scale, regionally modeled valuations of how flood risk reductions associated with hybrid coral reef restoration could benefit people, property, and economic activity along Florida and Puerto Rico's 1005 kilometers of reef-lined coasts. Restoration of up to 20% of the regions' coral reefs could provide flood reduction benefits greater than costs. Reef habitats with the greatest benefits are shallow, nearshore, and fronting low-lying, vulnerable communities, which are often where reef impacts and loss are the greatest. Minorities, children, the elderly, and those below the poverty line could receive more than double the hazard risk reduction benefits of the overall population, demonstrating that reef restoration as a nature-based solution can have positive returns on investment economically and socially by providing protection to the most vulnerable people.

INTRODUCTION

Coastal flooding and erosion from extreme weather events affect thousands of vulnerable coastal communities globally; the effects of coastal hazards are predicted to worsen during this century from population growth and climate change–driven sea-level rise (*1*–*3*). For example, the United States spends, on average, $500 million per year mitigating such coastal hazards and billions of dollars recovering following the impacts of tropical cyclones (*4*). In the US and globally, there is an urgent need to develop better risk reduction and adaptation strategies to reduce coastal flooding and associated hazards (*2*, *5*).

Coral reefs substantially reduce coastal flooding by dissipating up to 97% of incident wave energy (*6*) and thus provide coastal protection, including erosion control (*7*); coral reef–lined tropical coasts are among the most susceptible to increased flooding because of climate change and sea-level rise (*8*). Globally, coral reefs protect more than 200,000 people living on the coast from flooding annually (*9*); these populations are denser, growing faster, and composed of more people from lower-middle income groups than the global average (*10*). The coastal protection benefits provided by corals reefs (which extend hundreds to thousands of meters in the cross-shore direction) in the US were assessed using a rigorous, process-based, high-resolution risk modeling system to quantify their defense benefits along the US (*11*) at more than 18,100 people and $1.8 billion (in 2010 US dollars) in averted flood damages to property and economic activity per year (*12*). Because of the hazard risk reduction provided by existing coral reefs, reef restoration is increasingly being considered as a hazard mitigation strategy to reduce coastal risk to, and increase the resiliency of, tropical coastal communities (*9*).

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Quantitative assessments of where reef restoration can provide the most risk reduction benefits are lacking. Common objectives of coral reef restoration are to rebuild habitat and coral populations that have been lost or damaged because of storms and anthropogenic disturbances and to improve resilience to future disturbances (*13*–*15*). Restoration can be focused on coral species (e.g., replanting) or done in combination with structures to restore reef morphology. Planting or "ecological" restoration usually involves increasing the number of living corals on the reef in areas where the solid benthic substrate is available and the vertical structure remains (*16*, *17*). This is generally achieved through methods such as collecting and rehabilitating naturally broken coral fragments, propagating coral colonies, or transplanting living coral colonies (*18*). Structural restoration generally involves development of hybrid reefs using existing rocks/dead coral heads or the deployment of constructed metal or concrete forms. The needs and approaches for combining the restoration of corals and reef structures are similar to those developed over decades for oyster reef restoration (*19*), which long ago recognized the need for replacing structures on which these limestone-secreting organisms could settle and grow.

Structural reef restoration is often required to quickly replace the lost height and complexity of reef habitats with benefits to coral and human communities in areas where the reef has been lost owing to long-term bioerosion of the reef and/or physical damage, as has occurred over large stretches of Pacific and Caribbean reefs (*20*). These structures can then either be seeded by natural coral recruitment or more commonly "outplanted" with corals rescued from elsewhere or grown in nurseries to facilitate and speed development, which is sometimes identified as hybrid reef restoration (*13*). Enhancement of structural complexity has been shown to be able to increase coral recruitment by 400 to 600%, emphasizing the importance of enhancing structural complexity for the promotion of different functional groups (corals and fish), and is a key element in restoration of degraded coral reefs (*21*).

Restoration is increasingly designed to deliver both ecological and ecosystem service benefits to natural and human communities. These efforts are more broadly classed as nature-based solutions, which are used to protect, manage, or restore ecosystems to address societal challenges, providing benefits for people and the environment.

From a hydrodynamic perspective, outplanting corals on the existing seabed (green restoration) is valuable because it increases the hydrodynamic roughness of the seabed and, if attached on top of deployed structures (gray-green hybrid restoration), the reef is also made taller and, thus, the relative water depth is decreased. An increase in hydrodynamic roughness and reduction in water depth results in reduced wave energy and wave-driven water levels (*22*, *23*) that, in turn, reduce wave-driven run-up and flooding (*24*). The potential for reef restoration to reduce wave energy and wave-driven water levels has led to deployment and numerical modeling (*25*) of "gray-green" hybrid reefs to reduce coastal flooding and/or erosion to protect coastal communities.

The aftermath of Hurricanes Irma and Maria in the Caribbean spurred interest in nature-based coastal protection in tropical coastlines. As part of the recovery and restoration efforts following these natural disasters, the US federal government began discussing the possibility of implementing large-scale coral reef restoration in the areas affected by the hurricanes to help reduce the risk to and increase the resiliency of the areas' coastal communities. However, qualifying for postdisaster hazard mitigation funding requires benefit-to-cost analyses (BCAs) to assess whether the hazard risk reduction benefits provided by the potential mitigation activity is equal to or greater than the cost of the recovery activity. Restoration projects for hazard mitigation would need to abide by the same BCA criteria, and thus, coral reef restoration would need to be assessed in those same terms. While it has been applied to traditional measures such as breakwaters and bulkheads, such a framework has never been assessed for natural infrastructure alternatives for US federal hazard risk mitigation funding.

Here, we combined oceanographic, hydrodynamic, ecologic, social, and economic models to develop the first regional assessment of the flood risk reduction benefits, in social and economic terms, of potential reef restoration projects along more than 1005 km of shorelines of the state of Florida and the Commonwealth of Puerto Rico, US, at a 10-m^2 resolution. To do this, we used multidecadal wave and coastal water–level data; high-resolution bathymetric, topographic, and benthic habitat data; and physics-based, numerical hydrodynamic models to resolve the nonlinear wave and coastal water–level processes and quantify the effect of potential coral reef restoration on coastal flooding (see Materials and Methods). Water depths and flood zones were used to determine the people, number of buildings, and direct and indirect economic impacts, with current reefs and with theoretically restored reefs. The risk reduction benefits of hybrid restoration projects were calculated as the averted impacts assuming potential restoration that could produce a 1.25-m increase in reef height and increased hydrodynamic roughness representing over 5 m in the cross-shore direction, emplacing a 1-m–high artificial base structure and outplanting new, 0.25-m-high corals on top of the structure. The results provide (i) a direct quantification of the benefit-to-cost ratios (BCRs) of restoring reefs using hybrid methodology at regional scales, (ii) the role of geomorphology and coastal community structure on patterns of socioeconomic risk reduction, and (iii) insights into equity dimensions of nature-based adaptation investments along the contrasting geographies and socioeconomics of the state of Florida and the Commonwealth of Puerto Rico.

RESULTS

Coral reefs' hydrodynamic roughness and height cause increased friction and wave breaking that prevents coastal flooding from extending farther inland, as demonstrated for the 100-year storm's flood hazard zone with current coral reefs and with potentially restored hybrid reefs (Fig. 1A). The averted impacts to people (Fig. 1B) and combined direct damage to buildings and indirect economic disruption (Fig. 1C) in the zones protected by the potential restoration were assessed at a 10-m grid resolution. Potential flood mitigation would occur along most of the study regions. Flooding generally originates from low points in the coastline, such as depressions in dunes or stream mouths, and spreads inland along lower areas, often roads or upstreams and other drainages. In the case of both current reefs and potentially restored reefs, the area closest to the coast is flooded; however, the area receiving the most protection from coral reef restoration is not the beachfront areas, which still flood, but rather the areas farther inland. As discussed later, this pattern has important economic and social vulnerability implications.

Geophysical controls on flood risk

There is high spatial heterogeneity in the hazard risk reduction provided by potential hybrid coral reef restoration (Fig. 1). In many cases, there are no people and/or infrastructure onshore of the restoration sites or the people and/or infrastructure are at high elevation, and therefore, there is no potential socioeconomic risk reduction. However, in places where coral reef restoration reduced the socioeconomic risk, three primary geophysical factors control coastal flooding mitigation potential (characterized here as the greatest reduction in total water levels from the joint action of storm surge and wave-driven setup and run-up). First, coral reef restoration is significantly (n = 4023, r^2 = 0.185, $P < 0.0001$) more effective in reducing flooding potential on narrower reef complexes than broader ones (Fig. 2A) because much broader reefs attenuate more wave energy by dissipation across their width; thus, the relative contribution of a 5-m-wide restoration area on a reef thousands of meters wide is relatively negligible. Next, restoration projects are significantly (n = 4023, r^2 = 0.102, $P < 0.0001$) more effective in reducing coastal flooding potential when situated closer to shore (Fig. 2B) for similar reasons as for reef complex width. Last, restorations are significantly (n = 4023, r^2 = 0.091, $P < 0.0001$) more effective in reducing coastal flooding potential when situated at shallower water depths (Fig. 2C), because the effective increase in height (+1.25 m) of the modeled restorations represents a greater proportion of water depth relative to shallower waters and thus drives greater depth-induced wave breaking than at greater water depths. Together, these patterns indicate that coral reef restorations closer to shore in shallower water depths on narrower reefs are generally more effective at reducing coastal flooding potential than deeper ones farther from shore on broader reef complexes.

Coastal flood risk reduction provided by coral reef restoration

Along 1005 km of shorelines of the state of Florida and the Commonwealth of Puerto Rico, potential hybrid coral reef restoration would cause the 100-year coastal flood zone to decrease by 19.7 km^2, protecting 14,734 persons, $1.006 billion in property, and $797 million in economic activity (2023 US dollars). This scenario would reduce the risk to people by 18.6%, property damage by 20.4%, and economic disruption by 14.9% less. Across the study area, potential coral reef restoration would cause the 1-in-100-year flood damages to occur 20% less frequently.

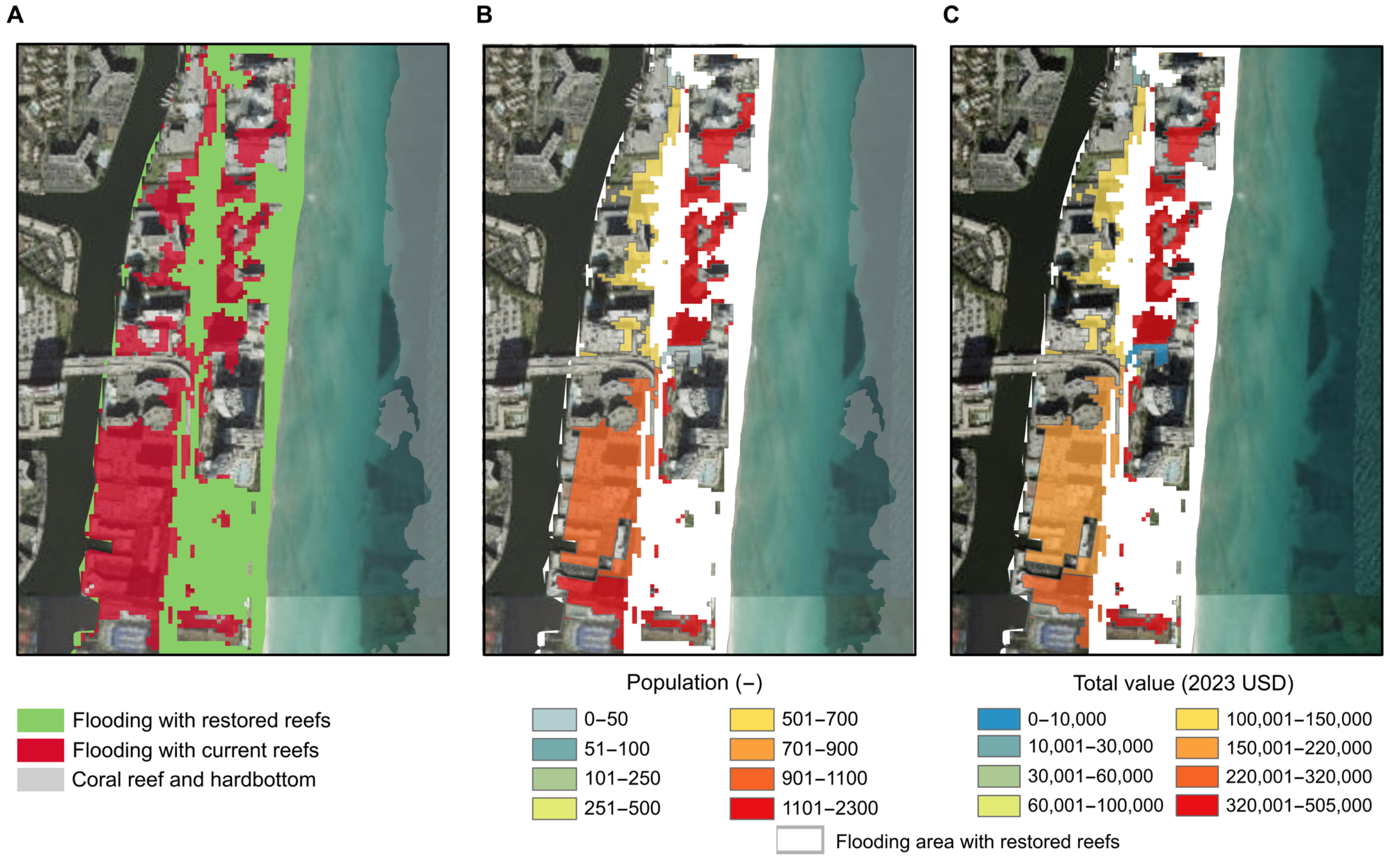

Fig. 1. Example maps of modeled coastal flooding in Miami, Florida, during the 100-year storm with current coral reefs and potentially restored coral reefs. (**A**) Flood extents with current reefs (red) and restored reefs (green). Thus, the red area denotes the region protected by potential reef restoration. (**B**) Number of people protected by reef restoration (colors). (**C**) Total value, in 2023 US dollars, of building damages and economic disruption adverted by reef restoration (colors). The storm-induced coastal flooding with restored coral reefs is smaller in area, thus affecting fewer people, buildings, and associated economic activity. USD, US dollars.

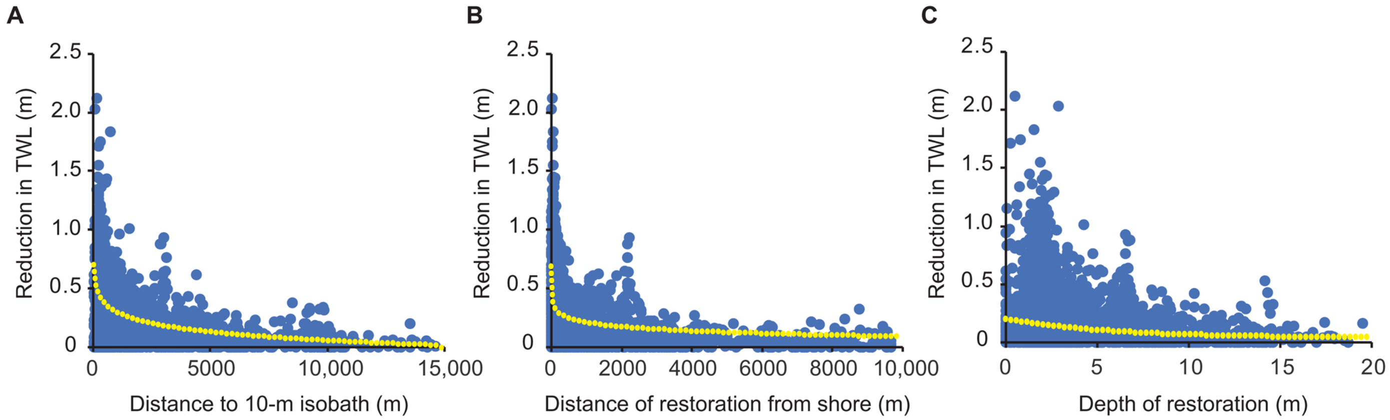

Fig. 2. Influence of coral reef morphology and location of a restoration on flood risk reduction potential, as denoted by total water levels (TWL; storm surge plus wave setup and run-up) at the coastline. (**A**) Distance to the 10-m isobath, an indicator of width of the reef complex. (**B**) Distance of restoration from shore. (**C**) Depth of restoration. Yellow lines are statistically significant ($P < 0.0001$) logarithmic regressions denoting trends in the results. Although there is high variation in flood risk reduction potential for coral reef restorations on narrow reef complexes at shallow depths close to shore because of variations in wave processes, the effectiveness of restorations drops off markedly with increasing width of the reef complex and depth and distance of the restoration from shore.

The averted flood impacts were integrated across the 10-, 50-, 100-, and 500-year storm return intervals to calculate the annual risk reduction benefits provided by potential coral reef restoration. The expected annual benefit (EAB), in terms of the annual number of people that could gain protection because of potential coral reef restoration, is 2249 (+13.0%) in Florida and 924 (+21.3%) in Puerto Rico (Table 1). The EAB, in terms of the annual value of buildings that could gain protection from potential coral reef restoration, is \$161 million (+14.2%) in Florida and \$20 million (+24.6%) in Puerto Rico. The EAB, in terms of the annual value of economic activity that could gain protection because of reef restoration, is \$174 million (+12.2%) in Florida and \$36 million (+22.1%) in Puerto Rico. The total EAB, adding direct damages and economic activity protected from coastal storm flooding by potential coral reef restoration, is \$335 million in Florida and \$56 million in Puerto Rico. Sectorally, the public would benefit relatively more (+0.7% public versus +0.2% private) from coral reef restoration in Florida, whereas the private sector would benefit more (+3.6% public versus +51.9% private) from restoration in Puerto Rico.

The EABs for people (Fig. 3, A and B) and the total economic value (Fig. 3, C and D) protected by potential coral reef restorations are concentrated along specific coastal areas across the regions' reef-lined shorelines, generally around low-lying population centers. The spatial distribution of benefits and the communities most protected demonstrate important differences between social and economic benefits. The average people and dollars protected per kilometer annually for the different regions, including undeveloped areas, varied from 0.002 and \$182 on Culebra and Vieques, respectively, to 0.057 and \$8834 in the Florida Keys, 0.201 and \$12,180 on Puerto Rico, and up to 0.926 and \$137,382 on the Florida mainland and adjacent barrier islands (Fig. 3 and Table 1).

At the regional scale (order of approximately hundreds of kilometers), the hazard risk reduction savings provided by coral reef restoration along Florida and Puerto Rico are >\$378 million/year, but at the local scale (order of ~10 m^2), the results demonstrate that there are numerous individual stretches of reef where restoration could help reduce future needs in adaptation and hazard mitigation. The economic value of potential coral reef restoration is the greatest along high-value, intensively developed, low-lying coastal areas, such as Miami, Florida, and San Juan, Puerto Rico (Fig. 3, C and D).

BCA of coral reef restoration

The costs of restoration in general, and hybrid reef restoration in particular, are highly variable. Across the Caribbean, there is high spatial variability in labor and production costs and there is a paucity of pilot projects. Now, the core construction costs of reef restoration have been demonstrated (*6*, *18*) to range from \$0.5 million/km to \$3 million/km, with a mean cost under \$2 million/km.

We used \$3 million/km, in 2023 US dollars, as our estimate hybrid reef restoration, which we believe is conservative, and below, we provide a further breakdown of costs and uncertainties. Because large-scale hybrid reef restoration is rare, maintenance costs are uncertain. While maintenance is expected to increase costs, it is also reasonable to expect economies as the scale of projects increases and practices improve. For example, the costs of outplanting corals are already decreasing. We base our hybrid cost estimates on more

Table 1. Distribution of Expected Annual Benefit (EAB), in terms of the annual number of people, buildings, economic activity, or total value of gained protection because of potential coral reef restoration and length of coastline where EAB exceeds specific thresholds.

Location	Sublocation	Length of coast (km)	Number of people (—)	Building damages (2023 USD)	Economic activity (2023 USD)	Total value (2023 USD)	Length of coast where restoration value >\$250,000 present value (km)	Length of coast where restoration value >\$3,000,000 total value (km)
Florida	Martin	37	16	\$2,238,526	\$1,091,418	\$3,329,943	6 (16%)	0 (0%)
Florida	Palm Beach	75	880	\$55,754,565	\$62,134,096	\$117,888,660	36 (48%)	9 (12%)
Florida	Broward	39	524	\$52,079,420	\$48,231,281	\$100,310,701	31 (79%)	8 (21%)
Florida	Miami-Dade	61	717	\$43,593,640	\$51,831,864	\$95,425,504	22 (36%)	9 (15%)
Florida	Upper Keys	67	38	\$3,611,296	\$3,867,300	\$7,478,596	14 (21%)	4 (6%)
Florida	Middle Keys	47	5	\$2,407,644	\$351,702	\$2,759,347	3 (6%)	0 (0%)
Florida	Lower Keys	54	69	\$1,433,639	\$5,751,287	\$7,184,926	6 (11%)	0 (0%)
Puerto Rico	San Juan	40	243	\$4,097,860	\$11,528,794	\$15,626,654	13 (33%)	2 (5%)
Puerto Rico	Vega Baja	44	88	\$3,787,127	\$3,252,428	\$7,039,556	9 (20%)	1 (2%)
Puerto Rico	Arecibo	49	171	\$2,568,499	\$6,388,837	\$8,957,336	10 (20%)	0 (0%)
Puerto Rico	Aquadilla	69	218	\$5,102,887	\$8,084,154	\$13,187,041	14 (20%)	1 (1%)
Puerto Rico	Mayaguez	69	90	\$1,274,119	\$3,570,813	\$4,844,932	10 (14%)	0 (0%)
Puerto Rico	Ponce	66	36	\$227,132	\$1,357,931	\$1,585,063	11 (17%)	1 (2%)
Puerto Rico	Guayama	64	34	\$664,511	\$1,254,889	\$1,919,400	9 (14%)	0 (0%)
Puerto Rico	Humacao	54	11	\$135,043	\$425,074	\$560,116	2 (4%)	0 (0%)
Puerto Rico	Ceiba	75	30	\$1,032,959	\$1,106,347	\$2,139,306	10 (13%)	0 (0%)
Puerto Rico	Culebra	26	1	\$37,643	\$43,105	\$80,748	0 (0%)	0 (0%)
Puerto Rico	Vieques	70	1	\$39,270	\$51,965	\$91,235	0 (0%)	0 (0%)

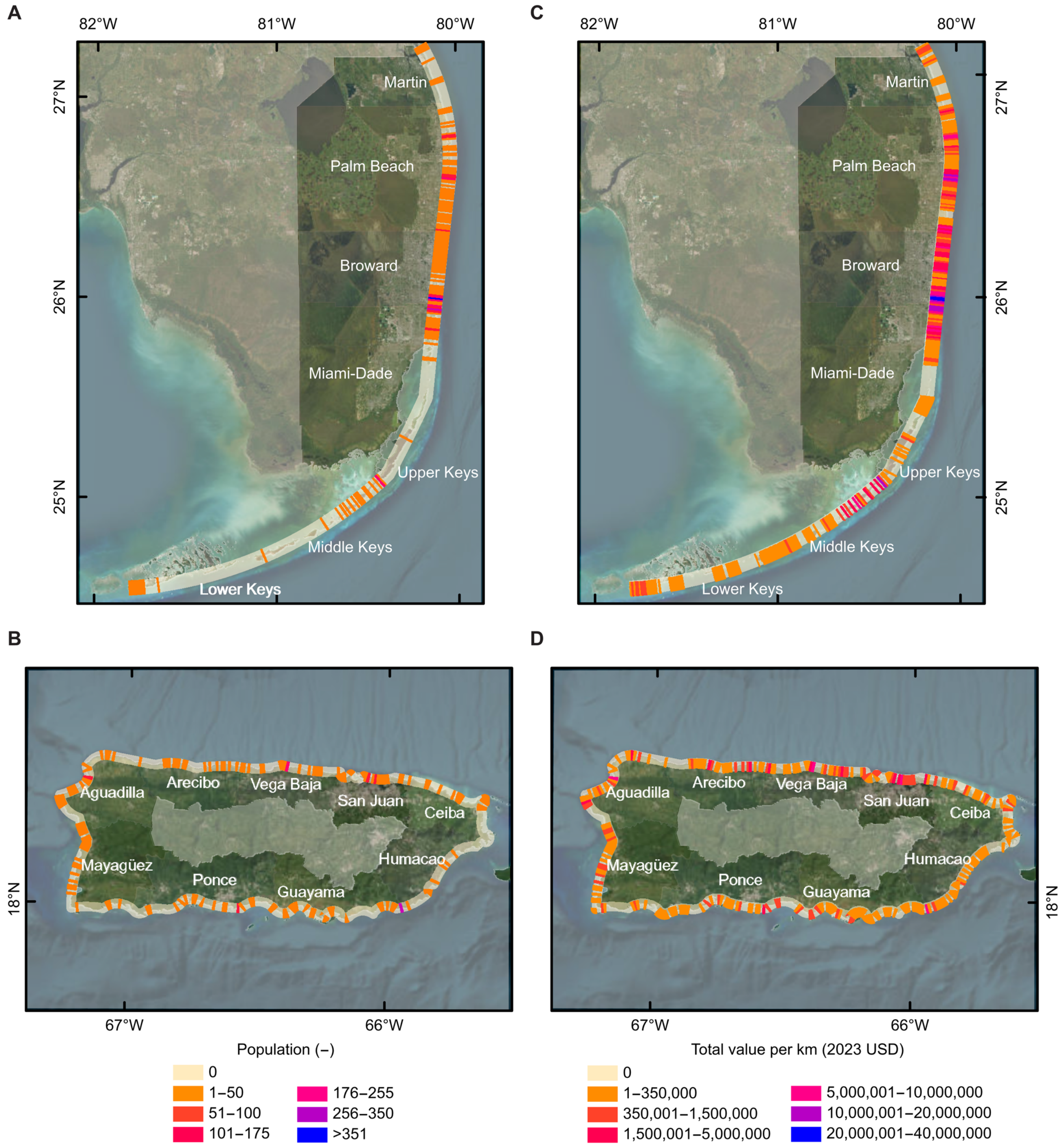

Fig. 3. Protection provided, per kilometer, from coastal flooding annually by potential coral reef restoration. (**A**) Total number of people protected in Florida. (**B**) Total number of people protected in Puerto Rico. (**C**) Total value, in 2023 US dollars, protected in Florida. (**D**) Total value, in 2023 US dollars, protected in Puerto Rico. Note the nonlinear color bar scales. Although there is high heterogeneity alongshore because of the distribution of housing and infrastructure, in general, there is a greater number of people potentially protected and greater damage and economic disruption potentially adverted by restored coral reefs in Florida than in Puerto Rico because of the lower-lying nature of the coastline that allows for greater inland flooding.

traditional concrete molds while noting that many current projects are focusing on three-dimensional concrete printing, which is likely to be substantially more cost efficient.

Presently, concrete base structures such as Reef Balls are $450 per unit (*26*). On the basis of 1.4-m-wide units at a 1:1 unit spacing, that would require six units to cover a 5-m-wide cross-shore and 5-m alongshore expanse, 1200 units/km to cover a 5-m-wide extent as modeled here, or $0.54 million/km of base structure. Assuming deployment costs similar to those (*27*) of 120 to 130% of structure production costs, that translates to $0.65 million/km to \$0.70 million/km to deploy hybrid base structures. Recent estimates from Florida as part of National Oceanic and Atmospheric Administration (NOAA)'s Mission: Iconic Reefs initiative indicate that the cost of restoration per *Acropora palmata* fragment is ~\$25 (*28*). At five outplants per unit (one on each side and one on top) on 1200 units/km, that would be 6000 outplants/km at \$25 per outplant, thus \$0.15 million/km to outplant *A. palmata* fragments on the deployed hybrid base structures.

Given a \$1.39 million deployment cost estimate (\$0.54 million/km for construction, \$0.70 million/km for deployment, and \$0.15 million/km to outplant corals) and our \$3 million/km estimate used here, that would leave \$1.61 million/km for maintenance costs, which would allow for multiple outplantings and maintenance of structures. Thus, we feel that the restoration break-even value of \$3 million/km used in our analyses is conservative, even including maintenance costs to make up for structural repairs and coral mortality because of thermal stress and/or disease.

Hybrid coral reef restoration projects for flood protection would be sited to maximize flood mitigation in a given area (*13*, *25*), which means that the average BCRs per kilometer of coastline (Fig. 4) likely underestimate the values that would be achieved from a specific restoration investment. Many of the 1-km sections have restoration benefits that exceed \$0.25 million/km per year, which results in a present value benefit of more than \$3 million/km over a 30-year investment lifespan at a 7% discount rate; this discount rate had been used by the US Army Corps of Engineers and US Federal Emergency Management Agency (FEMA) for decades, but it has recently been lowered to 3%, thus making the BCRs presented here conservative. This 30-year lifespan is conservative for infrastructure projects; for FEMA, the standard value for the useful life of flood infrastructure projects is 50 years (*29*).

If we assume conservatively that restoration will be \$3 million/km, then any projects with a present value greater than \$3 million/km (over a 30-year period at a 7% discount rate) would yield projects with BCRs >1. We identify projects with BCRs >1 as having a positive return on investment and as "cost effective"; there are many cost-effective potential project sites across the reef-lined coasts of Florida and Puerto Rico. Furthermore, there is new US federal guidance being evaluated that would lower discount rates for nature-based projects to 3%, which would result in many more restoration projects with positive returns on investment (*30*). Although the flood protection benefits are highly variable and widespread across these regions, restoration of 35 km (3%) of the regions' coral reefs is projected to have BCRs >1 in just 1 year (annual benefits exceeding the total cost of implementation) and thus could provide an immediate, positive return on investment (Fig. 4, A and B). Furthermore, restoration of more than 206 km (20%) of coastline would be cost effective, with BCRs >1 considering a 30-year project life and a 7% discount rate (*31*). The results demonstrate high immediate, as well as long-term, returns.

Distribution of social and economic benefits of reef restoration

The different geomorphologies, geographies, and social and economic patterns drive substantial differences between the absolute and relative socioeconomic risk reductions provided by potential coral reef restoration in Florida and Puerto Rico. In general, Florida is lower lying and has greater concentrations of people with higher real asset value and average gross domestic product (GDP) near the coast than in Puerto Rico, where the coastal zone is generally at higher elevation, the people are farther from the coast, and buildings have lower economic values. These coastal development patterns result in differences in who could benefit most from coral reef restoration when comparing absolute and relative changes in risk reduction to people, buildings, and economic activity (Fig. 5A). The results indicate that Florida could receive the greatest overall social and economic benefit in terms of people protected (243%), averted damages (849%), and economic interruption (467%), whereas Puerto Rico would benefit relatively more from coral reef restoration compared to its current level of risk to people (164%), buildings (444%), damages (173%), and economic interruption (181%). In both cases, the sites with the highest BCRs exist off locations of human populations, which generally are more affected by anthropogenic activities (*10*) and thus are likely candidates for restoration.

Demographics of risk reduction provided by coral reef restoration

As noted previously, the coastal zone areas receiving the most flood protection by potential hybrid coral reef restoration are not the beachfront, areas that often flood, but rather areas farther inland. Our examination of the effects of these cross-shore variations on the decrease in coastal flooding risk because of potential coral reef restoration for minorities, children (<16 years), the elderly (>65 years), and those below the poverty line relative to the overall population values demonstrates that people in all four of these categories would receive greater protection relative to the overall population (>239, >326, >261, and >256%, respectively), with most effects double or triple of the general population (Fig. 5B). This is explained by, as in most places, the strong gradients that exist in human demographics along the coast between those living in high-income structures versus those that live farther inland. These results demonstrate that coral reef restoration would provide greater protection from storm-driven coastal flooding to minorities and vulnerable people, typically at greater risk to natural disasters.

In comparison with the BCRs in purely economic terms, the results indicate significant differences in the return of investment for developed, built-up areas compared to protection of the most vulnerable people. However, the demographics of who benefits from existing coral reefs that serve as natural infrastructure (*12*) versus those who could benefit from reef restoration (Fig. 5) are stark and remain to be considered in risk hazard mitigation decisions.

DISCUSSION

This study represents the first valuation of nature-based coastal protection scenarios to identify and prioritize potential restoration sites at regional scales, which is of increasing interest around the globe (*31*, *32*). The socioeconomic valuations can help identify where to invest into restoration to address economic risks (*13*), climate justice, and social equity gaps and additionally can also help connect restoration planning to potential funding mechanisms (*33*). Comparisons of potential coastal adaptation benefits provided by the restoration of coral reefs can guide prioritization of restoration planning and implementation as a climate adaptation investment. Such assessments of benefits also provide a benchmark to assess future evaluations of the effectiveness of coral restorations after implementation as nature-based solutions to help communities reduce their risk to coastal hazards after implementation. Because most restoration projects do not

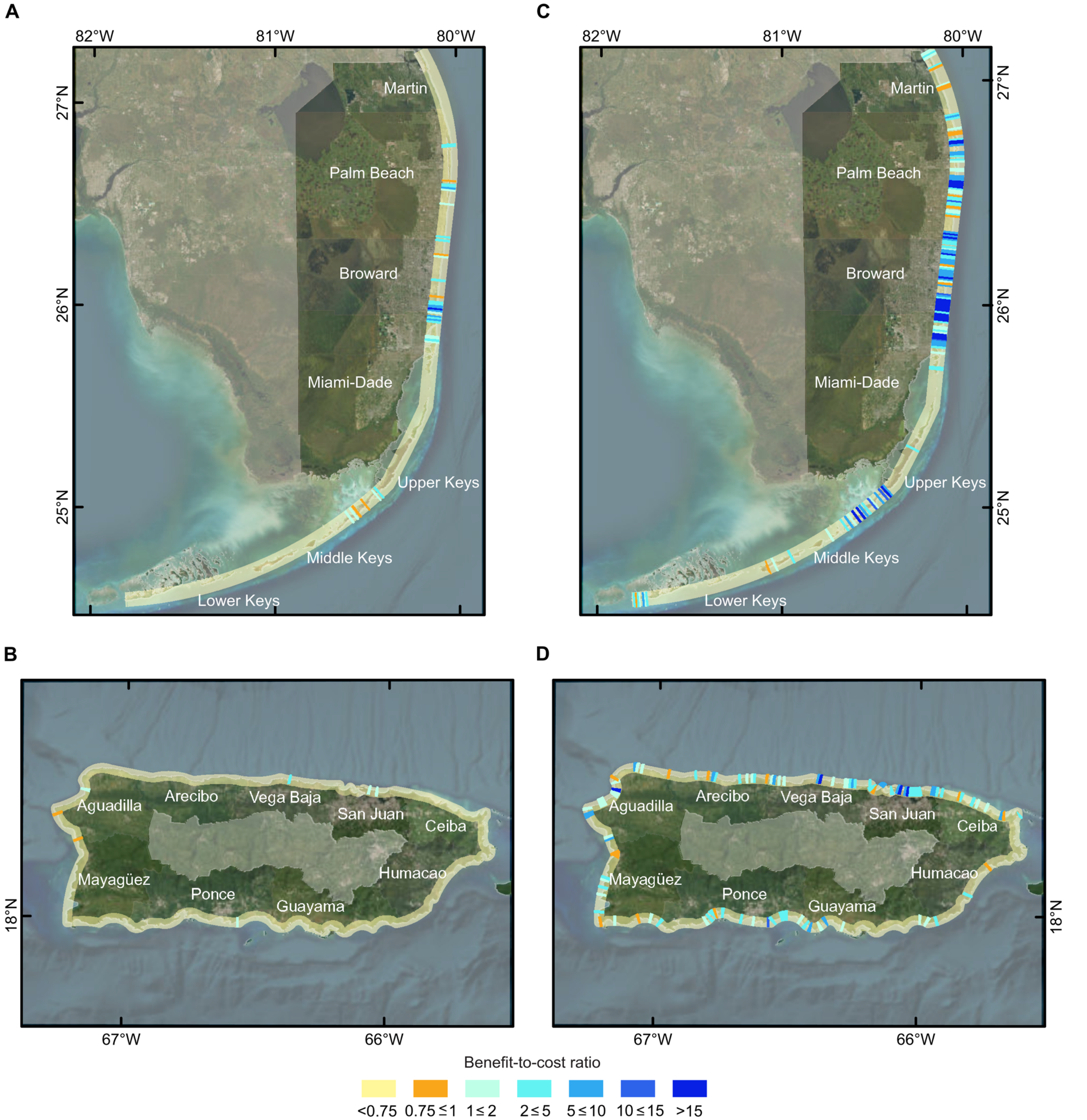

Fig. 4. Benefit-to-Cost Ratios (BCRs) of flood risk reduction of coral reef restoration, per kilometer. BCRs for an immediate return, or average annual benefit in 1 year after restoration, based on a $3 million/km restoration cost for (**A**) Florida and (**B**) Puerto Rico. BCRs over a 30-year lifespan, at a 7% discount rate, for (**C**) Florida and (**D**) Puerto Rico. Note the nonlinear color bar scales. Although the flood protection benefits of coral reef restoration are highly variable and widespread across these regions, areas projected to have BCRs >1 are therefore cost effective and would provide a positive return on investment.

take a quantitative, spatial perspective on predicting where the greatest return on investment will be for the diverse outcomes that are desired today, this study thus represents not only a model for coral ecosystem restoration but also other coastal ecosystems such as dunes, marshes, mangroves, and oyster reefs. The results shown here are modeled projections over a regional scale that indicate how and where to prioritize restoration within a region. It is recommended that finer-scale models are implemented to demonstrate how potential restoration locations at a local scale could influence effectiveness to meet restoration and coastal protection goals (*13*).

Overall, the greatest coastal flood hazard risk reductions of hybrid coral reef restoration projects occur at shallow depths, close to

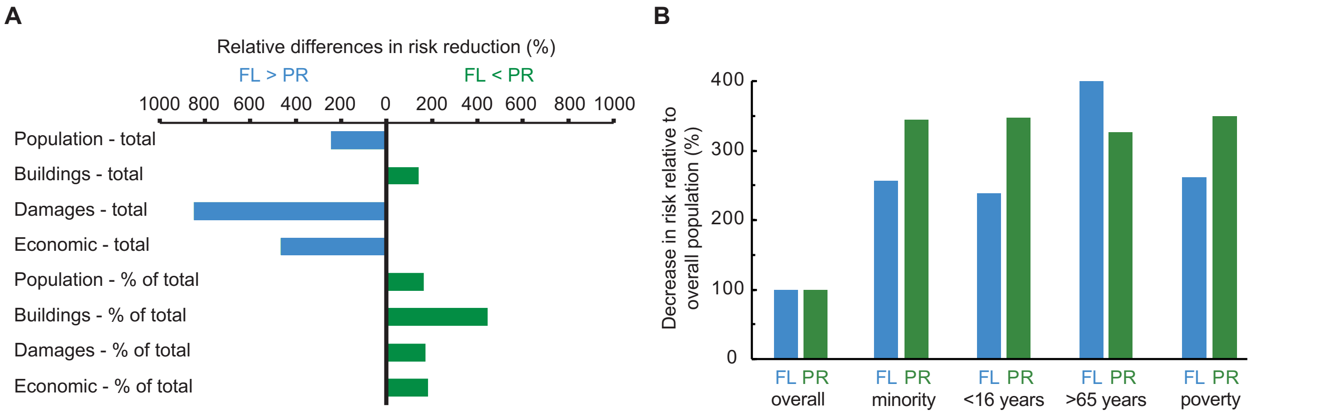

Fig. 5. Differences in coastal flood risk reduction provided by potential coral reef restoration between Florida (FL) and Puerto Rico (PR) for different socioeconomic factors. (**A**) Difference in absolute and relative change in coastal flooding risk reduction to people, buildings, and economic activity. These results demonstrate that although Florida would receive the greatest overall hazard risk reduction benefit from potential coral reef restoration in terms of people protected and averted damages to buildings and economic activity, Puerto Rico would benefit relatively more from potential restoration compared to its current risk from coastal flooding. (**B**) Percent decrease in coastal flooding risk relative to the overall population values for different social and economic categories. The categories are children (<16 years), the elderly (>65 years), minorities, and those below the poverty line. All categories have a greater decrease relative to the overall population, with most double or triple the general population. These results demonstrate that coral reef restoration would provide disproportionately greater protection to the most vulnerable people typically at greater risk to natural disasters such as storm-driven coastal flooding.

shore, on relatively narrow reefs fronting low-lying coastlines. These results provide a first-order screening guide to help assess where coral reef restoration would provide the ecosystem service of hazard risk reduction to coastal communities. For example, the coral reef restoration efforts that are kilometers offshore, such as the fore reefs of the Florida Keys as part of Mission: Iconic Reefs (*34*) or Australia's Great Barrier Reef (*35*), will likely not provide substantial hazard risk reduction services. There are numerous reasons (e.g., biodiversity, fisheries, tourism, and recreation) to restore coral reefs, but the areas to restore coral reefs for these ecosystem services may not align with those for hazard risk reduction (*13*).

Given the regional scale and the purpose of the analysis, here, we assume long sections of potential reef restoration. However, it is possible to deliver coastal protection benefits with much shorter sections of reefs on the basis of evidence from existing reef projects and artificial low-crested, submerged breakwaters. Coastal morphology (e.g., embayments and headlands) plays a huge role in project design and length, as does the distance to reef habitat offshore (Fig. 2). On the basis of coastal engineering analyses of detached breakwaters, the optimal breakwater length for reducing coastal erosion is, in general, on the order of two-thirds its distance offshore (*36*) for the farther offshore, and the shorter it is, the more it would allow waves from different (non-normal) directions and refraction around the structure. Current successful examples of hybrid coral reef restorations that have reduced wave energy and coastal erosion range from only ~0.1 km off the Marriott on Grand Cayman and ~0.27 km off Maiden Island, Antigua, to ~0.55 km off Carretera Bayahibe, Dominican Republic (*26*). Off San Juan, Puerto Rico, the FEMA-funded reef restoration project (*37*) will be 5 km long.

Thus, hybrid coral reef restoration/enhancement efforts on the scales modeled here on the order of hundreds to thousands of meters in length have already been deployed or funded for deployment, and governments and businesses have invested in completely artificial breakwater coastal protections over tens to hundreds of kilometers in Europe and Asia for centuries. With increasing risks from coastal development and climate change, the needs for coastal protection of one form or another will grow over very large sections of coastline. As the efficiency of development and deployment of such hybrid restoration reefs lessens with increasing scale (*27*), the probability of larger (longer, order of tens of kilometers) deployments does not seem far off, especially because the costs described here for hybrid coral reef restoration are half to an order of magnitude lower than traditional detached breakwaters (*6*) used for coastal protection while also providing numerous other benefits (e.g., fisheries and tourism) not quantified here.

In terms of cross-shore scale, as noted in numerous previous designs (*26*, *27*), a 5-m width in the cross-shore direction can be sufficient to induce wave breaking and thus dissipate enough energy (on the scale of natural reefs) to reduce flooding and create a hazard risk reduction benefit sufficient to feed BCAs. For example, a pilot in the Caribbean included modular units of more than 1 m high and 5 m wide that were specifically designed for erosion control and wave attenuation (*7*). However, the numerical model used here is sensitive to the number of grid elements able to represent effects on the hydrodynamics. Therefore, we consider the sensitivity of the model to include a minimum number of grid cells to represent the effect of the structure on the hydrodynamics. For a local engineering study, the resolution of models will be finer and narrower structures may be considered.

Environmental justice implications

A previous study exploring equity and coastal flooding exposure has examined the socioeconomics of flood risk and finds that minority and vulnerable populations are disproportionately exposed to hazards (*38*). Another study demonstrates that coral reef loss would disproportionately affect minorities and the most vulnerable (children, the elderly, and low-income) people in the US, particularly in the territories (*12*). However, these results offer first insight into how different hazard risk mitigation could prioritize return of investment by factoring economic BCRs compared to vulnerable people protected per dollar spent. On the basis of that previous finding (*12*) and because Puerto Rico has almost double the percentage of minorities [82.9% versus 47.1%, per (*38*)] but less than half the GDP per capita [$31,429 versus $63,081, per (*39*)] than Florida, we explored whether there are significant socioeconomic differences in the protection provided by potential coral reef restoration.

Furthermore, results demonstrate that hybrid reef restoration can provide much greater risk reduction to the private sector in Puerto Rico than in Florida because of the greater proportion of minorities with, in general, lower incomes. We also demonstrate that minorities and the most vulnerable people (children, the elderly, and those below the poverty line) could receive two to three times more protection from flooding by coral reef restoration relative to the general population in both the overall more affluent Florida, likely because of existing spatial trends in coastal flood risk inequities identified there (*38*), and Puerto Rico. On the basis of an assessment of population distribution and trends in coral reef–lined areas (*40*), the socioeconomic patterns described here are likely to be similar at a global scale (*10*). Our results indicate that investments in coral reef restoration could be a well-targeted help to contribute to environmental justice and social equity by reducing coastal flood hazard risk to, and increasing the resiliency of, those underrepresented and often underserved, vulnerable communities both in the US and around the globe (*38*).

Implications for risk mitigation strategies

The finding that potential hybrid coral reef restoration could reduce the 100-year storm's risk by 20% (Fig. 4) has also especially important implications for policy-makers and property owners in coral reef–lined coastal communities. The impact of the 100-year storm's flood zone is a long-standing metric to evaluate the possibility of an area being flooded (*41*), guides planning and development decisions, and sets financing and insurance rates in the US. For a property in the 100-year flood hazard zone (i.e., 1% chance of flooding in any given year), the probability of being flooded once in a 30-year period (a typical mortgage) is 26% (*12*). Coral reef restoration could reduce the likelihood of flooding during a 30-year mortgage period by more than one quarter (27%). This reduction in risk demonstrates how coral reef restoration can be an effective nature-based solution to reduce risk to many communities.

Our analyses identify where potential coral reef restoration could provide particularly high economic flood protection benefits. Coral reef restoration has been traditionally supported by the comparatively limited public and private funding for environmental conservation (*38*). However, funds for disaster management/recovery are orders of magnitude larger than funds for habitat conservation and restoration (*42*). Valuing coral reefs and their restoration for risk reduction services can allow increased funding opportunities for reef managers. For example, to qualify for predisaster hazard mitigation funding or postdisaster restoration funding, BCAs are often required to demonstrate that hazard risk reduction benefits are equal to or greater than the cost of the restoration activity.

A significant shortcoming of these BCAs is that there are little data on opportunity costs or maintenance costs for coral restoration projects, which are of a concern with increasing thermally induced coral bleaching; almost all the projects only report the initial or direct investment costs (*27*). The hybrid structures would be composed of both structural and ecological components, so the assumptions about the failure of restoration at large scales will still be supported by the enhancement of structural features. Also, substantial efforts are being made to develop corals more resilient to thermal and other stressors (*14*–*15*) and it is assumed those would be part of the outplanting mix, further reducing replacement costs. Last, we were conservative in almost all of the other modeling assumptions and we did not include other cobenefits such as tourism and recreation, which can significantly increase the value of restoration project benefits in BCAs.

These analyses are not meant to demand action everywhere but rather to prioritize where to act, which is to any management or conservation prioritization. We identify where to find cost-effective opportunities and priorities for restoration. All the costs identified in the review above are very small relative to the investments already being made to protect coastlines artificially. If there was sufficient financial support, restoration groups and businesses would rise to the nursery and planting challenge: Many programs are already outplanting more than 10,000 corals a year (*34*, *35*) and rapidly increasing in their efficiency, output, and robustness (*14*–*15*) of outplanted corals. As noted previously, if those restorations are close to shore and in shallow depths, they can reduce coastal flooding risk enough to meet hazard risk reduction guidelines (*29*, *30*).

Implications for new funding mechanisms for coral reef restoration

The results presented here show that hybrid coral reef restoration can be a cost-effective strategy for flood mitigation. Furthermore, it enables BCAs that would open new financing opportunities not previously available to reef managers, such as hazard mitigation, disaster recovery, and insurance (*43*, *44*). First, because coral reefs protect people and state, territorial, and national infrastructure from flooding, national agencies (e.g., FEMA and/or the US Army Corps of Engineers) could fund reef restoration through such mechanisms as predisaster hazard mitigation funds such as the $550 billion US 2020 Bipartisan Infrastructure Law. Second, disaster recovery funding, such as the billions of dollars appropriated by the US for recovery from the 2017 hurricanes (with ~$10 billion specifically for coastal flood prevention projects against hurricanes), could support reef restoration for building coastal community resilience. For example, the data presented here are being used by FEMA and NOAA to help identify sites in Puerto Rico where postdisaster recovery funding could be dedicated to restoring coral reefs to prevent future coastal flood damages. Last, the insurance industry can support reef restoration by insuring their coastal protection service, as first piloted in the Mesoamerican Reef (*45*) and now the state of Hawaii (*46*), or through new resilience insurance mechanisms for coral reef restoration projects (*44*, *47*).

Globally, many coral reef–lined tropical coasts are among the most susceptible to climate impacts from rising sea levels and increased storm action (*8*) and are the home to vulnerable, underserved minority communities (*10*). In many of these tropical nations that face national budget limitations for investing in coastal adaptation, coral reef restoration can become a local and more cost-effective method for coastal flood hazard mitigation than traditional hard, "gray" infrastructure (*6*). This is because, unlike levees and seawalls, whose costs increase nonlinearly with sea-level rise because the base of the structures must be disproportionally higher to increase the height of a structure while maintaining structural integrity, coral reefs can grow with rising sea levels to maintain their coastal protection function without additional future costs. Coastal communities, especially those with minority and vulnerable populations, could adapt this methodological approach to assess the cost effectiveness and possibly fund coral reef restoration on the basis of risk metrics, which could be combined with other ecosystem service valuations to better account for their natural capital and infrastructure as part of their economies (*48*). In many of these coastlines, coral reef restoration, as a nature-based solution, could be one cost-effective strategy to reduce risk, increase resiliency, and adapt to climate change to achieve environmental justice by addressing social equity issues.

MATERIALS AND METHODS

General methodology

The goal of the modeling approach was to quantify the flood risk reduction benefits of potential hybrid coral reef restoration in social and economic terms, at local scales, and with the greatest spatial granularity possible to inform local reef and coastal management decisions. For this, we combined engineering, ecologic, social, and economic models (*49*) to provide a quantitative valuation of the coastal protection benefits of potential coral reef restoration off the state of Florida and the Commonwealth of Puerto Rico, US.

The analysis is based on a risk quantification valuation framework that considers different storm probabilities and calculates EABs in social and economic terms (*11*, *12*). We used state-of-the-art, high-resolution flood modeling and damage calculation based on data and approaches recommended by FEMA (*50*, *51*). The risk modeling framework (*11*, *12*) integrated dynamic and hybrid wave downscaling of more than 61 years of data; extreme sea-level and storm-wave probability analysis; physics-based reef hydrodynamic and coastal flood modeling; geospatial analysis; and calculation of people, buildings, and direct and indirect economic flood damages. The approach determined flood hazard zones and the effect of restored coral reefs on them. The averted economic and social consequences were calculated from the differences between flood zones with and without restoration. The main steps of the methodological approach are described below.

Projecting the coastal hazards

Wave data covering the period 1948–2008 were obtained from the calibrated long-term, hourly hindcast Global Ocean Wave database (*51*). The offshore wave data were synthesized into 500 combinations of sea states (wave heights, periods, and directions) that best represented the range of offshore conditions using a maximum dissimilarity algorithm (*52*). The selected sea states were propagated within 200 m of shore using the physics-based Simulating Waves Nearshore (SWAN) spectral wave model (*53*). SWAN is a wave-averaged spectral action model that can accurately simulate wave propagation around reef-lined coasts (*54*–*56*). Standard SWAN settings (*54*) were used, but the directional spectrum was refined to 5° bins to better handle refraction and diffraction in and among islands. We used two levels of dynamically downscaled nested grids to accurately capture the propagation effects from regional scales (approximately tens of kilometers) down to management scales (~100 m). Details of grid, configuration, resolutions, and bathymetry sources are provided in (*57*). The propagated shallow-water wave conditions were extracted at 100-m intervals along the coastline at a water depth of ~30 m (fore reef) and reconstructed 61-year hourly time series using radial basis functions (*52*).

Ecosystem and flood modeling

The effect of hybrid coral reefs on hydrodynamics was simulated with a nonlinear wave model previously tested and validated for reef environments (*24*) on the basis of cross-shore transects created every 100 m alongshore. The coastal transects were defined using the Digital Shoreline Analysis System software version 4.3 in ArcGIS version 10.3 (*58*). Transects were cast in both landward and seaward directions using the smoothed baseline cast method with a 500-m smoothing distance, perpendicular to a baseline coastline digitized from US Geological Survey 1:24,000 quadrangle maps and smoothed in ArcGIS using the polynomial approximation with the exponential kernel algorithm and a 5000-m smoothing tolerance. Transects varied in absolute length so that each crossed the −30- and +20-m elevation contours. The bathymetric and coral coverage data were extracted along these shore-normal transects with a 1-m horizontal grid-cell resolution. The location of nearshore coral reefs and restorable hardbottom to site the potential restorations and their relative coral abundance to fine their hydrodynamic roughness were obtained from benthic habitat maps of coral cover percentage and spatial extent (*59*, *60*).

The hydrodynamic forcing for the hydrodynamic model was calculated for the 10-, 50-, 100-, and 500-year storm return periods by fitting a general pareto distribution (*61*) to each hourly significant wave height at the offshore ends of the shore-normal transects. Extreme water levels, which include the effect of tropical cyclones, with the same recurrence were taken from the nearest NOAA tidal station (*62*). The hydrodynamic forcing for each return period was then propagated over each shore-normal transect using the numerical model XBeach (*63*, *64*). XBeach solves the depth-averaged, nonlinear shallow-water equations and provides water-level variations up to the scale of infragravity long waves. XBeach has been advanced and successfully applied in reef environments to accurately predict the key reef hydrodynamics (*22*, *24*, *64*).

The XBeach reef models were run in hydrostatic mode along the cross-shore transects for each storm return period wave and water-level condition for 3600 s. The numerical horizontal resolution varied between 10 m seaward and 1 m landward depending on depth, with a maximum depth of 30 m on the fore reef to incorporate the relevant shoaling and wave breaking. The effect of higher bottom hydrodynamic roughness on incident wave decay was included through the incident wave friction coefficient (f_w) and the current and infragravity wave friction coefficient (c_f), as outlined in (*65*). The frictional drag provided by corals was parameterized using Chezy's formulation on the basis of the spatially varying reef configurations defined in the benthic maps on the basis of a meta-analysis of field, laboratory, and numerical modeling studies (*24*, *64*).

The modeling setting can be considered conservative for run-up and, thus, coastal flooding because of large swell events based on previous comparisons (*12*). A recent study characterized the differences between the hydrostatic mode and the nonhydrostatic modes of the XBeach model on reefs and determined good performance for both models but with the hydrostatic mode underestimating extreme wave run-up with respect to the nonhydrostatic mode (*65*). Therefore, the application of the hydrostatic mode in this study can be considered conservative but at a fraction of the computation cost (four to five times lower) of the nonhydrostatic mode. Although the cross-shore application of the models neglects longshore dynamics that occur on natural reefs, such as lateral flow, it also provided conservative estimates for wave run-up and the associated coastal flooding.

On the basis of input from stakeholders, scientists, and decision-makers, we developed a generalized restoration scenario that considered (i) the likelihood of delivering flood reduction benefits, (ii) existing coral restoration practices, and (iii) permitting factors such as depth for potential navigational hazards. The restoration represents placement of 1-m-high solid engineered structures, such as a Reef Ball (*25*), with outplanted new, small corals on top of the structure over a distance of 5 m in the cross-shore direction. This is represented in the model by a +1.25-m increase in height and 0.45 and 0.13 increases in hydrodynamic roughness for f_w and c_f, respectively, owing to the presence of 50 to 90% coral cover over the 5-m-wide extent. An algorithm sited this restoration scenario along the entire length of reef with the following conditions. Restoration lines along and across shore were sited on continuous mapped coral/hardbottom habitat of greater than 100 m in alongshore length (spanning two cross-shore profiles), in proximity to the 3-m depth contour and with depth constraints of no shallower than 2 m or deeper than 7 m because of operational considerations.

The same wave and sea-level forcing conditions were propagated in XBeach using the original model configuration but with modified shore-normal transects to account for the elevated coral reef height and friction because of the theoretical restoration. Total water depths (setup plus run-up) were calculated along each transect at a resolution of 1 m and extracted to a geospatial format for subsequent flood mapping.

Flood damages and benefits

Wave-driven total water level depths and extents were then computed from XBeach model flood points between adjacent shore-normal transects for the four return intervals to develop flood mask layers for the total water levels with and without restoration. The flood masks were derived as the product of a natural neighbor interpolation and a distance-weighted multiplier between 0 and 1, calculated as an exponential function of distance from the flood extent along each transect. To correct areas of disconnected backshore pooling, any pixel regions that were discontinuous with the coastline were removed. This method, improved from the approach used in the national valuation in (*11*, *12*), allowed for a more realistic representation of flood spatial connectivity between transects while honoring the known flood extents.

The resulting number of people threatened, number and magnitude of building units (by building type) damaged, and the indirect economic impact were then computed using the flood extents and depths. The number of people threatened by wave-driven flooding and their associated demographic attributes were determined from the US Census Bureau's TIGER/Line database (*66*) on the basis of 2010 census data. The buildings and other infrastructure affected were calculated using FEMA's flood exposure data in the HAZUS database at the census-block level (*51*, *67*). The damage degree for each building type (residential, commercial, industrial, etc.) was calculated using the damage functions in HAZUS to obtain the percentage of damage from the local flood water depths (*68*). The economic value of the damage, in dollars, was calculated for each asset as the building value per unit area multiplied by the damage degree; the number of flooded buildings was similarly calculated. Results of people, economic damage, and number of buildings flooded were computed at a 10-m^2 resolution within all flood zones.

The total economic impact of wave-driven coastal flooding included not only the physical damage to the buildings but also the disruption of people and businesses' incomes and, thus, the contribution to the GDP of housing and commercial/industrial infrastructure, respectively. The economic activity indirectly protected was calculated by multiplying the 2010 average contribution to GDP per person (*66*) by the number of people living in the land protected by coral reef restoration. Similarly, the indirect economic impact from commercial and industrial activities was calculated by multiplying each building protected by coral reef restoration by the 2010 average of 15.1 employees per business (*68*) and the average contribution to GDP per person. In the absence of data linking the people living in an area to where they work, these analyses assumed that housing and the economic activity protected for businesses from coastal flooding were independent. The HAZUS 2010-dollar values were translated to US 2023-dollar values using the US Bureau of Labor Statistics (*69*) inflation calculator.

The damages associated with each return period flood zone were used to calculate the expected annual damage (EAD) as the frequency-weighted sum of damages for the full range of possible damaging flood events (*70*). The EAD is a measure of flood risk in a given year and was calculated for the two scenarios, with present-day reefs and with the potential coral reef restoration scenario, per (*11*, *12*)

$$\mathrm{EAD} = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{1}{T_i} - \frac{1}{T_{i+1}}\right)\left(D_i + D_{i+1}\right) \quad (1)$$

where i refers to the number of return periods (n), T_i is the return period, and D_i represents the damages for the probability of $1/T_i$ (e.g., the flooding associated with a return period of 100 years has a probability of occurrence of 1% in a given year).

The flood risk reduction value of coral reef restoration was then determined as the difference in people, infrastructure, and dollar value affected between the simulations with current coral reefs and with potential coral reef restoration. The EAB is a measure of the annual risk reduction value of coral reef restoration and was calculated as

$$\mathrm{EAB} = \mathrm{EAD}_{\text{current reefs}} - \mathrm{EAD}_{\text{restored reefs}} \quad (2)$$

Calculation of BCRs

BCRs were calculated by dividing the net present value of benefits and costs over a typical 30-year investment lifespan. The net present value of annual benefits was calculated applying a discount rate of 7%, which is conservative for typical coastal infrastructure projects, to the EABs. Costs were assumed to be the upfront cost of restoration (*71*), and there was no maintenance based on pilot experiences of hybrid reefs (*7*). Values were calculated for 1-km sections, which aggregated benefits of native 100-m benefits calculated along the shore (data availability), which, in turn, were a result of adding up benefits (10 m by 10 m) on land. BCRs were also calculated using a 1-year lifespan to demonstrate immediate return of selected coral reef restoration sections.

Uncertainties in the flood risk model

Flood risk models are affected by different uncertainty factors. The main uncertainty sources involve the hydrodynamic modeling, bathymetry, elevation, damage models, and socioeconomic changes (*72*). A sensitivity analysis for US coral reef coasts was included in (*12*). The hydrodynamic analysis can be considered conservative in the difference between the current and restored reef scenarios, but the absolute flood results can be nonconservative in the presence of certain coastal features such as inlets and culverts. Other local coastal features, such as local defense structures, are not included in the regional-scale (~10 m^2) digital elevation models and may also influence some local flooding results. In some instances, the hydraulic connectivity effects may be partly missing, which can result in overestimation in areas protected by coastal structures but underestimation in culverts and inlets.

The focus of this effort is to address coastal risk through coral reef restoration by comparing the no-action scenario with possible restoration scenarios. Sea-level rise and other effects of climate change will change coastal risk, but our goal here was not to characterize changes in risk but rather compare risk reduction options, leaving climate effects equal. As noted previously in the text, the long-term costs, such as how the efficiency of the hybrid may decrease with sea-level rise, do not play into the BCAs necessary for FEMA funding, which require an immediate return on investment because traditional coastal defense structures such as seawalls and breakwaters provide full benefit immediately upon installation. If sea-level rise was taken into account and if there was no coral growth, then the hazard risk reduction benefits would decrease with time as the sea level rose. Although outside the scope of this paper, one of the proposed arguments for using nature-based solutions such as coral reefs (and marshes, mangroves, etc.) is that they can self-adapt, recover, evolve, and grow with sea-level rise (*73*), thus maintaining the hazard risk reduction benefits.

The necessity of using dynamic flood modeling, rather than passive or simplified flood methods (e.g., bathtub approach) that may cause large errors, has been demonstrated (*72*). Previous regional coastal flood models (*73*–*76*) have also relied on process-resolving cross-shore hydrodynamics with similar transect spacing (100 m) and model setups. A sensitivity study of model spatial resolution (*12*) indicated that for low-lying coastal zones, increasing the transect spacing leads to underestimating the flooding, whereas for more complex and steeper coastal zones, larger grid spacing leads to overestimating. Thus, increased model spatial resolution reduced overestimation in the resulting flooding impacts and made the results more conservative than with coarser resolution approaches applied in previous larger-scale modeling efforts (*72*, *77*).

The precision of elevation model and damage functions has been shown to dominate the overall uncertainty in coastal flood damage models at local scales (*77*, *78*). Therefore, this analysis relies on bathymetric and topographic data at the highest resolution available at regional scales and the damage curves for each building type correspond to the official curves included with HAZUS, which were developed on the basis of local empirical data on building damage vulnerability for the US (*50*, *67*). Additional uncertainty factors affecting the flood results include the joint probability of forcing conditions (waves, sea levels, and storm duration) and differences in the spatial distribution of people and building types and building values within the census and HAZUS tracts, respectively.

REFERENCES AND NOTES

1. S. Hallegatte, C. Green, R. J. Nicholls, J. Corfee-Morlot, Future flood losses in major coastal cities. *Nat. Clim.Change* **3**, 802–806 (2013).
2. J. Hinkel, D. Lincke, A. T. Vafeidis, M. Perrette, R. J. Nicholls, R. S. J. Tol, B. Marzeion, X. Fettweis, C. Ionescu, A. Levermann, Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3292–3297 (2014).
3. C. D. Storlazzi, S. B. Gingerich, A. van Dongeren, O. M. Cheriton, P. W. Swarzenski, E. Quataert, C. I. Voss, D. W. Field, H. Annamalai, G. A. Piniak, R. McCall, Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Sci. Adv.* **4**, eaap9741 (2018).
4. Federal Emergency Management Agency, "Coastal flood risks" (2024); www.fema.gov/flood-maps/coastal.
5. National Research Council, *Reducing Coastal Risk on the East and Gulf Coasts* (The National Academies Press, 2014), p. 208; 10.17226/18811.
6. F. Ferrario, M. W. Beck, C. D. Storlazzi, F. Micheli, C. C. Shepard, L. Airoldi, The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat. Commun.* **5**, 3794 (2014).
7. B. G. Reguero, M. W. Beck, V. N. Agostini, P. Kramer, B. Hancock, Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada. *J. Environ. Manage.* **210**, 146–161 (2018).
8. S. Vitousek, P. L. Barnard, C. H. Fletcher, N. Frazer, L. Erikson, C. D. Storlazzi, Doubling of coastal flood frequency within decades due to sea-level rise. *Sci. Rep.* **7**, 1399 (2017).
9. M. W. Beck, I. J. Losada, P. Menéndez, B. G. Reguero, P. Díaz-Simal, F. Fernández, The global flood protection savings provided by coral reefs. *Nat. Commun.* **9**, 2186 (2018).
10. A. S. Wong, S. Vrontos, M. L. Taylor, An assessment of people living by coral reefs over space and time. *Glob. Change Biol.* **28**, 7139–7153 (2022).
11. C. D. Storlazzi, B. G. Reguero, A. Cole, E. Lowe, J. B. Shope, A. E. Gibbs, B. A. Nickel, R. T. McCall, A. R. van Dongeren, M. W. Beck, "Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction" (U.S. Geological Survey Open-File Report 2019–1027, 2019), 42 p.
12. B. G. Reguero, C. D. Storlazzi, A. E. Gibbs, J. B. Shope, A. D. Cole, K. A. Cumming, M. W. Beck, The value of U.S. coral reefs for flood risk reduction. *Nat. Sustain.* **4**, 688–698 (2021).
13. T. S. Viehman, B. G. Reguero, H. S. Lenihan, J. H. Rosman, C. D. Storlazzi, E. A. Goergen, M. F. Canals Silander, S. H. Groves, D. M. Holstein, A. W. Bruckner, J. V. Carrick, B. K. Haus, J. B. Royster, M. S. Duvall, W. I. Torres, J. L. Hench, Coral restoration for coastal resilience: Integrating ecology, hydrodynamics, and engineering at multiple scales. *Ecosphere* **14**, e4517 (2023).
14. D. Lirman, S. Schopmeyer, Ecological solutions to reef degradation—Optimizing coral reef restoration in the Caribbean and Western Atlantic. *PeerJ* **4**, e2597 (2016).
15. M. C. Ladd, M. W. Miller, J. H. Hunt, W. C. Sharp, D. E. Burkepile, Harnessing ecological processes to facilitate coral restoration. *Front. Ecol. Environ.* **16**, 239–247 (2018).
16. E. C. Shaver, B. R. Silliman, Time to cash in on positive interactions for coral restoration. *PeerJ* **5**, e3499 (2017).
17. L. Boström-Einarsson, R. C. Babcock, E. Bayraktarov, D. Ceccarelli, N. Cook, S. C. A. Ferse, B. Hancock, P. Harrison, M. Hein, E. Shaver, A. Smith, D. Suggett, P. J. Stewart-Sinclair, T. Vardi, I. M. McLeod, Coral restoration—A systematic review of current methods, successes, failures and future directions. *PLOS ONE* **15**, e0226631 (2020).
18. E. Bayraktarov, P. J. Stewart-Sinclair, S. Brisbane, L. Boström-Einarsson, M. I. Saunders, C. E. Lovelock, H. P. Possingham, P. J. Mumby, K. A. Wilson, Motivations, success, and cost of coral reef restoration. *Restor. Ecol.* **27**, 981–991 (2019).
19. R. S. Smith, J. L. Pruitt, Oyster restoration to recover ecosystem services. *Ann. Rev. Mar. Sci.* **17**, 10.1146/annurev-marine-040423-023007 (2024).
20. K. K. Yates, D. G. Zawada, N. A. Smiley, G. Tiling-Range, Divergence of seafloor elevation and sea level rise in coral reef ecosystems. *Biogeosciences* **14**, 1739–1772 (2017).
21. R. Yanovski, A. Abelson, Structural complexity enhancement as a potential coral-reef restoration tool. *Ecol. Eng.* **132**, 87–93 (2019).
22. A. Pomeroy, R. Lowe, G. Symonds, A. Van Dongeren, C. Moore, The dynamics of infragravity wave transformation over a fringing reef. *J. Geophys. Res.* **117**, C11022 (2012).
23. O. M. Cheriton, C. D. Storlazzi, K. J. Rosenberger, Observations of wave transformation over a fringing coral reef and the importance of low-frequency waves and offshore water levels to runup, overwash, and coastal flooding. *J. Geophys. Res. Oceans* **121**, 3121–3140 (2016).
24. E. Quataert, C. Storlazzi, A. van Rooijen, O. Cheriton, A. van Dongeren, The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *Geophys. Res. Lett.* **42**, 6407–6415 (2015).
25. F. E. Roelvink, C. D. Storlazzi, A. R. van Dongeren, S. G. Pearson, Coral reef restorations can be optimized to reduce coastal flooding hazards. *Front. Mar. Sci.* **8**, 653945 (2021).
26. Reef Ball Foundation, "Designed and restored reefs and aquatic ecosystems: Reef Ball Foundation" (2024); www.reefball.org/.
27. University of Miami, "Unique hybrid reefs deployed off Miami Beach" (2023); https://news.miami.edu/stories/2023/03/unique-hybrid-reefs-deployed-off-miami-beach.html.
28. National Oceanographic Atmospheric Administration, "Restoring seven iconic reefs: A mission to recover the coral reefs of the Florida Keys" (2022); www.fisheries.noaa.gov/southeast/habitat-conservation/restoring-seven-iconic-reefs-mission-recover-coral-reefs-florida-keys.
29. Federal Emergency Management Agency, *BCA Reference Guide* (Federal Emergency Management Agency, 2009), p. 108.
30. M. W. Beck, N. Heck, S. Narayan, P. Menéndez, B. G. Reguero, S. Bitterwolf, S. Torres-Ortega, G.-M. Lange, K. Pfliegner, V. P. McNulty, I. J. Losada, Return on investment for mangrove and reef flood protection. *Ecosyst. Serv.* **56**, 101440 (2022).
31. M. S. Vicksburg, U.S. Army Engineer Research and Development Center, *International Guidelines on Natural and Nature-Based Features for Flood Risk Management*, T. S. Bridges, J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, R. K. Mohan, Eds. (U.S. Army Engineer Research and Development Center, 2021); https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/41946/3/NNBF-Guidelines-2021.pdf.

32. L. Diep, T. McPhearson, Nature-based solutions for global climate adaptation. *Nature* **606**, 653 (2022).
33. A. E. Stovall, M. W. Beck, C. D. Storlazzi, J. Hayes, J. Reilly, J. Koss, D. Bausch, *Coral Reef Restoration for Risk Reduction (CR4): A Guide to Project Design and Proposal Development* (U.S. Coral Reef Task Force, 2022), 31 p.; https://coralreef.gov/assets/about/cr4_guide_nov2022_508.pdf.
34. National Oceanic and Atmospheric Administration, "Restoring seven iconic reefs: A mission to recover the coral reefs of the Florida Keys" (2019), 46 p.; https://media.fisheries.noaa.gov/dam-migration/restoring_seven_iconic_reefs_-_a_mission_to_recover_the_coral_reefs_of_the_florida_keys.pdf.
35. L. Bay, D. Mead, L. Boström-Einarsson, "Reef Restoration and Adaptation Program: Intervention Summary. A report provided to the Australian Government by the Reef Restoration and Adaptation Program" (2019), 21 p.
36. K. Mangor, N. K. Drønen, K. H. Kaergaard, N. E. Kristensen, *Shoreline Management Guidelines* (DHI, 2017); www.dhigroup.com/marine-water/ebook-shoreline-management-guidelines.
37. Federal Emergency Management Agency, "FEMA allocates millions to restore coral reefs in the coast of San Juan" (2023); www.fema.gov/press-release/20230613/fema-allocates-millions-restore-coral-reefs-coast-san-juan.
38. M. C. Montgomery, J. Chakraborty, Assessing the environmental justice consequences of flood risk: A case study in Miami, Florida. *Environ. Res. Lett.* **10**, 095010 (2015).
39. U.S. Census Bureau, "2010 ACS demographics and housing estimates" (2022); https://data.census.gov/table?q=United+States&table=DP05&tid=ACSDP1Y2017.DP05&g=010XX00US&lastDisplayedRow=29&vintage=2017&layer=state&cid=DP05_0001E.
40. M. D. Hendricks, S. Van Zandt, Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environ. Justice* **14**, 87–97 (2021).
41. W. E. Highfield, S. A. Norman, S. D. Brody, Examining the 100-year floodplain as a metric of risk, loss, and household adjustment. *Risk Anal.* **33**, 186–191 (2013).
42. E. B. Barbier, J. C. Burgess, T. J. Dean, How to pay for saving biodiversity. *Science* **360**, 486–488 (2018).
43. E. McCreless, M. W. Beck, Rethinking our global coastal investment portfolio. *J. Ocean Coast. Econ.* **3**, 6 (2016).
44. B. G. Reguero, M. W. Beck, D. Schmid, D. Stadtmuller, J. Raepple, S. Schussele, K. Fliegner, Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecol. Econ.* **169**, 106487 (2020).
45. B. G. Reguero, F. Secaira, A. Toimil, M. Escudero, P. Díaz-Simal, M. W. Beck, R. Silva, C. Storlazzi, I. J. Losada, The risk reduction benefits of the mesoamerican reef in Mexico. *Front. Earth Sci.* **7**, 125 (2019).
46. State of Hawaii, Thirty-first Legislature, "Senate Concurrent Resolution Number 159: Urging the Department of Land and Natural Resources to examine and consider purchasing reef insurnace to support nature-based solutions to protect Hawaii's coastaline and coastal infrastructure from natural disasters" (2021); www.capitol.hawaii.gov/sessions/session2021/bills/SCR159_SD1_.htm.
47. K. R. H. Wagner, Designing insurance for climate change. *Nature Clim. Ch.* **12**, 1070–1072 (2022).
48. World Bank, *The Changing Wealth of Nations 2021: Managing Assets for the Future* (World Bank, 2021); https://openknowledge.worldbank.org/handle/10986/3640.
49. K. A. Cumming, A. D. Cole, C. D. Storlazzi, B. G. Reguero, J. B. Shope, C. L. Gaido, T. S. Viehman, B. A. Nickel, M. W. Beck, "Projected flooding extents and depths based on 10-, 50-, 100-, and 500-year wave-energy return periods for the State of Florida, the Commonwealth of Puerto Rico, and the Territory of the U.S. Virgin Islands for current and potentially restored coral reefs" (2021); https://doi.org/10.5066/P9ZQKZR9.
50. C. Scawthorn, P. Flores, N. Blais, H. Seligson, E. Tate, S. Chang, E. Mifflin, W. Thomas, J. Murphy, C. Jones, M. Lawrence, HAZUS-MH flood loss estimation methodology—II. Damage and loss assessment. *Nat. Haz. Rev.* **7**, 72–81 (2006).
51. B. G. Reguero, M. Menéndez, F. J. Méndez, R. Mínguez, I. J. Losada, A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards. *Coast. Eng.* **65**, 38–55 (2012).
52. P. Camus, F. J. Mendez, R. Medina, A hybrid efficient method to downscale wave climate to coastal areas. *Coast. Eng.* **58**, 851–862 (2011).
53. N. Booij, R. Ris, L. Holthuijsen, A third generation wave model for coastal region, I: Model description and validation. *J. Geophys. Res.* **104**, 7649–7666 (1999).
54. R. Hoeke, C. Storlazzi, P. Ridd, Hydrodynamics of a bathymetrically complex fringing coral reef embayment: Wave climate, in situ observations, and wave prediction. *J. Geophys. Res. Ocean.* **116**, C04018 (2011).
55. C. D. Storlazzi, E. P. L. Elias, P. Berkowitz, Many atolls may be uninhabitable within decades due to climate change. *Sci. Rep.* **5**, 14546 (2015).
56. S. Taebi, C. Pattiaratchi, Hydrodynamic response of a fringing coral reef to a rise in mean sea level. *Ocean Dyn.* **64**, 975–987 (2014).
57. C. D. Storlazzi, B. G. Reguero, K. A. Cumming, A. Cole, J. B. Shope, C. L. Gaido, T. S. Viehman, B. A. Nickel, M. W. Beck, "Rigorously valuing the coastal hazard risks reduction provided by potential coral reef restoration in Florida and Puerto Rico" (U.S. Geological Survey Open-File Report 2021–1054, 2021); https://doi.org/10.3133/ofr20211054.
58. E. R. Thieler, E. A. Himmelstoss, J. L. Zichichi, T. L. Miller, "Digital Shoreline Analysis System (DSAS) version 3.0: An ArcGIS extension for calculating shoreline change" (U.S. Geological Survey Open-File Report 2005–1304, 2005); https://pubs.er.usgs.gov/publication/ofr20051304.
59. Florida Fish and Wildlife Conservation Commission - Fish and Wildlife Research Institute, "Unified Florida reef tract map version 2.0" (2016); http://ocean.floridamarine.org/IntegratedReefMap/UnifiedReefTract.htm.
60. National Oceanic and Atmospheric Administration, "Benthic habitats of Puerto Rico" (2021); https://products.coastalscience.noaa.gov/collections/benthic/e95usvi_pr/default.aspx.
61. F. J. Méndez, M. Menéndez, A. Luceño, I. J. Losada, Estimation of the long-term variability of extreme significant wave height using a time-dependent Peak Over Threshold (POT) model. *J. Geophys. Res. Oceans* **111**, 1–13 (2006).
62. National Oceanic and Atmospheric Administration, "Extreme water levels—Annual exceedance probability curves" (2017); https://tidesandcurrents.noaa.gov/est/.
63. D. Roelvink, A. Reiners, A. van Dongeran, J. van Thiel de Vries, R. McCall, J. Lescinski, Modelling storm impacts on beaches, dunes and barrier islands. *Coast. Eng.* **56**, 1133–1152 (2009).
64. A. van Dongeren, R. Lowe, A. Pomeroy, D. Mihn Trang, D. Roelvink, G. Symonds, R. Ranasinghe, Numerical modeling of low-frequency wave dynamics over a fringing coral reef. *Coast. Eng.* **73**, 178–190 (2013).
65. E. Quataert, C. Storlazzi, A. van Dongeren, R. McCall, The importance of explicitly modelling sea-swell waves for runup on reef-lined coasts. *Coast. Eng.* **160**, 103704 (2020).
66. U.S. Census Bureau, "2010 Statistics of U.S. businesses (SUSB) annual datasets by establishment industry database" (2010); www.census.gov/data/datasets/2010/econ/susb/2010-susb.html.
67. C. Scawthorn, N. Blais, H. Seligson, E. Tate, E. Mifflin, W. Thomas, J. Murphy, C. Jones, HAZUS-MH flood loss estimation methodology. I: Overview and flood hazard characterization. *Nat. Haz. Rev.* **7**, 60–71 (2006).
68. N. J. Wood, J. Ratliff, J. Peters, "Community exposure to tsunami hazards in California" (USGS Scientific Investigations Report 2012–5222, 2013); https://pubs.er.usgs.gov/publication/sir20125222.
69. U.S. Bureau of Labor Statistics, "CPI inflation calculator" (2023); https://www.bls.gov/data/inflation_calculator.htm.
70. A. Olsen, Q. Zhou, J. Linde, K. Arnbjerg-Nielsen, Comparing methods of calculating expected annual damage in urban pluvial flood risk assessments. *Water* **7**, 255–270 (2015).
71. B. G. Reguero, M. W. Beck, D. N. Bresch, J. Calil, I. Meliane, Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLOS ONE* **13**, e0192132 (2018).
72. M. U. Parodi, A. Giardino, A. van Dongeren, S. G. Pearson, J. D. Bricker, A. J. H. M. Reniers, Uncertainties in coastal flood risk assessments in Small Island Developing States. *Nat. Hazards Earth Syst. Sci. Discuss.* **20**, 2397–2414 (2020).
73. L. T. Toth, C. D. Storlazzi, I. B. Kuffner, E. Quataert, J. Reyns, R. McCall, A. Stathakopoulos, Z. Hillis-Starr, N. H. Holloway, K. A. Ewen, C. G. Pollock, T. Code, R. B. Aronson, The potential for coral reef restoration to mitigate coastal flooding as sea levels rise. *Nat. Commun.* **14**, 2313 (2023).
74. T. R. Anderson, C. H. Fletcher, M. W. Barbee, B. M. Romine, S. Lemmo, J. M. S. Delevaux, Modeling multiple sea level rise stresses reveals up to twice the land at risk compared to strictly passive flooding methods. *Sci. Rep.* **8**, 14484 (2018).
75. A. Tomás, F. J. Mendez, R. Medina, F. F. Jaime, P. Higuera, J. L. Lara, M. D. Ortiz, M. F. Alvarez de Eulate, A methodology to estimate wave-induced coastal flooding hazard maps in Spain. *J. Flood Risk Manag.* **9**, 289–305 (2016).
76. P. L. Barnard, L. H. Erikson, A. C. Foxgrover, J. A. Finzi Hart, P. Limber, A. C. O'Neill, M. van Ormondt, S. Vitousek, N. Wood, M. A. Hayden, J. M. Jones, Dynamic flood modeling essential to assess the coastal impacts of climate change. *Sci. Rep.* **9**, 4309 (2019).
77. N. Pascal, M. Allenbach, A. Brathwaite, L. Burke, G. Le Port, E. Clua, Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach. *Ecosyst. Serv.* **21**, 72–80 (2016).
78. P. Menéndez, I. J. Losada, S. Torres-Ortega, A. Toimil, M. W. Beck, Assessing the effects of using high-quality data and high-resolution models in valuing flood protection services of mangroves. *PLOS ONE* **14**, e0220941 (2019).

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