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The value of US coral reefs for flood risk reduction

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Habitats, such as coral reefs, can mitigate increasing flood damages through coastal protection services. We provide a fine-scale, national valuation of the flood risk reduction benefits of coral habitats to people, property, economies and infrastructure. Across 3,100 km of US coastline, the top-most 1 m of coral reefs prevents the 100-yr flood from growing by 23% (113 km²), avoiding flooding to 53,800 (62%) people, US$2.7 billion (90%) damage to buildings and US$2.6 billion (49%) in indirect economic effects. We estimate the hazard risk reduction benefits of US coral reefs to exceed US$1.8 billion annually. Many highly developed coastlines in Florida and Hawaii receive annual benefits of over US$10 million km⁻¹, whereas US reefs critically reduce flooding of vulnerable populations. This quantification of spatial risk reduction can help to prioritize joint actions in flood management and environmental conservation, opening new opportunities to support reef management with hazard mitigation funding.

Tropical storms represent the most common and costliest natural disasters across the United States and globally[1–3]. Communities in low-lying coastal zones are currently some of the most at risk from natural hazards but also increasingly threatened by rising sea levels[4,5], intensifying storms, more powerful ocean waves[6] and expanding coastal development[7–9]. As storm costs mount, communities are increasingly looking for effective measures to protect low-lying coastal communities that do not cause negative environmental impacts and that can contribute to coastal sustainability[10,11].

Ecosystems such as reefs, beaches, dunes and wetlands provide an effective first line of defence against these hazards and represent a promising option to adapt to the increasing climate impacts[12–14]. However, these protection services are disappearing as ecosystems continue to be lost at alarming rates globally from both natural and human pressures[15,16]. These losses could escalate flood risk[17] in just years to levels not anticipated by sea-level rise for decades or a century[18]. Multilateral agencies (for example, the World Bank), government agencies (for example, US Army Corps of Engineers, USACE) and even the insurance industry increasingly acknowledge the role of ecosystems in reducing losses and risk[13,19] but alignment of hazard mitigation and environmental management is still widely lacking[20]. Coral reefs are one of the most diverse ecosystems but also one of the most effective natural barriers against the impacts of storms[14,17,21,22]. In the United States, coral reefs line >3,100 km of the most at-risk coastlines across Florida, Hawaii and the US Trust Territories. However, recent measurements in Hawaii, Florida and the US Virgin Islands (USVI) indicate that coral reefs have eroded more than 1 m vertically over the past decades[23]. These trends are likely to be exacerbated in the future due to climate change effects and anthropogenic stressors to coral reefs[24–26].

Coral reef management and restoration can improve reef health but it will require increasing resources[27,28]. Funds dedicated to coral restoration and conservation are very limited compared to funding for hazard mitigation, climate adaptation and storm recovery. In 2018, for example, the United States provided about US$15 billion for USACE to construct flood and storm damage reduction projects, of which >US$10 billion was dedicated to States and Territories impacted by hurricanes Harvey, Irma and Maria[29]. In comparison, the most ambitious project in reef restoration in the United States, Iconic Reefs in the Florida Keys, proposes ~US$5 million yr⁻¹ (http://go.nature.com/3ceWKx7).

Risk reduction funds could support ecosystem management goals if the natural coastal protection benefits were valued using rigorous approaches required by risk managers. However, few studies have rigorously addressed the economic value of coastal ecosystems in reducing damages to coastal communities[30]. The development of risk-based valuations of ecosystem-based flood protection has been limited by the lack of high-resolution data on bathymetry, topography, ecosystems and economic assets and the difficulty in modelling complex hydrodynamic processes across large regions. For these reasons, previous studies do not model flooding directly[31,32] or rely on global-scale data and simplified physics-based modelling approaches[17,33]. Yet, recent technological and data advances now make it possible to quantify and directly assess flood losses and the benefits of coastal ecosystems for reducing them with unprecedented rigour and spatial definition.

Here, we considerably advance conventional probabilistic risk-modelling frameworks[17,34,35] to evaluate flood damage for the coral reef-lined US coasts of the States of Florida and Hawaii and the Territories of Puerto Rico, USVI, American Samoa, Guam and the Commonwealth of the Northern Mariana Islands (CNMI). We use high-resolution data on bathymetry, topography, coral distribution and cover and socio-economics with state-of-the-art, physics-based hydrodynamic models that resolve the nonlinear processes of wave breaking, wave-driven water levels, run-up and coastal flooding at 10-m resolution, across the scale of the nation. Multidecadal wave and coastal water-level data were used to drive physics-based, numerical models to quantify the effect of the reefs on nearshore hydrodynamics and onshore flooding. Water depths and flood zones were calculated across the coral reef-lined US coasts to determine the people, number of buildings, direct and indirect economic impact and critical facilities at risk of coastal flooding. The risk reduction benefits were calculated as the averted impacts between present-day coral reefs and a scenario that assumes a 1 m reduction in reef height, on the basis of historic measurements. These new approaches and data make it possible to assess the benefits of coral

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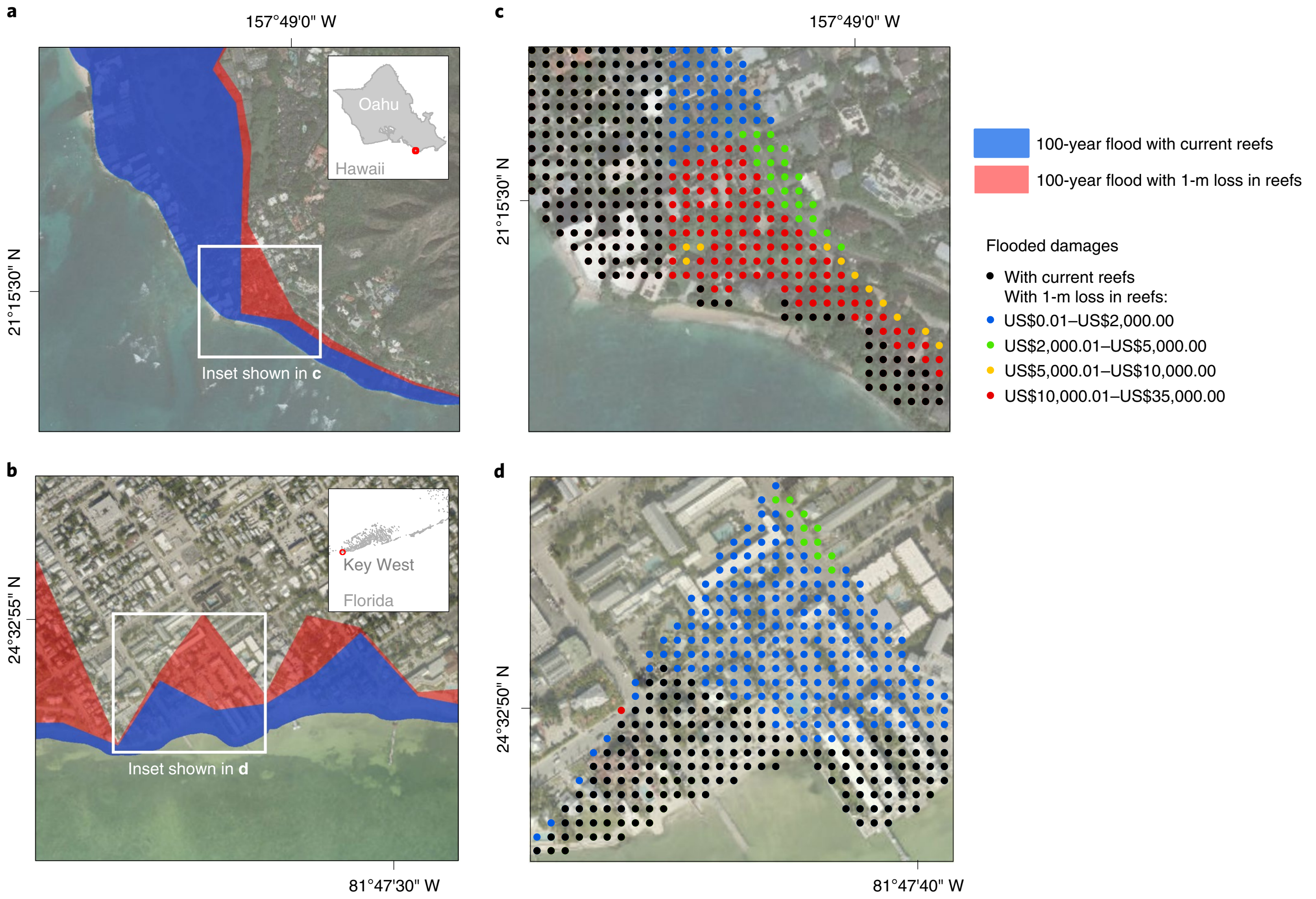

Fig. 1 | Changes in the 100-yr flood hazard zones with current coral reefs and with the loss of the top-most 1 m of reefs. **a**, South Oahu, Hawaii. **b**, Key West, Florida. The blue regions denote the flooding extent from a 100-yr storm with present coral reefs and the red regions denote the additional flooding extent with 1 m of coral reef loss (beyond the blue region) such that the region protected by coral reefs from a 100-yr storm is the red band. **c**, South Oahu, Hawaii. **d**, Key West, Florida. The black dots denote the grid cells flooded during the 100-yr storm with coral reefs at present. The coloured dots show the damage prevented by coral reefs from a 100-yr storm, at 10-m^2 scale. The maps were created using ESRI ArcGIS v.10.7.1. The satellite images were sourced from World_Imagery from ESRI with transparency added in ArcGIS.

reefs and the consequences of their loss with spatial granularity that are directly applicable to flood risk planning and management.

Results

Coral reefs reduce flood risk across the United States. Coral reefs provide wave energy attenuation that prevents coastal flooding from extending farther inland, as illustrated in Fig. 1 for the 100-yr flood hazard zone, averting impacts to buildings, people and the coastal economy. The averted flood damages can be integrated across storm probabilities to calculate annual risk reduction benefits. These flood prevention benefits for people (Fig. 2) and economic value (Fig. 3) provided by reefs every year are concentrated along specific coastal areas across the reef-lined shorelines of the United States.

However, these flood protection benefits are widespread across all States and Territories with coral reefs (Fig. 3). Approximately 10% of US coral reefs (325 km) have annual flood reduction benefits >US$1 million km^{-1} yr^{-1} (Table 1) but there are 686 km of coastline where reefs provide benefits >US$0.25 million km^{-1} yr^{-1} (Fig. 3). However, the spatial distribution of benefits and the ranking of communities most protected (Supplementary Table 1) demonstrate important differences between social (Fig. 2) and economic benefits (Fig. 3).

Nationwide savings in coastal flood damages. Nationwide, coral reefs provide substantial savings from storm-induced coastal flooding to lands, people, buildings, critical facilities and indirect economic disruption (Fig. 4a). Across 3,100 km of US coastline, the top-most 1 m of coral reefs prevents the 100-yr flood zone from increasing by 23%, which would cause flooding to 62% more people, 90% more buildings damages and 49% indirect economic effects. In absolute terms, this represents an increase in the 100-yr floodplain by 113 km^2 (>11,000 ha), affecting an additional 53,833 persons, US$2.7 billion in property and US$2.6 billion in economic activity. Furthermore, coral reefs also protect 38 critical facilities and 50.4 km of roads from the 100-yr flood (which represents a 16 to 41% increase in present risk, depending on the type of infrastructure; Supplementary Fig. 1). Nationwide, the top-most 1 m of coral reefs also prevents that the 1-in-100-yr flood damages from occurring ten times more often (Fig. 4a).

Annually, US coral reefs reduce coastal flooding to 18,180 people. The expected economic value of these protective effects is US$1.8 billion across the United States; this protection represents a risk reduction of 79% over present-day flood risk. Of the US$1.8 billion, US$826 million correspond to avoided direct damages to buildings, with the residential properties of homeowners receiving the greatest annual protection at US$623 million yr^{-1}

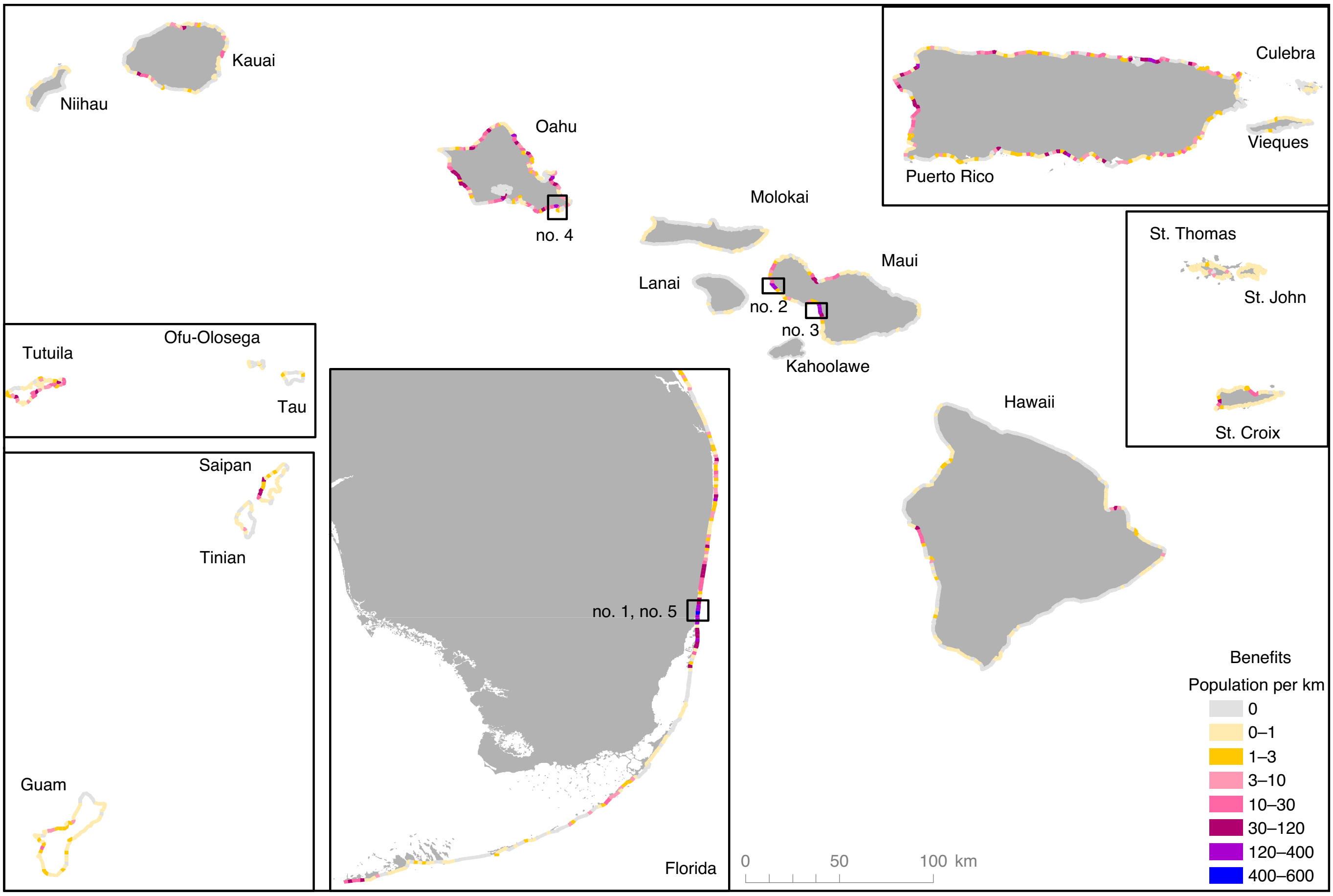

Fig. 2 | Annual social risk reduction benefits provided by US coral reefs. The map shows the distribution of people who are protected from flooding by the top-most 1 m of coral reefs each year. Results at 10-m^2 resolution are aggregated into 1-km coastal sections. The colours represent the number of people protected in each 1-km coastal section for visualization purposes. The five locations with the greatest risk benefits are indicated by numbers 1–5; the values and locations are listed in Supplementary Table 1. The map was created using ESRI ArcGIS v.10.7.1. The state outlines were sourced from the Feature Service Feature Classes from ESRI. Guam, CNMI and American Samoa are Shapefile Feature Classes created by USGS.

(Fig. 4c). In comparison, annual benefits to commercial buildings are valued at US$158 million (82% risk reduction), whereas the benefits to the other types of buildings combined are US$44.6 million. Furthermore, coral reefs also protect 32 essential, lifeline and transportation facilities and >42 km of coastal roads per year, which are important for the coastal economy beyond the property value (Fig. 4b).

Regional differences. The nationwide risk reduction benefits from US coral reefs exhibit stark differences between regions (Figs. 2, 3 and 5). Coral reefs in Hawaii, Florida and Puerto Rico accrue most of the most risk reduction benefits (Fig. 5a). These three regions account for 93% of the coastal flood reduction benefits to people every year. The State of Hawaii receives the greatest total economic risk reduction benefit from reefs, valued at US$831 million yr^{-1} in direct and indirect damages; the economic flood protection in Hawaii is greater than the benefits in all the other regions combined. In the Hawaiian Islands, Oahu (US$394 million yr^{-1}) and Maui (US$375 million yr^{-1}) receive the largest total economic flood protection from coral reefs. Furthermore, reefs prevent annual flooding to 10% of the total low-lying land in Maui (7.6 km^2 of land). However, by subregions, mainland Florida's coral reefs provide the bulk of the economic benefit (Supplementary Table 2) because of substantial high-value, developed low-lying areas. The average annual risk reduction US$ value per km of reef is ~US$1.4 million in Florida, compared to ~US$0.8 million in Hawaii.

Inequality aspects of flood risk reduction benefits. The results show important differences in the areas most protected by coral reefs when absolute economic benefits (US$) are compared with other risk metrics such as the relative increase in risk (% increase) or vulnerable people protected (social benefit). Whereas the more highly developed and populated areas in the States of Florida and Hawaii receive the largest absolute (US$) economic benefits, the Territories of Puerto Rico, American Samoa and USVI benefit the most when looking at the relative increase in flood risk from a 1-m reef loss. In these Territories, reefs prevent risk from doubling relative to current risk (Fig. 5b).

Furthermore, these territories are also where reefs protect the most vulnerable people. Of the more than 34,400 people at risk nationwide every year (Fig. 4a), 17% of them are children, 18% elderly (>65 yr), 7% low income and 35% are minorities (Supplementary Fig. 2a). We find that reefs disproportionately protect minorities and low-income people. For example, 1 m of reef loss would increase the annual risk to low-income people by +263% in Puerto Rico, 127% in America Samoa and 120% in USVI, compared to the 77% national average or a 21% increase in Hawaii (Supplementary Fig. 2a). For minorities, annual flood risk would increase by +293%

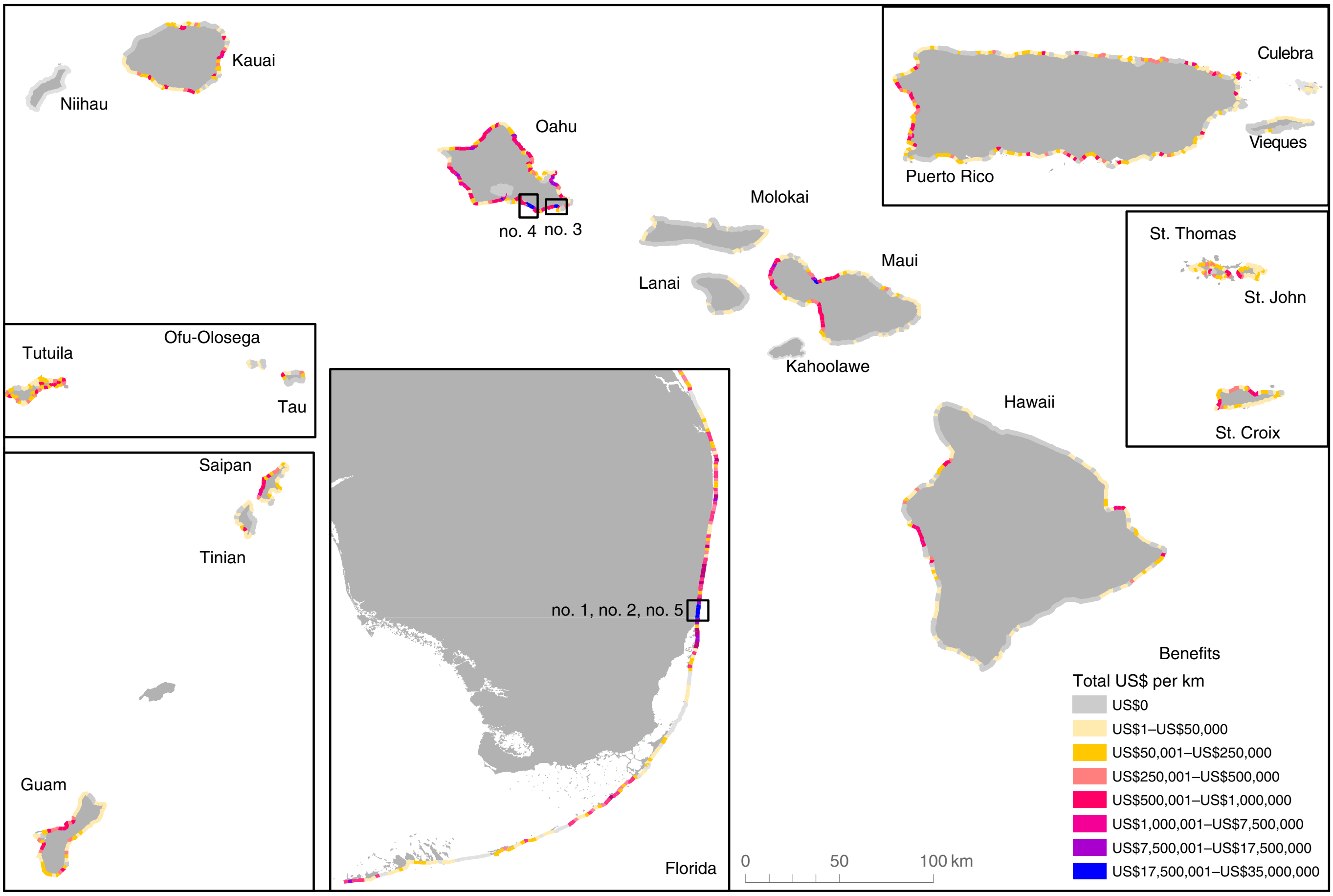

Fig. 3 | Annual economic risk reduction benefits provided by US coral reefs. The map shows the distribution of total economic losses (direct building damages and indirect economic disruption) that are prevented from flooding by the top-most 1 m of coral reefs per year. Results at 10-m^2 resolution are aggregated into 1-km coastal sections for visualization purposes. The colours represent the US$ of flood damages prevented by reefs in each 1-km coastal section. The five locations with the greatest risk benefits are indicated by numbers 1–5; the values and locations are listed in Supplementary Table 1. The map was created using ESRI ArcGIS v.10.7.1. The state outlines were sourced from the Feature Service Feature Classes from ESRI. Guam, CNMI and American Samoa are Shapefile Feature Classes created by USGS.

in Puerto Rico, 120% in American Samoa and 122% in USVI, compared to a national average of 68% (Supplementary Fig. 2a).

Discussion

This study represents a rigorous valuation of the coastal flood protection benefits of a marine ecosystem. It provides a benchmark to value and manage coastal ecosystems as natural infrastructure for protecting coastal areas. The bottom-up spatial characterization of the protective service of coral reefs indicates where communities would benefit most from maintaining and/or restoring reefs as part of hazard mitigation and climate adaptation strategies. At the national scale, the hazard risk reduction savings provided by US coral reefs are substantial (>US\$1.8 billion yr^{-1}). At the local scale (10 m^2) the results make it possible to identify individual reef stretches where conservation, restoration and active management of coral reefs could help reduce future needs in adaptation and hazard mitigation (see data for spatial information in ref. [36]).

Our analyses also pinpoint key stretches of shoreline where coral reefs provide particularly high economic flood protection benefits. Reefs reduce flood damages to many coastal neighbourhoods in Hawaii, Florida, Puerto Rico and the USVI by a factor of two and, in some instances, by factors of more than five (Supplementary Fig. 2). Many reefs provide flood protection benefits of >US\$10 million km^{-1} yr^{-1}. Their economic value is greatest along high value, intensively developed, low-lying coastal areas, such as Hawaii or Florida but even within States there is large variation in benefits (Figs. 2 and 3). For example, the Florida Keys have the third largest living coral reef system in the world but those reefs have lower risk reduction US\$ value per km of reef than other reefs offshore of the intensely developed areas of mainland Florida, such as Miami. However, these flood protection benefits are widespread across all States and Territories with coral reefs: 686 km of coastlines have reefs providing benefits >US\$0.25 million km^{-1} yr^{-1} and 325 km of these coastlines present annual flood reduction benefits >US\$1 million km^{-1} yr^{-1} (Fig. 3).

Reefs have important social benefits as well. Coral reefs off Puerto Rico, America Samoa and the USVI do not lead the ranking of economic benefits but they proportionately protect the most vulnerable, including young, old and minority populations, at levels more than double any other region (Supplementary Fig. 2a). Reefs also protect >42 km yr^{-1} of coastal roads and other critical infrastructure that can be critical lifelines to coastal communities, particularly for islands across the United States. Reefs also protect land that has not yet been highly developed or populated, for example in islands such as Maui, where low-lying coastal land is scarce and where coastal development may increase[37].

Across the United States, coral reefs prevent risk of a 100-yr storm from becoming a 10-yr risk (Fig. 4a). These changes in flood risk

Table 1 | Length of coastline with high risk reduction economic savings provided by US coral reefs

Region	Location	Annual expected benefit		
		Length of reef-lined coast (km) with benefit ≥US\$0.25 million km^{-1} yr^{-1}	Length of reef-lined coast (km) with benefit ≥US\$1 million km^{-1} yr^{-1}	Length of reef-lined coast (km) with benefit ≥US\$10 million km^{-1} yr^{-1}
Hawaii	Kauai	32	10	–
	Maui	62	38	12
	Oahu	158	112	12
	Hawaii	38	28	–
Florida	Peninsula	116	70	12
	FL Keys	46	16	–
Puerto Rico	Puerto Rico	104	26	–
American Samoa	Tutuila	30	1	–
Guam, CNMI	Guam	36	4	–
	Saipan	18	6	–
	Tinian	2	2	–
USVI	St. Thomas	16	4	–
	St. John	6	2	–
	St. Croix	22	6	–
Total		686	325	36

The values indicate length of coastline where the top-most 1 m of coral reefs protect at least US\$0.25 million, US\$1 million and US\$10 million in direct damages to buildings and indirect economic disruption, respectively.

have especially important implications for property owners and policy makers in coral reef-lined coasts. The impact of the 100-yr storm is the longstanding metric in the United States for determining and acting upon the possibility of an area being flooded[38]; it guides local planning and development decisions, triggers insurance purchases and other household adjustments and serves as a fundamental indicator of where it is safe to build. For a building in the 100-yr flood hazard zone (that is, 1% chance of flood damage any given year), the probability of being flooded once in a 30-yr period (a typical home mortgage) is 26%. With 1 m of reef loss, the likelihood of flooding during a 30-yr home mortgage period increases to 96%. This example pinpoints how coastal ecosystem loss is a risk multiplier to many communities, atop the threats of climate change, but that has been overlooked and not yet quantified. Furthermore, the timelines during which this risk could materialize are much shorter (on the basis of historic measurements) compared to other drivers of risk such as sea-level rise.

The results also provide important insights into the performance of coral reefs for coastal hazard risk reduction during storms. The wave attenuation performance of coral reefs is reduced during extreme storms that raise water levels[21,39,40], which would suggest proportionally lower protection from a hydrodynamic perspective, for high return periods storms. However, we find that the risk reduction benefits remain relatively constant across probabilities, even when coral reefs become less hydrodynamically effective. We find that the risk reduction value of reefs increases in relative terms from the 10- to the 50-yr storms and then remains consistently in the range of 50–60% for people, 80–90% in damages to buildings and 40–50% in indirect economic savings across high return periods (Fig. 4a). Furthermore, the coastal low-lying land that reefs protect from flooding remains relatively unchanged at ~20% across all storm probabilities (Fig. 4a). It appears that this is explained by the influence of coastal development patterns. The effects of reefs are twofold: (1) reefs reduce water depths and damages in the existing flood hazard zone but also (2) avert new damages on higher land presently not at risk but with large concentrations of people, buildings and economic activity.

At the national level, flood protection is an important service of coral reefs but occurs in addition to other ecosystem services they provide such as tourism, fisheries and recreation. All the non-hazard risk reduction services of coral reefs have been estimated to be US\$2.1 billion yr^{-1} for the same geography[41]. On the basis of the calculations provided here, the US\$1.8 billion yr^{-1} in flood protection benefits is the greatest service coral reefs provide in the United States. Economic value, for flood protection or other services, is therefore just one measure of the value of reefs. Areas with little development will yield low flood protection benefits (US\$) but these may be priority areas for conservation investments in potentially more pristine reefs.

Implications and new opportunities for reef management and conservation. There is enormous interest in coral reefs worldwide and growing concern about the pace of their decline. The present-day savings in coastal flood damages that adjacent communities receive from coral reefs could quickly represent real costs if reef degradation continues. The evidence indicates that substantial coral cover loss and >1 m of physical erosion of the seabed has occurred in less than three decades[23] and already exceeds the expected increase in sea levels for the near future. Given the mounting threats and stressors impacting coral reefs such as land-based pollution, warming temperatures and ocean acidification[25,42], without action, coastal flood risk could increase in a similar magnitude to that expected from sea-level rise and tropical cyclones by the end of the century if this historic trajectory continues[18,43]. Therefore, conserving and maintaining healthy reefs could represent one of the most cost-effective risk management strategies to avoid future coastal flood impacts. Furthermore, better-managed reefs could also show capacity to buffer some of the effects of global warming[44–46].

These services can be valued, managed and maintained as natural infrastructure. Yet, reef conservation and restoration have been supported traditionally by the comparatively limited public and private funding for environmental conservation[20]. However, funds for disaster management and climate adaptation are tens to hundreds of times larger than funds for habitat conservation and restoration[47]. Valuing reefs for their risk reduction service therefore opens new

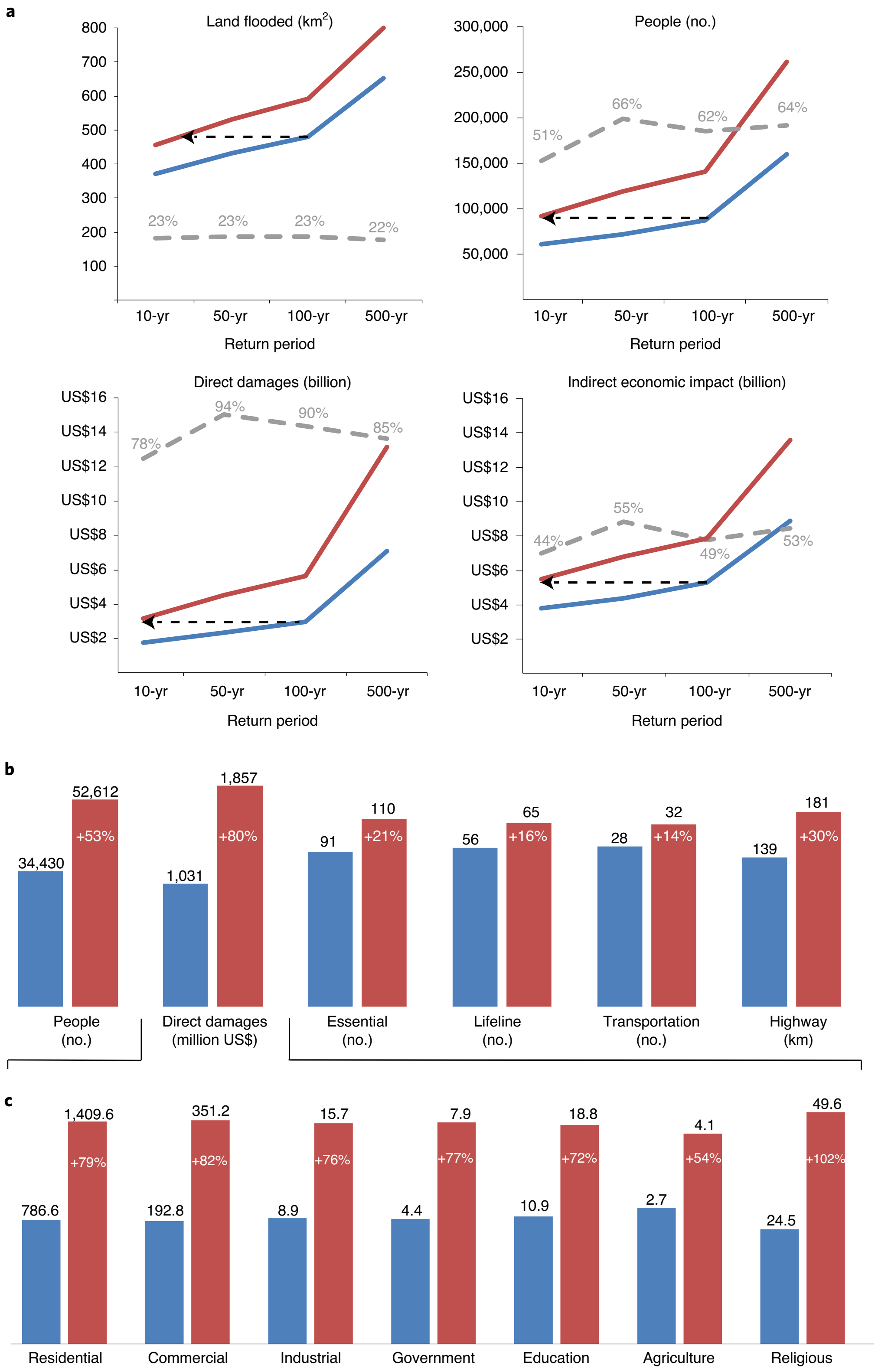

Fig. 4 | Nationwide estimates of risk and flood protection benefits provided by US coral reefs. a, Risk for different storm return periods to land, people, direct damages to buildings and indirect economic disruption. The blue lines represent flood risk with present-day coral reefs; the red lines represent flood risk with the loss of the top-most 1 m of coral reefs. The dashed black arrows indicate how the 100-yr flood risk will change with the loss of the top-most 1 m of coral reefs. The dashed grey lines represent the percentage change (% risk increase) between both scenarios. **b**, Expected annual damages (labels on bars) and percentage avoided damage (annotated as a percentage in bars) for people (counts), flood damages (US$ million), roads (km) and critical infrastructure (buildings). The blue bars represent the expected annual damages with reefs and the red bars represent the expected annual damages with the loss of the top-most 1 m of coral reefs. **c**, Breakdown of expected annual damages by building type. Coral reefs provide substantial social and economic protection to coastal communities, both across storm return periods (**a**) and in annual terms (**b** and **c**).

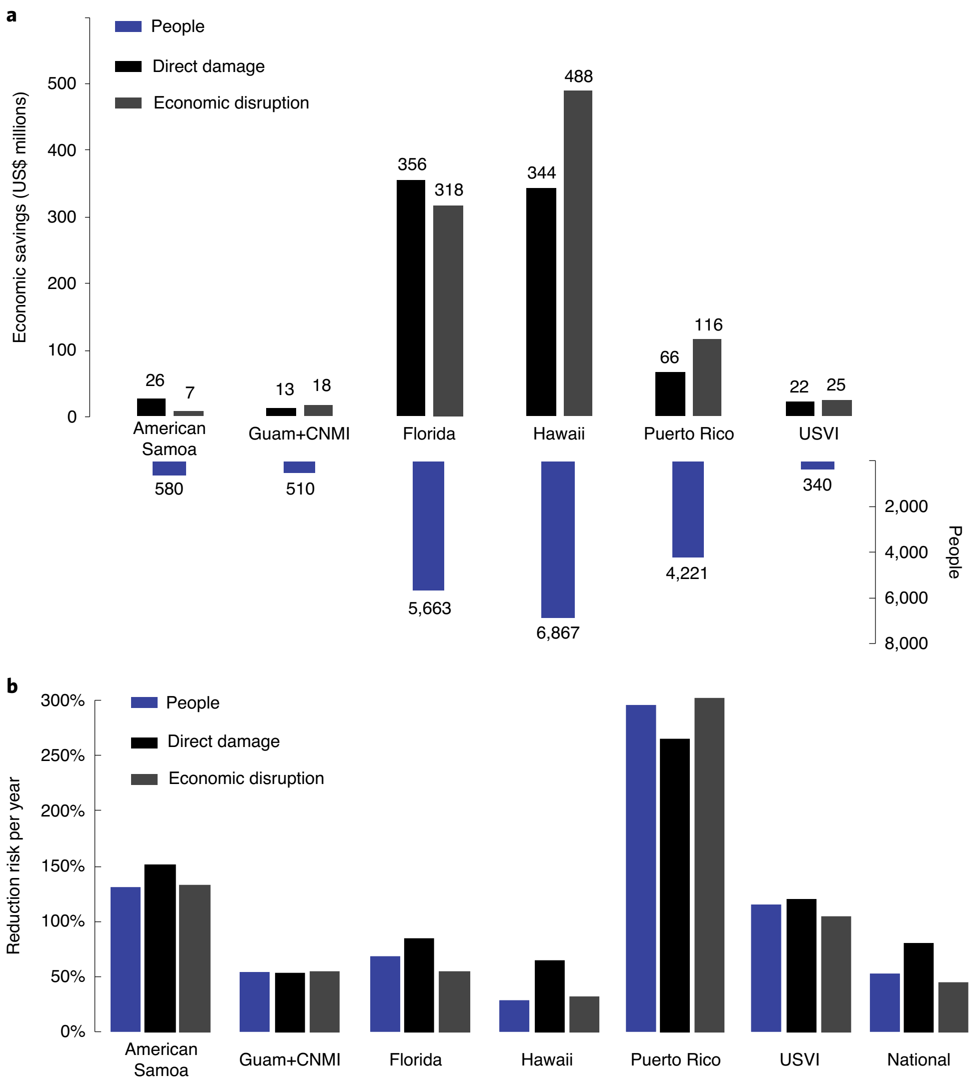

Fig. 5 | Regional differences and inequality aspects of the risk reduction provided by US coral reefs. a, Flood risk reduced by coral reefs per year by regions, in terms of total people, direct damages to buildings and economic disruption. **b**, Percentage of risk reduced by coral reefs. Regional differences are stark and, within the same region, there are differences between the percentage of risk reduced for people versus economic assets. A breakdown by subregion is provided in Supplementary Table 2.

important funding opportunities for reef managers. The use of hazard mitigation funds for reef restoration could also be transformative for the future of coral reefs.

Importantly, the value of coral reefs for flood protection opens new financing opportunities for habitat management through risk management funds not previously available to reef managers, such as hazard mitigation, disaster recovery and insurance[20]. First, because coral reefs protect people and state, territorial and national infrastructure from flooding, national agencies (for example, US Federal Emergency Management Agency (FEMA) and USACE) could fund reef restoration through such mechanisms as predisaster hazard mitigation funds. Second, disaster recovery funding, such as the US$ billions appropriated by the United States for recovery from the 2017 hurricanes (with ~US$10 billion specifically for coastal flood prevention projects against hurricanes), could support reef restoration for resilience building. The values presented here help make the required case that reefs are cost-effective for flood mitigation funding and this evidence is being used by the National Oceanic and Atmospheric Administration (NOAA) and FEMA to help identify sites where postdisaster funding could be dedicated for maintaining and enhancing the capacity of coral reefs to prevent coastal flood damages. Third, the insurance industry can support incentives for habitat conservation and restoration, for example by insuring their coastal protection service as recently piloted in the Mesoamerican Reef[18] or through new resilience insurance mechanisms for coral reef restoration projects[48].

More broadly, the opportunities for natural coastal protection to align ecosystem concerns and economic incentives requires coordination across many agencies. These results help critically inform the work of the US Coral Reef Task Force, which represents >20 federal, state and territorial agencies. On the basis of these new insights, the US Coral Reef Task Force is starting to consider reefs as national infrastructure for their storm protection benefits and there are bills being considered in the United States that would codify this role. These analyses also open new policy instruments that could account for the health and status of coral reefs, including, for example, dynamic coastal setbacks that could consider the contribution to coastal risk from ecosystem degradation, similar to shoreline management for sea-level rise erosion in Hawaii[49,50] or the United Kingdom[51].

At a global scale, many coral reef-lined coasts are among the most vulnerable to climate impacts from rising sea levels, increased storm action and loss of ecosystems. In many of these tropical nations, coral reefs are also more cost-effective for flood hazard mitigation than are hard, 'grey' infrastructure[14]. These vulnerable communities could adapt this methodological approach to value their natural infrastructure because advances in remote sensing and high-performance computing are increasingly making it possible. In many of these coastlines, often with national budgets limitations for investing in coastal protection and adaptation, informed investments to maintain the flood protection capacity of coral reefs could be one of the most cost-effective strategies to manage risk and adapt to climate change.

Methods

General methodology. The goal of the risk-modelling approach used here was to quantify the flood risk reduction benefits of coral reefs 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 that provide a quantitative valuation of the coastal protection benefits of coral reefs off populated coastlines of the United States and its Trust territories.

The analysis is based on a risk quantification valuation framework that factors in different storm probabilities and calculates expected annual benefits in social and economic terms[35]. We used state-of-the-art, high-resolution flood modelling and damage calculation based on data and approaches recommended by FEMA[52,53]. The risk-modelling framework (Supplementary Fig. 3) integrated wave downscaling of >61 yr of data; extreme sea levels and storm probability analysis; physics-based reef hydrodynamic and coastal flood modelling; geospatial analysis; and calculation of people, buildings, critical infrastructure and direct and indirect economic flood damages. The approach quantified flood hazard zones, the role of coral reefs in reducing flooding and the averted economic and social consequences. The main steps are described below.

Projecting the coastal hazards. Wave data covering the period 1948–2008 were obtained from the altimetry-calibrated long-term, hourly hindcast Global Ocean Wave (GOW) database[54] (Supplementary Fig. 3a). The offshore wave data were synthesized into 500 combinations of sea states (wave heights, mean wave periods and wave directions) that best represented the range of offshore conditions using a maximum dissimilarity algorithm (Supplementary Fig. 3b)[55]. The selected sea states were propagated to the fore reef using the physics-based simulating waves nearshore (SWAN) spectral wave model[56]. SWAN solves the spectral action balance equation and has been shown capable of accurately simulating wave propagation around reef-lined islands[57–59]. Standard SWAN settings[56] were used but the directional spectrum was refined to five-degree bins to better handle refraction and diffraction in and amongst islands. We used three levels of dynamically downscaled nested grids, depending on the region, to accurately capture the propagation effects from the scale of island groups (order of ten in km) down to scales of <100 m. Details of grid, configuration, resolutions and bathymetry sources can be consulted in ref. [60]. The propagated shallow-water wave conditions were extracted at 100-m intervals along the coastline, at a water depth of ~30 m and used to reconstruct 61-yr hourly time series using radial basis functions[55].

Ecosystem and flood modelling. The location of nearshore coral reefs and relative coral abundance was obtained from benthic habitat maps of coral cover percentage and spatial extent (Supplementary Table 3). The effect of coral reefs on hydrodynamics were simulated with a nonlinear wave model previously tested and validated for reef environments[39] on the basis of cross-shore transects created every 100 m alongshore. The coastal transects were defined using the Digital Shoreline Analysis System (DSAS) software v.4.3 in ArcGIS v.10.3 (ref. [61]). 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 (USGS) 1:24,000 quadrangle maps and smoothed in ArcGIS using the polynomial approximation with exponential kernel algorithm and a 5,000-m smoothing tolerance. Transects varied in absolute length to cross 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 hydrodynamic forcings for the model were calculated for the 10-, 50-, 100- and 500-yr storm return periods by fitting a general pareto distribution[62] to each hourly significant wave-height time series at a depth of ~30 m. Extreme water levels with the same recurrence were taken from the nearest NOAA tidal station, which include the effect of tropical cyclones[63]. The hydrodynamic forcing for each return period was then propagated over each 100-m-spaced shore-normal transects using the numerical model XBeach[64,65]. XBeach solves the depth-averaged, nonlinear shallow-water equations and provides water-level variations up to the scale of long (infragravity) waves. XBeach, originally derived for sandy beaches, has been advanced and successfully applied in reef environments to accurately predict the key reef hydrodynamics[21,39,64,66].

The XBeach reef models were run in hydrostatic (surf-beat) mode along the cross-shore transects for each storm return period wave and water-level conditions for 3,600 s. The numerical horizontal resolution varied between 10 m seawards and 1 m landwards, depending on depth, with a maximum depth of 30 m on the fore reef to incorporate the relevant shallow-water effects. The models generally stabilized after 100–150 s of simulation and thus generated good statistics on waves and wave-driven water levels for each of the storm conditions. The effect of higher bottom 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 by van Dongeren et al.[64]. The frictional drag provided by corals was parameterized using Chezy's formulation on the basis of the spatially varying reef configurations. On the basis of a meta-analysis of field, laboratory and numerical modelling studies[39,64], values for f_w and c_f were given on the basis of coral coverage (Supplementary Table 4) along each profile as defined from the benthic maps.

The modelling setting can be considered conservative for run-up due to large, long-period swell events on the basis of previous comparisons. A recent study[67] characterized the differences between the surf-beat mode and the non-hydrostatic modes of the XBeach model on reefs and determined good performance for both models but with the surf-beat mode underestimating extreme wave run-up with respect to the non-hydrostatic mode. Therefore, the application of the surf-beat mode in this study can be considered conservative but at a fraction of the computation cost (four to five times lower) of the non-hydrostatic 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 infragravity waves and wave run-up. The morphodynamic change in the models was not included.

The degraded reefs were simulated by specifying in the numerical model: (1) reduced depth for the reefs of 1 m; and (2) reduced coral reef friction, assumed to be the same as the default sand values. These assumptions are based on observed changes in degraded reefs. Yates et al.[23] detected >1 m of seabed erosion during the last decades offshore from many sections of northern Florida Keys (see fig. 3 in ref. [23]), >1 m offshore and up to 2–3 m nearshore in USVI; and widespread loss >2 m offshore from Maui. Here, we consider 1 m of loss as a conservative scenario because these trends are likely to be exacerbated in the future associated with climate change effects and other stressors to coral reefs[24–26]. Furthermore, vertical coral reefs accretion[68] would not be sufficient to keep pace with the sea-level rise projected for the twenty-first century[69,70], so a relative submergence of reefs could be even larger than the 1 m of loss observed in the past.

These estimates could also be conservative given the expected impact of ocean acidification and warming, which would jeopardize the capacity of degraded and stressed coral reefs to maintain coastal protection at present and under rising sea levels[26,71]. Evidences also show substantial flattening of reefs across the Caribbean as architectural complexity had declined nonlinearly with the near-disappearance of the most complex reefs since 1969[72]. The loss of friction represents a severe flattening of the reef and reef matrix degradation, which was translated into the models through frictional loss assuming that the reefs will show similar friction as the no-reef sections. 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 loss of coral reef height and friction. Water depths were calculated along each transect at a resolution of 1 m and extracted to a geospatial format for subsequent flood mapping.

Assessing flood damages and benefits. Water depths along the shore-normal transects were interpolated between adjacent shore-normal transects to develop spatial flood zones for each of the storm return intervals and model run: with coral reefs and with 1 m of reef loss. The flood hazard zones were built by creating a minimum-bounding polygon between neighbouring flood points. The flood points were interpolated to create a flood depth raster using natural neighbour interpolation within the extent of the flooding zones.

The somewhat variable nature of the inland flooding extents (Fig. 1) was produced by the interpolation between adjacent profile models every 100 m alongshore. The extents of inland flooding vary from one profile to the next because the cross-shore profiles intersect different bathymetries, coral reefs and flood up and over different topographies. For example, a coastal section with high coral cover, a steep shoreface and high terrestrial elevations may limit flood extent, but may be adjacent to another area with less coral cover, a more gently slope or low-lying topography that would flood farther onshore than the neighbouring transect.

The people impacted, number of building units (by building type) and the direct and indirect economic damages were then computed using the flood extents and depths. The number of people flooded and their associated demographic attributes were determined from the US Census Bureau (2016) TIGER/Line database, on the basis of 2010 census data. The buildings and other infrastructure impacted was calculated using FEMA flood exposure data in the HAZUS database at the census-block level[52,53]. Tsunami hazard exposure data were used for the territories with no flood hazard exposure data (Guam, American Samoa and the CNMI), at a resolution of $1\,\text{km}^2$. The HAZUS data were projected into the respective Universal Transverse Mercator coordinate system for each region.

A damage-degree for each building type (residential, commercial, industrial and so on) was calculated using the damage functions in FEMA-HAZUS to obtain the percentage of damage from the local flood water depths[73]. The economic value of the damage (US\$ value) was calculated for each asset as the building value per unit area multiplied by the damage-degree. Similarly, the number of flooded buildings was also calculated. Critical infrastructure in the flooded zones, obtained from the HAZUS database, was also counted. Results of people, economic damage, number of buildings and critical infrastructure facilities flooded were created at 10-m spaced points within all flood zones. The calculated damages were aggregated by infrastructure type following the same building categories in HAZUS (residential, commercial, industrial, agricultural, religious, government and education buildings). To calculate relative flood impacts, we also computed the total people and buildings in the low-lying coastal zone, defined as the extent between the coastline and the 20-m ground height, with a limit distance from the shoreline of 1 km.

The total economic impact of wave-driven coastal flooding included the physical damage to the buildings themselves but also to the disruption of the incomes of people and businesses and thus the contribution to the gross domestic product (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[74] by the number of people living in the land protected by coral reefs. Similarly, the indirect economic impact from commercial and industrial activities were estimated by multiplying each building by the 2010 average of 15.1 employees per business[74] and the average contribution to GDP per person. In the absence of data linking the people living in an area to where they work, the model assumed that housing and the economic activity protected for businesses from coastal flooding were independent.

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[75]. 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 loss of the top-most 1 m of reefs, as:

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

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 $1/T_i$ (for example, the flooding associated with a return period of 100-yr has a probability of occurrence of 1% in a given year).

The flood risk reduction value of coral reefs was then determined as the difference in people, infrastructure and US\$ value impacted between the simulations with coral reefs and with 1 m of reef loss. An expected annual benefit (EAB), a measure of the annual risk reduction value of coral reefs, is hence calculated as:

$$\mathrm{EAB} = \mathrm{EAD}_{\text{with 1-m reef loss}} - \mathrm{EAD}_{\text{with reefs}}$$

Discussion of flood risk advancements in reef environments. This study advances previous hazard flood mapping in many regions of the United States because actors usually ignored for flood risk modelling (for example, FEMA flood zones) in other regions and ecosystems are key for coral reef-lined coasts. Flood modelling approaches generally use wave models based on the action balance equation (for example, SWAN) and storm surge models through two-dimensional depth-integrated (or three-dimensional) shallow-water equations (for example, ADCIRC) at typical resolutions of 100 m or larger. The physics and resolution in these models are adequate to study the flood reach of a major hurricane but insufficient to represent the effects and processes of wave-dominated environments. These modelling approaches may be adequate for other coastal ecosystems such as saltmarshes and mangroves[19] but not for coral reef environments where the wave action and nonlinear effects are dominant[39,76], even during hurricane conditions[77].

Previous assessments of the risk reduction provided by ecosystems had been limited by several factors: the resolution of global data and model simplifications[32,78]; lack of precision in local coastal processes, such as nonlinear interaction between waves, sea levels and coral reefs[39,40]; low resolution topography and asset distribution; and passive flooding models such as bathtub approaches[17,18] that do not accurately reproduce dynamic coastal flooding. Recent research on hydrodynamics of reef environments have developed fully nonlinear models of wave-driven flooding[39,79,80]. Yet these advances have only been locally applied or relied on synthetic reef conditions and only represent a first-order assessment. Furthermore, measuring risk not only requires modelling flooding but also local, probabilistic assessment of people and infrastructure impacted. All these factors are necessary for developing flood risk maps that can inform local actions and decisions.

This study addressed these limitations by considering the key processes of coral reefs in coastal flooding using nonlinear hydrodynamic and flood modelling, local topography, bathymetry and coral characteristics. For this, we had to take into account important factors. First, the complex geometry of coral reefs requires substantial high-resolution modelling and data. Second, the hydrodynamic roughness of reefs provides attenuation through frictional drag but required factoring in spatially variable coral cover and the resulting hydrodynamic roughness and thus friction[21]. Third, wave breaking over reefs involves complex nonlinear interactions in wave energy and infragravity components that dominates coastal flooding[39,64,77]. Fourth, wave-driven flooding requires calculation of water depths through dynamic modelling over the coastal topography, instead of simple and passive flooding methods such as bathtub or geospatial simplifications based on total water levels on the shoreline[81]. These factors are particularly relevant for extreme flooding in reef environments, as demonstrated during Hurricane Haiyan in the Philippines[77]. Thus far, these technical challenges have made only possible such precision at local studies[39,64] or required important assumptions at larger domains[17].

Discussion of uncertainties in the flood risk model. Flood risk models are affected by different uncertainty factors. The main uncertainty sources involve the hydrodynamic modelling, bathymetry, elevation, damage models and socioeconomic changes[82]. The hydrodynamic analysis can be considered conservative in the difference between reef and degraded-reef scenarios but the absolute flood results can be non-conservative in the presence of certain coastal features such as inlets and culverts. Other local coastal features, such as local defence structures, are not included in the national-scale 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.

Previous large-scale studies have also pointed out the need of using dynamic flood modelling, in contrast with passive or simplified flood methods (for example, bathtub approach) that may cause large errors (for example, estimated in 35–54% for Hawaii[81]). Regional coastal flood models have also relied on process-resolving cross-shore hydrodynamics with similar transect spacing (100 m) and model set-ups[81,83,84]. Although these studies do not assess the sensitivity to flood model transect spacing, it is one factor that can affect the flood risk results. A sensitivity study focusing on model spatial resolution indicates that for low-lying coastal zones, increasing the transect spacing leads to underestimation of the flooding, whereas for more complex and steeper coastal zones, larger grid spacing leads to overestimation (Supplementary Fig. 4). Overall, the area, people, building damaged and the indirect economic damages due to flooding increase with decreasing spatial resolution, with mean ± 1 s.d. differences of $5.5 \pm 3.9\%$, $8.6 \pm 8.9\%$, $11.6 \pm 11.8\%$ and $7.5 \pm 7.3\%$, respectively, for the entire modelling framework. Thus, increasing model spatial resolution reduces overestimation in the resulting flooding impacts and makes the results more conservative than with coarser resolution approaches as in previous larger-scale modelling efforts (for example, refs. [17,33]).

Studies specifically focused on characterizing the uncertainty in coastal flood damage models at local scales have determined that the elevation model and damage functions dominate the overall uncertainty[82,85]. Therefore, this analysis relies on bathymetric and topographic data at the highest resolution available for the United States and Territories. The damage curves for each building type correspond to the official curves included with FEMA-HAZUS, which were developed on the basis of local empirical data on building damage vulnerability for the United States[52]. Other additional uncertainty factors affecting the flood results include the joint probability of forcing conditions (waves, sea levels and storms duration) and differences in the spatial distribution of building stock and exposure value.

Data availability

All data needed to evaluate the conclusions are present in the paper, the Supplementary Information and databases referenced therein. The flood extents and depths that support the findings of this study are available in ScienceBase at https://doi.org/10.5066/P9KMH2VX

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Author contributions

B.G.R., C.D.S. and M.W.B. designed and conceptualized the research and methodological approach. B.G.R., C.D.S., A.E.G., J.B.S., A.D.C. and K.A.C. performed the hazard analysis, reef modelling and damage calculations. B.G.R., C.D.S., M.W.B. and K.A.C. analysed the results and worked on the visualization. B.G.R., C.D.S. and M.W.B. wrote the manuscript together.

Competing interests

The authors declare no competing interests.

Additional information

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