Marine Policy 146 (2022) 105311

Contents lists available at ScienceDirect

Marine Policy

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

Shoreline protection by the world's coral reefs: Mapping the benefits to people, assets, and infrastructure☆

Lauretta Burke [a], Mark Spalding [b,c,*]

[a] World Resources Institute, 10 G St. NE, Washington DC 20002, USA
[b] The Nature Conservancy, Strada delle Tolfe, 14, Siena 53100, Italy
[c] Department of Zoology, University of Cambridge, Cambridge CB2 3EJ, UK

ARTICLE INFO

Keywords:
Coral reef
Shoreline Protection
Wave attenuation
Vulnerability
Ecosystem services
Valuation

ABSTRACT

The important role of coral reefs in protecting people, economies and infrastructure is widely acknowledged. Coral reefs are highly effective at reducing wave energy and thereby diminishing the impact of both flooding and erosion in coastal areas. Understanding these benefits, and their spatial distribution, can play a critical role in driving efforts to protect or even restore coral reefs, with critical societal benefits. Simple, high-resolution models were used to generate a global map which suggests that 26 % of the coastline of the world's coral reef nations receive some protection benefits, and that, over decadal periods some 5.3 million people and $109 billion of GDP are protected by coral reefs. Separate maps show the values at the shore and plot the reefs providing those values. Differences exist between metrics (population, GDP and night-time lights as a metric for infrastructure) raising the importance of considering ecosystem service values with multiple metrics, including non-monetary values. Patterns of protection are highly heterogeneous, however many of the most important areas are adjacent to highly developed shores and many of these receive little or no management attention.

1. Introduction

Coral reefs are widely known for their role in attenuating waves [1,2], a function that provides critical coastal protection to people, assets, and infrastructure [3–6]. One estimate suggests that reef crests alone dissipate an average of 86 % of the wave energy passing over them, a figure that rises to 97 % when reef flats are factored in [3]. Models of wave attenuation are already being used to estimate the benefits from reefs in specific locations [7,8], and powerful tools can be used to quickly develop such models (https://naturalcapitalproject.stanford.edu/software/invest) for other locations. Science-driven approaches are also being used to optimize solutions for coral reef restoration projects [5,6].

With the growing risks posed by climate change, calls have increased to secure adaptation capacity against inevitable change, even as countries are also working on mitigating greenhouse gas emissions [9]. Coral reefs are critical assets in adaptation, situated on the front line of coastal defense against the likely threat of rising seas and increasing storm intensity. In addition to breaking waves, they have some capacity for regrowth following damage; and for vertical growth, which in ideal circumstances may enable them to build upward at the same rate as sea level rise [10,11]. Climate change is, of course, also threatening the survival of coral reefs themselves, but their large physical structures should ensure some continuity of protection for some years even if the living structure is degraded or lost.

Understanding the patterns of coastal protection by coral reefs and highlighting areas of particular importance is critical. Such efforts are being made in a number of local settings [for example, 12,13,14]. At the same time, regional or global-scale estimation of these benefits can be important in raising awareness, influencing policy, and in supporting broad-scale management and funding interventions, for example linked to the Sustainable Development Goals [15], the Disaster Risk Reduction Framework [16] and the commitments for National Adaptation Plans under the UNFCC [17]. Valuable work has already been conducted at the global scale [18], and has led to the first global estimates of the benefits of this protection, albeit at low spatial resolutions [4,19,20].

This study seeks to complement this earlier global work building a higher resolution map of the coastal protection provided by coral reefs that (a) looks at reduced flooding at the shoreline and (b) projects those values back out to the coral reefs themselves. While it takes a simpler

☆ Support for this analysis was provided by the United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF).
* Corresponding author at: The Nature Conservancy, Strada delle Tolfe, 14, Siena 53100, Italy.
E-mail addresses: octopus_lb@outlook.com (L. Burke), mspalding@tnc.org (M. Spalding).

https://doi.org/10.1016/j.marpol.2022.105311
Received 4 March 2022; Received in revised form 7 September 2022; Accepted 16 September 2022
Available online 29 September 2022

approach in terms of wave modeling and economic impact estimation, the current work targets the developing of maps at much finer resolution, with maps based on a 500 m grid, enabling a first ever view of the likely benefits accruing to many small island states. At these improved resolutions, it identifies areas of key importance which might benefit from greater management attention and more detailed local study.

2. Methods

Risk arises from a combination of hazard, exposure, and vulnerability (Fig. 1):

- **Hazard:** The probability of potentially damaging phenomena, such as a storm or wave-induced flooding
- **Exposure:** The people; livelihoods; infrastructure; and economic, social, and cultural assets that could be adversely affected by a hazard
- **Vulnerability:** The likelihood that assets will be damaged, destroyed, or affected when exposed to a hazard, which natural and human modifiers could mitigate.

In many models, vulnerability includes both physical and social factors. Our model focuses on physical vulnerability, examining the risk of coastal flooding to people and assets and the role of coral reefs in reducing vulnerability and mitigating that risk. Social and economic factors may also mitigate the societal costs of such flooding; this study does not address them.

Datasets were selected to capture key components of hazard, exposure, and vulnerability, which were combined to develop metrics of risk for population, monetary assets, and infrastructure. Fig. 2 summarizes this approach, with more detailed methods in the text.

2.1. Exposure

Our base model of exposure uses a map of coastal areas likely to be flooded as a result of a combination of sea level rise, tide, and storm surge from CoastDEM v.2.1 [22] (www.climatecentral.org) for all coral reef countries and territories. This focuses on a potential flood height of 5 m . This height has been used by other researchers [23] and provides a proxy for potential short-term high-intensity impacts (e.g., through a combination of storm surge, wave setup and interannual oceanographic phenomena). Global models show extreme sea level events of 5 m and greater for 100 year storm events to be relatively widespread, and that these are likely to increase considerably with sea level rise [24]. Other researchers have opted for even greater potential flood heights, of 10 m [20]. Our choice of the lower 5 m limit is more realistic, while also providing a pointer toward future risk from rising sea level and increasing erosion. To capture the risk of storm damage and erosion on higher coasts, a 500-m coastal strip for all coasts irrespective of elevation was incorporated.[1] The area of investigation was limited to a maximum inland extent of 5 km, though most coastal areas have much narrower low-lying belts.

Within these areas, three metrics of exposure were developed:

- **Population:** The populations in coastal areas were derived from WorldPop 2020, which provides population data over a 30″ grid (approximately 1-km at the equator) for 2020.
- **GDP:** Data on GDP in purchasing power parity (GDP–PPP) for 2019 are from Aalto University, in Finland, at the same resolution as population [25]. These data are used as an indicator of the monetary value of goods and services provided within an area, adjusted for the relative price of goods in that area.
- **Nightime lights (NTL)**: Data on NTL are from the 2016 NASA Earth at Night Map. Light intensity is measured on a scale of 0–255, at a resolution of 15″ (approximately 500 m at the equator). NTL data are correlated with GDP, carbon dioxide emissions, and electricity consumption [26], which makes them a useful proxy for the relative value of infrastructure, including areas where they may be limited resident population, such as roads, ports, and airports. They can also capture areas of high value (such as hotel zones) where resident populations may be relatively small.

The three metrics are correlated, but each has some distinctive features. At the grid-cell level in low, exposed areas, population and GDP-PPP are relatively closely correlated (correlation coefficient = 0.62). This result is to be expected given the strong spatial relationship between people and GDP.[2] The correlation between infrastructure (as measured by NTL) and both population and GDP-PPP is much lower (correlation coefficient = 0.34 in both pairings), as infrastructure often exists in areas of low population density. In the analyses that follow, values from each of these three measures of exposure were assigned to the closest 500-m coastal grid cell using the Euclidean Allocation tool in ArcGIS.

2.2. Hazard

Coral reefs are highly effective at attenuating wave energy. This function can be critical in avoiding human impacts, especially during storm events. A model of these hazards was built using the wind and wave indicators from InVEST, reported at roughly 1-km intervals along the world's coasts [20,27]. These data are derived from peak (top 10 %) historic wind and wave records over the period 1997–2007. These peak records are converted to simple scores of wind and wave intensity: based on the size of these two hazards, using quintiles of the global records, with each hazard scored across a range of 1–5.

Coastal grid cells were assigned the wind and wave values (summed to give scores from 2 to 10) of the nearest InVEST data points.[3] The result is a relative metric giving an indication of the likely hazard from wind and waves for any coastal point, an indicator of the threat which may be posed by erosion and flooding during extreme conditions in any place.

Storm surges, which are a major hazard in many coral reef areas, are only indirectly moderated by coral reefs – reefs have little or no direct influence on the surges themselves, however by reducing wave energy during storm events, reefs can still reduce the overall impacts of this hazard [28]. Likewise with sea level rise, reefs cannot act as a direct barrier, however healthy reefs can accrete vertically enabling them to "keep up" with some level of sea level rise, while the depositional processes, often driven by storm events can equally play a critical role in maintaining coastalines and islands and allowing their continued vertical growth [10,29].

[1] Incorporating the 500-m coastal strip expanded the area identified as low exposed coastal area by 12 % compared with the original data from Climate Central.

[2] The spatial correlation between each pair of the three asset types in low exposed areas was calculated in ArcMap using Band Collect Statistics, to provide a measure of dependency between the layers. The correlation is the ratio of the covariance between the two layers divided by the product of their standard deviations. See https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-band-collection-statistics-works.htm.

[3] The wind and wave hazard index points are spaced at approximately 1 km. Coastal cells were assigned the value of the closest point based – either the nearest point within 1.5 km (if there is one), otherwise 2.5 km or 10 km. If the coastal cell still did not have a value, it was assigned the global average value of 6.

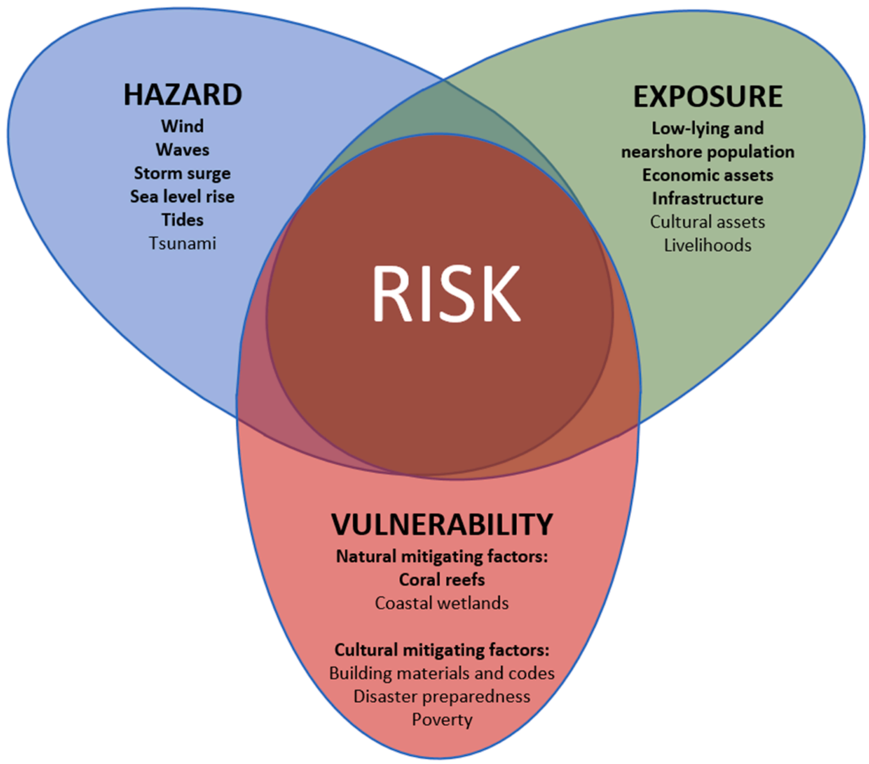

Fig. 1. Components of risk: Hazard, exposure, and vulnerability (based on the risk framework diagrams devised by the Intergovernmental Panel on Climate Change [21]). Factors in bold are used in the model.

2.3. Vulnerability

Vulnerability can be thought of as the inverse of a population's ability to avoid or mitigate risk. Both socioeconomic and natural factors affect a population's vulnerability. This analysis focuses solely on the role coral reefs play in reducing vulnerability.

Although reefs are highly effective at attenuating waves, their effect is most powerful over short distances, particularly during storm events, when wind-driven processes can enable the reformation of waves over relatively short distances. To account for this diminishing level of protection with increasing distance between the reef and shore, three tiers of protective capacity were assigned to coastal grid cells:

- within 500 m of a coral reef (high protection)
- within 2 km of a coral reef (medium protection)
- behind a barrier reef (low protection)
- none of the above (no protection)

The 2-km distance represents the "maximum effect distance" for coral reefs used by InVest [20]. Our decision to include barrier reefs was based on observations that barrier reefs have important effects, notably on large oceanic waves. Although wind-driven waves build up in the lagoons behind barrier reefs, they rarely reach the heights of the oceanic waves that break on the outer edges of barrier reefs [30,31].

Our coral reef layer was the 500-m gridded layer used in [32], built largely from a globally consistent, satellite-derived map. For barrier reefs, a polygon dataset reflecting some 30 barrier reefs was developed, informed largely by [33]. The larger barrier reefs were subdivided in order to constrain their influence to relevant shoreline sectors, giving a total of 83 barrier reef units.

The architecture and porosity of any reef system will affect the degree of wave attenuation. For this work, the coastal protection provided by nearshore reefs were adjusted to account for the density of coral reefs nearby (the number of 500-m resolution reef grid cells within 2 km of the coastal cell).

Relative scores of coastal protection value by reefs were applied to coastal cells in the following manner. Initial coastal protection scores were assigned to coastal cells based on reef proximity, with relative scores of 100 where there were reefs within 500 m, 50 where reefs were within 2 km, and 25 for coastal cells within the influence of a barrier reefs. These relative scores were then modified as follows:

- **High protection**: Coasts within 500 m of a reef were given a base value of 100, but this number was adjusted up or down by up to 50 % depending on the density of the adjacent reef (number of 500 m resolution reef grid cells within 2 km of the coastal cell). (See Appendix A for details.)
- **Medium protection**: Coasts with reefs that were 500–2000 m away were given a base value of 50, but this number was adjusted up or down by up to 50 % depending on the density of the adjacent reef.
- **Low protection**: Coasts with no local protection (ie. no reefs < 2 km), which lay behind barrier reefs, were given a fixed value of 25.

The resulting "relative protection index" ranges from 0 (unprotected) to 150 (highest protection).

2.4. Evaluating risk: integrating exposed assets, hazards, and vulnerability

To assess risk, the values for exposure, hazards, and vulnerability were combined for each of the three metrics of potential human impact: population, GDP, and infrastructure (as measured by NTL). The exposure metrics, which represent the maximum possible values that could be affected, were first reduced based on the degree of likely hazard intensity. The combined wind-wave scores were converted to percentages. The lowest possible score is 2 (20 % at risk); the highest possible score is 10, implying that 100 % of the population and all exposed assets would be at risk. Given that the source data were based on the highest wind and

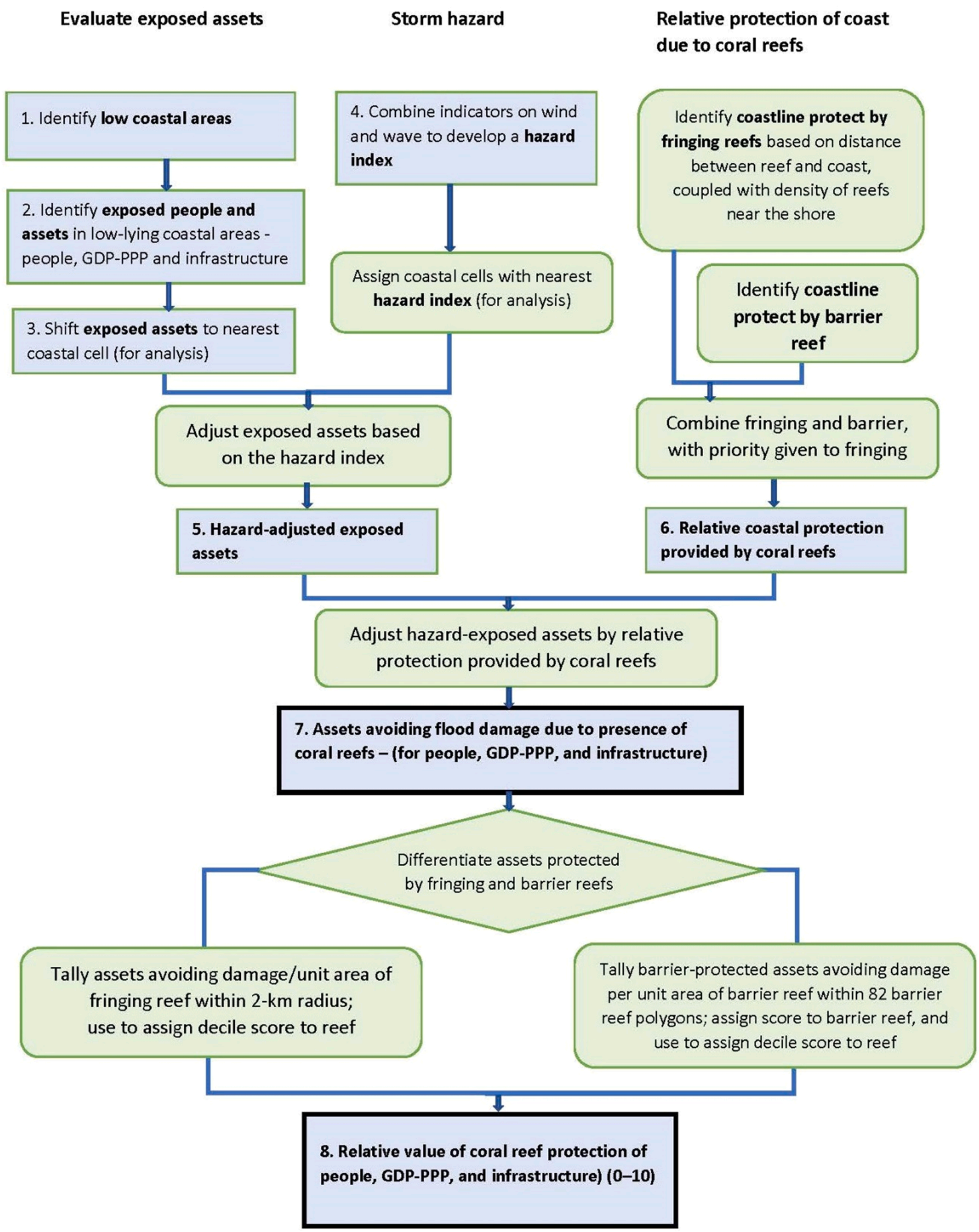

Fig. 2. Summary of methodology for assessing shoreline protection. Blue filled boxes indicate interim products (green frame) or key final outputs (black frame, Outputs 7 and 8). Green boxes indicate analytical processes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

wave metrics over a 10-year period, our estimates of risk and risk reduction are relevant over a similar, decadal, timeframe.

In the next step, the presence of coral reefs were incorporated to generate final risk scores. The relative protection index was rescaled to range from 0 to 75 and applied as a percentage reduction in the hazard-adjusted exposure. This seems a conservative adjustment, given evidence that reefs can attenuate up to 97 % of wave energy [1,3]. These modifiers reduce the vulnerability of all coasts near reefs by between 12.5 % (barrier reefs) and 75 % (for coral reefs within 500 m and a high density of coral within 2 km).

The resulting values represent the risk reduction provided by coral reefs – in terms flood damages avoided over a decade. These “avoided damages” were estimated for coastal cells in terms of population, GDP and infrastructure.

Alongside the direct calculation of value was linked to the coastline, mapping of the reefs providing this value is also important, as these are the natural assets which need to be managed in order to support or even to enhance these critical functions. Hence, the final results at the coast were also reprojected out to the coral reefs, weighting the distribution by both distance from shore and reef density. For this stage, the findings are presented as relative scores (1−10) rather than absolute values (see Appendix A for details on the method).

In the last stage of this work, the coastal protection benefits of coral reefs were spatially compared to coral reef conservation efforts represented by protected areas. Marine Protected Areas (MPAs) are the only globally mapped management intervention, but they are also the most

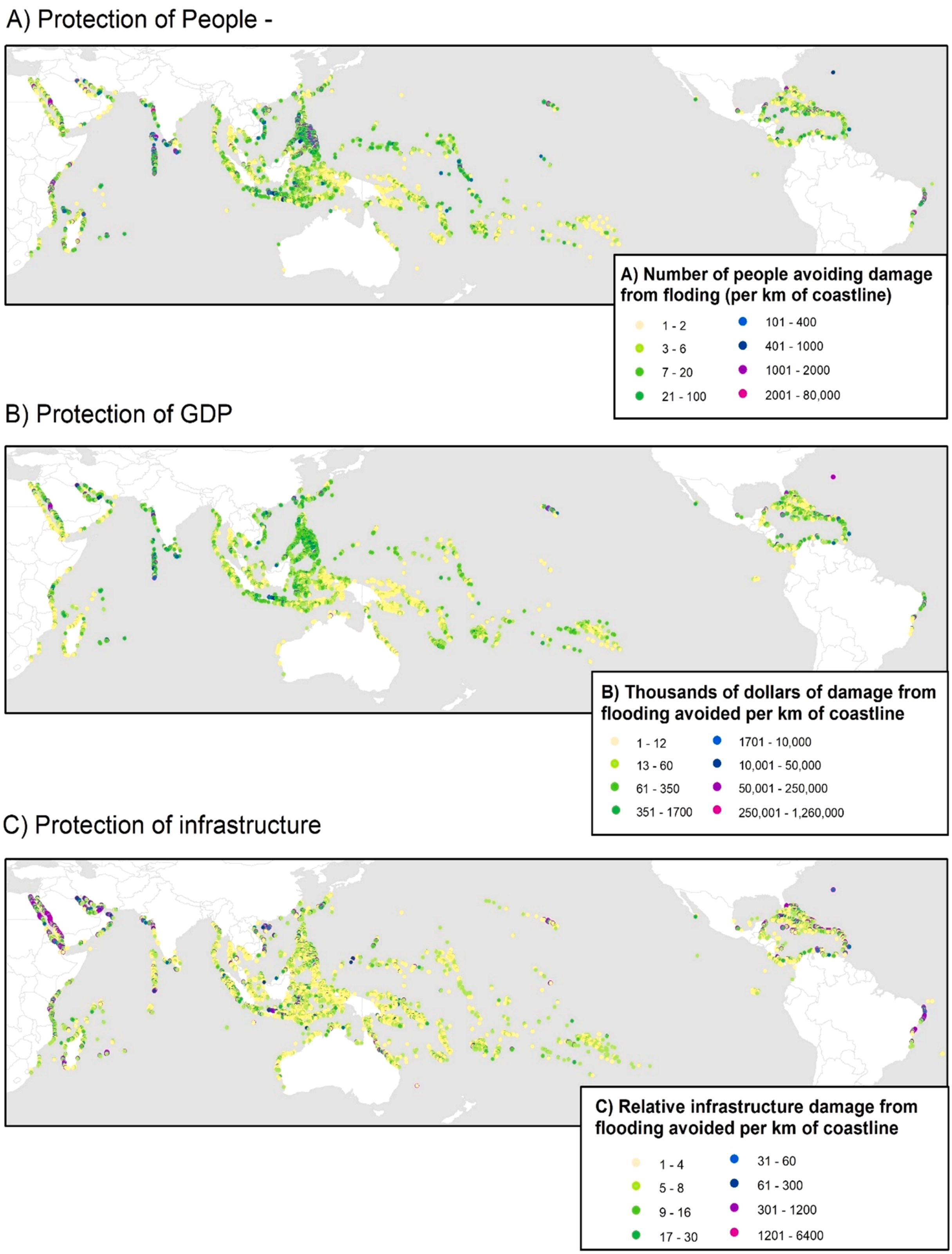

Fig. 3. Coral reef protection against global flood risk to people, GDP, and infrastructure (per decade). (Data groupings represent geometric intervals, rounded for clarification.) A higher resolution version of this map is provided in Appendix A.

widely used means to try to safeguard coral reefs. For this work, our map of reefs protecting assets (scores of 1–10) were overlaid and intersected with a dissolved layer of all categories of extant protected areas, regardless of category [34].

3. Results

Over 120 countries and territories in the world have coral reefs. In these countries, coral reefs provide some protection to 26 % of the coastline—a total of more than 230,000 km of coastline (See Appendix A for information on coastline sources). Less than half of these protected coastlines have human populations or assets. Nevertheless, coral reefs provided protection from decadal flooding for some 5.3 million people and US$109 billion equivalent of GDP-PPP. Global summary maps are presented in Fig. 3.

The distribution of these benefits is highly heterogeneous. Fig. 4 provides examples in greater detail, illustrating the coastal protection reefs provide to people, GDP, and infrastructure for sites in Asia and the Caribbean. In this figure the maps show these values as relative scores, projected to the reefs themselves.

The vast majority of protection in our model comes from nearby fringing reefs, particularly areas of high nearshore reef density. Barrier reefs add only marginal protection, primarily in just a few countries (notably Belize, Cuba, the Philippines, and Palau). This finding is expected, given the threat from wind-driven waves that can re-form behind such barriers. In the model, fringing reefs provide protection to 99 % of people and 98.5 % of GDP, whereas barrier reefs help protect just 1 % (60,000 people) and 1.5 % of GDP.

3.1. Protecting people

Table 1 presents the findings by region. More than 200 million people live in the almost 2.9 million square kilometers (km^2) of low-lying and potentially exposed coastal lands in the coral reef countries of the world (about 4 % of the population of those countries). Only a small proportion live close to coral reefs. Our models suggest that 15.4 million people world-wide are at risk from storm and sea level rise threats in areas receiving some protection from coral reefs. About 5.3 million of these people (35 %) are likely to benefit from flooding and damage protection by coral reefs over a 10-year period. They are distributed along almost 100,000 km of populated coastlines. There is considerable spatial variability in the level of risk reduction: on average, coral reefs protect 55 people per km of populated coast, but about 10 % of these coasts protect more than 100 people per km and there are about nearly 600 km of coasts where reefs protect more than 1000 people per km. These highest-value reefs are located alongside urban shores and are widely distributed in every coral reef region of the world (see Fig. 3).

Regional patterns show considerable variation. On average, coral reefs protect nearly 35 % of hazard-exposed people living along coasts in coral reef countries, but the figure is just 22 % in Australia, rising to 41 % in the Pacific.

National statistics further highlight this variability (see Table 3). Many of the world's poorest coastal countries and small islands states are major beneficiaries, with more than 1.7 million people in the Philippines alone benefitting from protection by coral reefs.

3.2. Protecting GDP and infrastructure

The patterns emerging for GDP and infrastructure are broadly similar, although with some important differences. Globally, more than $305 billion of GDP-PPP assets are located in low-lying areas directly adjacent to coral reefs; more than a third of these assets ($109 billion) receive direct protection from decadal-scale flooding events thanks to their proximity to coral reefs (Table 2). In almost all regions, coral reefs reduce flooding damage by more than 34 % of hazard-adjusted GDP-PPP (ranging from 24 % in Australia to 47 % in the Pacific). In many low-lying island areas, such as the Maldives, French Polynesia, the Federated States of Micronesia, and Hawaii, coral reefs reduce the risk of hazard-adjusted GDP-PPP by more than half (Table 3).

NTL data provide a more direct indicator for infrastructure values. Units of brightness are best portrayed as relative indicators. The presence of coral reefs protects more than a third of the coastal infrastructure at risk from storm and sea level rise from decadal damage. The patterns are similar to those for protection of people and GDP, but again with some important differences. Many high-intensity NTL areas are far away from dense populations. They include industrial areas (e.g., the northern Persian Gulf) and some tourist areas (e.g. the north coast of Jamaica and Mexico's Yucatan Peninsula), where resident population density may be low but infrastructure, in the form of beachfront accommodation, may nevertheless by valuable.

3.3. Redistributing values to reefs

The statistics presented above indicate values linked to the coastline where such values are felt by coastal communities, but they do not directly indicate which reefs may be providing those values. Understanding the contribution of particular reefs to those values provides an alternative view, which may be critical for managers, while also providing a framework for placing these values alongside other ecosystem service values such as fisheries benefits. For this reason the actual values linked to reefs, presented on a relative scale of 1–10, are also provided. The coastal and reef-based maps are similar, although the reef maps show how values depend on the distribution and density of the reef.

Fig. 5 illustrates the importance of the barrier reef for the western margins of South Sulawesi, Indonesia, where the barrier reef of the Spermonde Archipelago provides protection to coastal populations around the town of Makassar and adjacent areas. By contrast, the role of the barrier reef on the nearby eastern shore of South Sulawesi is negligible, as extensive nearshore reefs provide more effective protection. (Appendix A provides additional maps of coastal protection values shifted to the reefs providing the protection.).

3.4. Managing reefs

Some 42 % of coral reefs are located in some form of marine protected area (MPA)—a larger share than for most marine habitats [34]. Of coral reefs protecting people, GDP, or infrastructure, 36–39 % of reefs are in MPAs. However such statistics are dominated by those reefs offering relatively low levels of protection. Only 18–20 % of fringing reefs—which offer the greatest protection—are located in MPAs, and even fewer of the coral reefs in the top decile of protection value. Globally, only 15 % of the most important reefs for protecting population are in MPAs, and only 17 % of those protecting GDP or infrastructure are in MPAs, suggesting that a considerable focus of conservation attention is on more remote coral reefs which do not provide coastal protection benefits. Table 4 provides a regional breakdown of these figures.

4. Discussion and conclusions

Previous studies highlight the importance coral reefs in protecting human life and infrastructure [3,4,7]. This study uses simple models with high-resolution data to estimate the distribution of the value of coral reefs. It provides maps that can be viewed and reviewed in the context of national settings and planning, even for relatively small island states and territories.

In line with previous studies, our results show that reefs are providing critical coastal protection in almost every country in which they exist. The results also show the very high spatial variability in the level of protection. Reefs protect people along almost 100,000 km of coastline, but the reefs protecting the most people are very narrowly

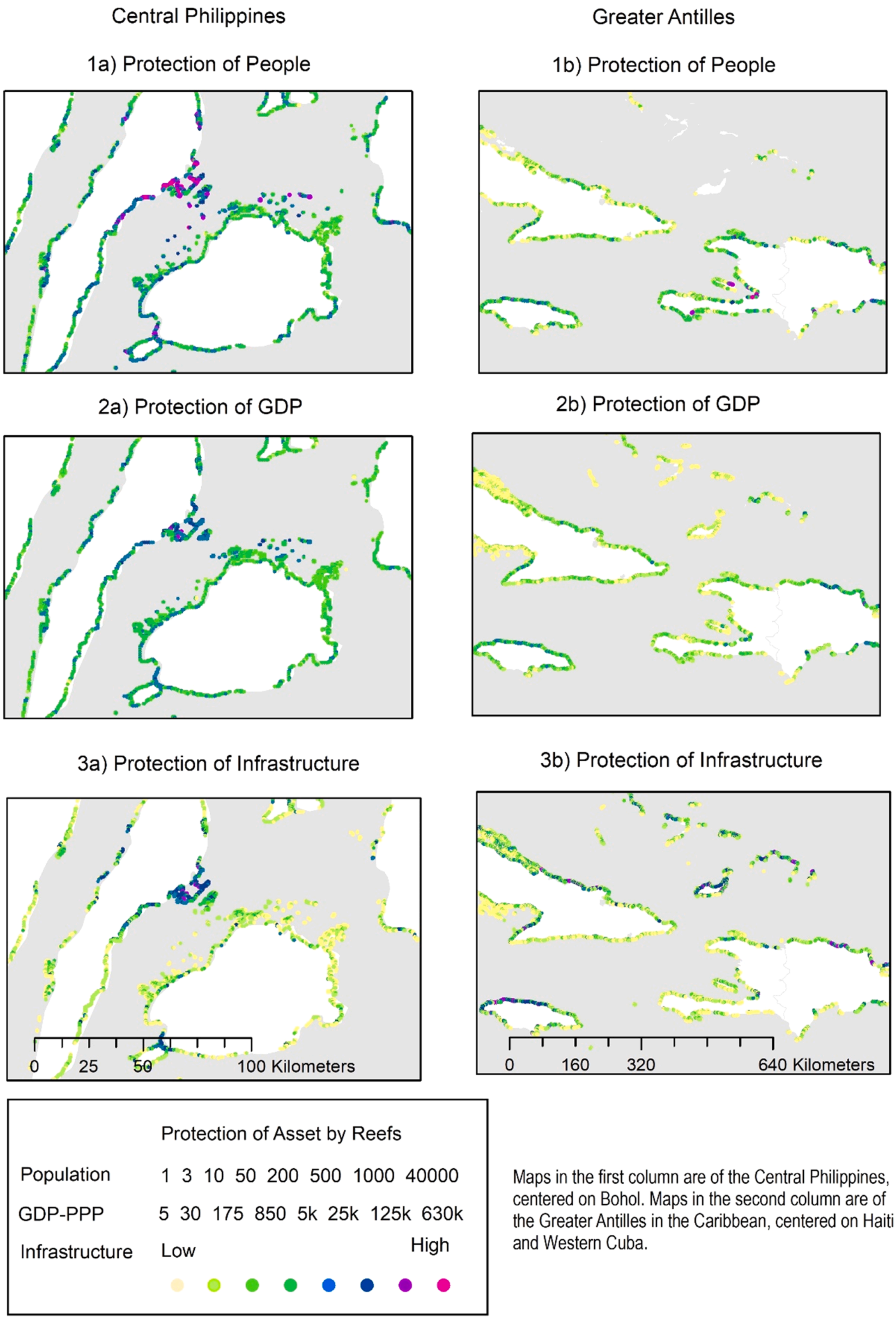

Fig. 4. Coral reef protection against flood risk to people, GDP, and infrastructure per decade in the central Philippines and Greater Antilles.

Table 1
Protection provided by coral reefs in low-lying areas, by region.

Region	Coral reef area (km^2)	Population 2020 (thousands)		Avoided flood damage over 10 years		
		Exposed population in low-lying coastal areas	Population in hazard-adjusted, low-lying coastal areas near reefs[a]	Population avoiding flooding (thousands)[b]	Percent of total coastal population avoiding flooding	Percent of hazard-adjusted population near reefs avoiding flooding
Americas	26,607	36,055	2763	833	2.3	30.2
Australia	42,315	1627	54	12	0.7	21.6
East and Southeast Asia	72,652	103,541	7227	2558	2.5	35.4
Indian Ocean	27,864	42,086	2839	1002	2.4	35.3
Middle East	14,249	11,704	1528	547	4.7	35.8
Pacific	65,979	9939	964	395	4.0	41.0
Total	**249,666**	**204,951**	**15,375**	**5348**	**2.6**	**34.8**

Table 2
Protection of GDP and infrastructure provided by coral reefs in coastal areas, by region.

Region	GDP-PPP 2019 ($ billions)		Flooding damage avoided as a result of coral reefs		
	Exposed GDP in low-lying coastal areas	Hazard-adjusted exposed GDP in low-lying coastal areas near coral reefs	GDP-PPP saved by avoiding flooding ($ billions over 10 years)	Percentage of GDP-PPP loss avoided in low-lying coastal areas	Percentage of GDP-PPP loss avoided in hazard-adjusted areas near coral reefs
Americas	1439.0	77.2	27.2	1.9	35.2
Australia	118.9	4.1	1.0	0.8	24.3
East and Southeast Asia	3165.0	89.7	32.0	1.0	35.7
Indian Ocean	485.1	32.7	11.2	2.3	34.2
Middle East	519.5	78.7	26.9	5.2	34.2
Pacific	136.3	23.0	10.8	7.9	46.9
Total	**5863.8**	**305.5**	**109.0**	**1.9**	**35.7**

Table 3
Protection of people, GDP, and infrastructure provided by coral reefs over a 10-year period, for the 15 jurisdictions with largest coral reef areas.

Country/ territory	Coral reef area (km^2)	Thousands of people avoiding flooding	Percent of hazard-adjusted exposed population avoiding flooding	Millions of dollars protected from flooding	Percent of hazard-adjusted exposed GDP protected from flooding	Relative units of infrastructure protected from flooding	Percent of hazard-adjusted exposed infrastructure protected from flooding
Australia	41,832	11,011	21	1,006,227	24	80,807	22
Indonesia	39,781	605,714	30	9,115,578	30	360,408	32
Philippines	24,505	1,718,923	38	14,610,046	38	224,570	37
Papua New Guinea	14,592	27,381	36	190,197	40	73,254	38
New Caledonia	7450	9936	18	573,332	20	23,824	25
Solomon Islands	6748	34,710	39	135,109	44	54,515	41
Fiji	6570	22,505	33	532,735	35	30,042	38
French Polynesia	5981	27,183	53	767,502	56	55,927	53
Maldives	5281	174,850	55	3,672,246	55	33,905	60
Saudi Arabia	5281	205,374	39	13,393,894	39	381,362	36
Cuba	4931	62,390	26	1,437,647	28	87,413	22
Micronesia	4925	21,853	64	90,349	66	17,851	61
Bahamas	4081	26,560	31	1,405,337	32	93,565	36
Madagascar	3934	81,557	43	175,361	42	49,244	39
United States (Hawaii)	3834	70,343	58	6,792,913	57	56,405	51

distributed. More than 1 million people are estimated to be protected by reefs along just 600 km of coastline.

Not surprisingly, all of the maps and models show close correlation between risk-reduction values of reefs and the degree of coastal development, however, the three broad metrics used reveal different aspects of these values. GDP-PPP is a simple, monetized value, strongly influenced by national wealth. It consequently shows a concentration of value in countries with higher GDP. By contrast, coral reefs play a particularly important role in protecting people in all heavily populated coastal areas, but many poorer countries stand out, especially on the

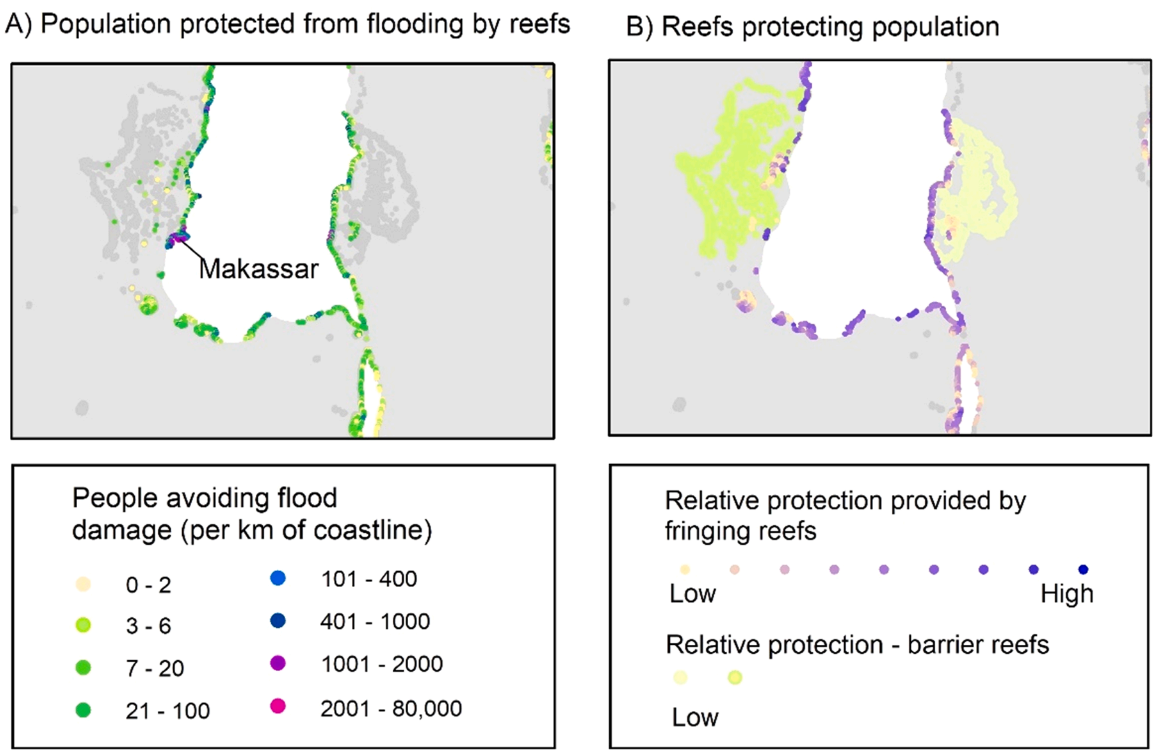

Fig. 5. Protection against flooding damage by fringing and barrier reefs in South Sulawesi, Indonesia. A – the levels of protection provided by reefs, shown at the coast, and indicating the quite high levels of protection, notably in more densely populated areas. B – The same values projected out to the reefs that provide them – while barrier reefs are found on both eastern and western shores, the lack of extensive nearshore fringing reefs in the west greatly increases the importance of the role of the offshore barrier reef in protecting people.

Table 4
Proportion of coral reefs in MPAs, and proportion of coral reef protected people and assets contained within marine protected areas (MPAs).

Region	Percentage of all reefs in MPAs	People		GDP-PPP		Infrastructure	
		Percentage of reefs providing protection to people in MPAs	Percentage of top decile of reefs protecting people in MPAs	Percentage of reefs providing protection to GDP-PPP in MPAs	Percentage of top decile of reefs protecting GDP-PPP in MPAs	Percentage of reefs providing protection to Infrastructure in MPAs	Percentage of top decile of reefs protecting infrastructure in MPAs
Americas	43.1	31.9	26.7	30.2	27.1	32.2	27.5
Australia	86.3	99.3	n.a.	95.9	n.a.	91.1	37.7
East and Southeast Asia	28.1	17.5	11.8	21.0	16.3	19.4	20.7
Indian Ocean	39.6	17.2	19.8	18.5	11.1	15.3	10.0
Middle East	18.9	8.5	2.5	14.0	5.7	14.3	7.3
Pacific	24.8	20.7	12.3	20.5	28.4	20.3	11.9
Total	**42.2**	**35.7**	**15.0**	**35.6**	**17.3**	**39.0**	**16.5**

Note: n.a. Not available – Australia does not have any reefs in the top decile for protection of people or GDP.
Further results from this work, including maps and tables, can be seen in Appendix A. In addition, the data will be made available to be explored and downloaded from www.resourcewatch.org and https://oceanwealth.org/

islands of Southeast Asia, East Africa and much of the Pacific. NTL appear to show a different pattern, with a far more heterogeneous spread, with patches of high values often directly adjacent to lower-value areas, probably capturing the intense light emissions from urban, industrial, and even tourism centers, which, particularly in poorer countries, are somewhat isolated from one another (NTL values are far more continuous in some wealthier settings, such as the Middle East and southern Florida).

Such differences can be best illustrated by example. Madagascar and the US state of Hawaii have similar coral reef extent and a similar size population protected by reefs. However, the spared GDP is nearly 40 times greater in Hawaii than in Madagascar (see Table 3). Such figures underline the importance of considering value across a variety of metrics. In Madagascar, the low monetary value of coral reefs for coastal protection greatly underestimates their importance to people.

The shortfall in conservation management of key protective reefs is notable, because conservation efforts frequently target remote and undisturbed biodiversity [35] or governments avoid management challenges by targeting conservation efforts on largely unutilized remote reefs [36]. By contrast, the very proximity to people of many of the reefs highlighted in this model means that they may have already been affected by local pressures [32]. They may be overlooked for conservation attention because of their already degraded state, creating a vicious circle in which ongoing failure to manage leads to continuing pressures and further degradation. Reefs degraded by local impacts may also have less resilience to larger-scale challenges, such as climate change [37], which could lead to progressive degradation in reef condition following extreme events, with eventual loss of the reef [38].

National commitments under international conventions regularly draw attention to the need to protect ecosystem services alongside biodiversity [39]. One way to break out of the cycle of degradation of protective reefs could simply be to target management efforts at some overlooked but high-value reefs. Protected areas may form part of this management response, but they may not be sufficient; other management interventions may be needed to prevent *ex situ* threats such as sedimentation and pollution [40]. Restoration of damaged reefs may also be an option in some locations to enable a more rapid recovery of coastal protection benefits [5,41].

Climate change is already affecting many coral reefs. Heat-induced coral death and subsequent erosion, exacerbated by sea level rise and changes in storm intensity, may reduce their wave protection function [42,43]. Set against these concerns, many healthy reefs may be able to "keep up" with most predicted rates of sea level rise and recover relatively quickly after storm events [44]. Furthermore, the physical structure of reefs can remain largely intact for some years after die-off events. Although the picture of resilience and recovery is complex, there is growing evidence that many reefs have a considerable capacity to recover from coral die-offs where local threats such as pollution and overfishing are managed and reduced [45,46]. There is also good evidence that recovering corals are slightly better adapted to heat and thus better able to survive future heating events [46,47].

Unchecked global warming will have dire consequences for coastal protection. But good management may buy time. Meanwhile, drawing attention to the clear and irreplaceable value of reefs in protecting millions of people, billions of dollars of GDP, and vital coastal infrastructure can add to the powerful arguments for better management and the urgent need to radically reduce greenhouse gas emissions in the shortest possible timeframe.

Our work provides a model at high resolution for the world's coasts. Its simple approach contrasts with the more process-based global flooding model of Beck et al. [4]. In that model, reduced resolution prevents the assessment of fine-scale patterns of human use and occupancy, leaving many island coasts, including some small island countries, unquantified. Looking broadly, the two global approaches show some correlation, especially for people protected (using national statistics, Pearson's r (119) = 0.78, $p < 0.001$). The overall numbers are very different, however. Our outputs, signifying decadal values, reveal annual protection values that are on average 20 times those of Beck et al. (i.e., approximately twice as high annually). Some of the same authors of the Beck et al. study recently published a high-resolution study for the coasts of the United States and its territories [48] that shows considerably higher values, much closer to our own, with a high correlation (Pearson's r (5) = 0.88, $p < 0.05$).

The results presented here are from models. However, they draw attention to important values and locations where such values are concentrated. The transparent nature of our models will enable potential users to better understand the values presented and to interpret the findings in relation to local knowledge.

One of the key input layers on which many of our findings depend is the global map of coral reefs. Our base map of reefs was derived largely from a globally consistent map of shallow structural reefs [32], gridded to a 500-m cell size. The use of a different base map would greatly affect the maps and value estimates. The source chosen is in keeping with the purpose of the analysis - it focuses on shallow structural coral reefs, which are considered most important in coastal protection.

Future work in this area might benefit from refinements to the input layers. It would also be valuable to explore models and approaches that look at the impacts of potential change arising through both loss and recovery of reefs under different scenarios.

Our models provide a baseline against which researchers can better understand one of the core values of coral reefs: coastal protection. The clear differences among the three metrics used in this study—the effects on people, GDP, and infrastructure—point to the risk of relying on a single metric, particularly monetary value. They also present an approach in which multiple values, including biodiversity [49,50], can be placed alongside other human-centered values [51] to build a holistic and comprehensive base for planning and decision-making in the world's coral reef countries.

CRediT authorship contribution statement

Lauretta Burke: Conceptualisation, Methodology, Formal analysis, Writing – original draft, Visualization. **Mark Spalding:** Conceptualisation, Methodology, Writing – original draft, Visualization.

Acknowledgements

Peter Kerins (WRI), Rachel Thoms (WRI), and Kate Longley-Wood (TNC) provided technical input on data and modeling. Katie Arkema and Becky Chaplin-Kramer (Stanford/Natural Capital Project) generously shared data and advice on shoreline modeling. Kristian Teleki (WRI) encouraged the analysis and Charlotte Schep gracefully managed finances. Katie Wood facilitated graphics and Barbara Karni edited the report. Support for this analysis was provided by the United Nations Environment Programme (UNEP) uner a Global Environment Facility (GEF) grant (GEF Project ID 10424).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105311.

References

[1] J. Madin, K. Black, S. Connolly, Scaling water motion on coral reefs: from regional to organismal scales, Coral Reefs 25 (4) (2006) 635–644, https://doi.org/10.1007/s00338-006-0137-2.
[2] A.R. de Alegria-Arzaburu, I. Mariño-Tapia, C. Enriquez, R. Silva-Casarín, M. González-Leija, Morphodynamics of a Caribbean beach fringed by a coral reef, Coast. Eng. Proc. 1 (33) (2012) 119.
[3] 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) 9, https://doi.org/10.1038/ncomms4794.
[4] 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 (1) (2018) 2186, https://doi.org/10.1038/s41467-018-04568-z.
[5] 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. Manag. 210 (2018) 146–161, https://doi.org/10.1016/j.jenvman.2018.01.024.
[6] 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 (440) (2021), https://doi.org/10.3389/fmars.2021.653945.
[7] 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), https://doi.org/10.3389/feart.2019.00125.
[8] K.K. Arkema, G.M. Verutes, S.A. Wood, C. Clarke-Samuels, S. Rosado, M. Canto, A. Rosenthald, M. Ruckelshaus, G. Guannel, J. Toft, J. Fariesa, J.M. Silvera, R. Griffina, Anne D. Guerry, Embedding ecosystem services in coastal planning leads to better outcomes for people and nature, PNAS 112 (24) (2015) 7390–7395, https://doi.org/10.1073/pnas.1406483112.
[9] I.R. Noble, S. Huq, Y.A. Anokhin, J.A. Carmin, D. Goudou, F.P. Lansigan, B. Osman-Elasha, A. Villamizar, A. Patt, K. Takeuchi, Adaptation Needs and Options, in: Intergovernmental Panel on Climate Change (Ed.), Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 1: Global and Sectoral Aspects, Cambridge University Press, Cambridge, 2014, pp. 833–868.
[10] G. Masselink, E. Beetham, P. Kench, Coral reef islands can accrete vertically in response to sea level rise, Sci. Adv. 6 (24) (2020) eaay3656, https://doi.org/10.1126/sciadv.aay3656.
[11] M.D. Spalding, A.L. McIvor, M.W. Beck, E.W. Koch, I. Möller, D.J. Reed, P. Rubinoff, T. Spencer, T.J. Tolhurst, T.V. Wamsley, B.Kv Wesenbeeck, E. Wolanski, C.D. Woodroffe, Coastal ecosystems: a critical element of risk reduction, Conserv. Lett. 7 (3) (2013) 293–301, https://doi.org/10.1111/conl.12074.

[12] M.B.S.F. Costa, M. Araújo, T.C.M. Araújo, E. Siegle, Influence of reef geometry on wave attenuation on a Brazilian coral reef, Geomorphology 253 (2016) 318–327, https://doi.org/10.1016/j.geomorph.2015.11.001.

[13] M. Jeanson, F. Dolique, M. Sedrati, O. Cohen, J. Bertier, A. Cavalin, J. Charpentier, E.J. Anthony, Wave modifications across a coral reef: Cap Chevalier, Martinique Island, J. Coast. Res. 75 (10075) (2016) 582–586, https://doi.org/10.2112/si75-117.1.

[14] G. Faivre, G.V. da Silva, J. Aimbie, D. Ware, R. Tomlinson, B. Mackey, H. Zhang, Coastal processes within a coral reef lagoon system: Erakor Lagoon, Efate Island, Vanuatu, J. Coast. Res. 95 (SI) (2020) 1427–1432, https://doi.org/10.2112/si95-276.1.

[15] UNGA, 70/1. Transforming our world: the 2030 Agenda for Sustainable Development, United Nations General Assembly, 2015.

[16] UNGA, 69/283. Sendai Framework for Disaster Risk Reduction 2015–2030, United Nations General Assembly, 2015.

[17] UNFCCC, National Adaptation Plans, 2021. 〈https://unfccc.int/topics/adaptation-and-resilience/workstreams/national-adaptation-plans〉. 2022.

[18] M. Beck, G.-M. Lange, Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs, Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), World Bank,, Washington, DC, 2016, p. 166.

[19] P. Menéndez, I.J. Losada, S. Torres-Ortega, S. Narayan, M.W. Beck, The global flood protection benefits of mangroves, Sci. Rep. 10 (1) (2020) 4404, https://doi.org/10.1038/s41598-020-61136-6.

[20] R. Chaplin-Kramer, R.P. Sharp, C. Weil, E.M. Bennett, U. Pascual, K.K. Arkema, K. A. Brauman, B.P. Bryant, A.D. Guerry, N.M. Haddad, M. Hamann, P. Hamel, J. A. Johnson, L. Mandle, H.M. Pereira, S. Polasky, M. Ruckelshaus, M.R. Shaw, J. M. Silver, A.L. Vogl, G.C. Daily, Global modeling of nature's contributions to people, Science 366 (6462) (2019) 255–258, https://doi.org/10.1126/science.aaw3372.

[21] C.B. IPCC, V. Field, T.F. Barros, D. Stocker, D.J. Qin, K.L. Dokken, M.D. Ebi, K. J. Mastrandrea, G.-K. Mach, S.K. Plattner, M. Allen, P.M. Tignor, Midgley, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press,, Cambridge, UK, 2012.

[22] S.A. Kulp, B.H. Strauss, CoastalDEM v2.1: A high-accuracy and high-resolution global coastal elevation model trained on ICESat-2 satellite lidar, Clim. Cent. (2021) 17.

[23] E. Cooper, L. Burke, N. Bood, Coastal Capitall. The Economic Contribution of Belize's Coral Reefs and Mangroves, WRI Working Paper, World Resources Institute,, Washington DC, 2009, p. 53.

[24] E. Kirezci, I.R. Young, R. Ranasinghe, S. Muis, R.J. Nicholls, D. Lincke, J. Hinkel, Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century, Sci. Rep. 10 (1) (2020) 11629, https://doi.org/10.1038/s41598-020-67736-6.

[25] M. Kummu, M. Taka, J.H.A. Guillaume, Gridded global datasets for gross domestic product and human development index over 1990–2015, Sci. Data 5 (1) (2018), 180004, https://doi.org/10.1038/sdata.2018.4.

[26] J. Proville, D. Zavala-Araiza, G. Wagner, Night-time lights: a global, long term look at links to socio-economic trends, PLoS ONE 12 (3) (2017), e0174610, https://doi.org/10.1371/journal.pone.0174610.

[27] R. Sharp, J. Douglass, S. Wolny, K. Arkema, J. Bernhardt, W. Bierbower, N. Chaumont, D. Denu, D. Fisher, K. Glowinski, R. Griffin, G. Guannel, A. Guerry, J. Johnson, P. Hamel, C. Kennedy, C.K. Kim, M. Lacayo, E. Lonsdorf, L. Mandle, L. Rogers, J. Silver, J. Toft, G. Verutes, A.L. Vogl, S. Wood, K. Wyatt, InVEST User's Guide., The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund, 2020.

[28] A. Vila-Concejo, P. Kench, Storms in coral reefs, in: P. Ciavola, G. Coco (Eds.), Coastal Storms, John Wiley & Sons Ltd, 2017, pp. 127–149.

[29] C.T. Perry, L. Alvarez-Filip, Changing geo-ecological functions of coral reefs in the Anthropocene, Funct. Ecol. 33 (6) (2019) 976–988, https://doi.org/10.1111/1365-2435.13247.

[30] D.P. Callaghan, P.J. Mumby, M.S. Mason, Near-reef and nearshore tropical cyclone wave climate in the Great Barrier Reef with and without reef structure, Coast. Eng. 157 (2020), 103652, https://doi.org/10.1016/j.coastaleng.2020.103652.

[31] S.L. Gallop, I.R. Young, R. Ranasinghe, T.H. Durrant, I.D. Haigh, The large-scale influence of the Great Barrier Reef matrix on wave attenuation, Coral Reefs 33 (4) (2014) 1167–1178, https://doi.org/10.1007/s00338-014-1205-7.

[32] L. Burke, K. Reytar, M. Spalding, A.L. Perry, Reefs at Risk Revisited, World Resources Institute, The Nature Conservancy, WorldFish Center, International Coral Reef Action Network, UNEP World Conservation Monitoring Centre and Global Coral Reef Monitoring Network, Washington, D.C., 2011.

[33] M.D. Spalding, C. Ravilious, E.P. Green, World Atlas of Coral Reefs, University of California Press, Berkeley, California, 2001.

[34] UNEP-WCMC, IUCN, Protected Planet: The World Database on Protected Areas (WDPA). January 2021, UNEP-WCMC and IUCN, Cambridge, UK, 2021.

[35] N.J. Gownaris, C.M. Santora, J.B. Davis, E.K. Pikitch, Gaps in protection of important ocean areas: a spatial meta-analysis of ten global mapping initiatives, Front. Mar. Sci. 6 (650) (2019), https://doi.org/10.3389/fmars.2019.00650.

[36] R. Devillers, R.L. Pressey, A. Grech, J.N. Kittinger, G.J. Edgar, T. Ward, R. Watson, Reinventing residual reserves in the sea: are we favouring ease of establishment over need for protection? Aquat. Conserv.: Mar. Freshw. Ecosyst. 25 (4) (2015) 480–504, https://doi.org/10.1002/aqc.2445.

[37] E.S. Darling, T.R. McClanahan, J. Maina, G.G. Gurney, N.A.J. Graham, F. Januchowski-Hartley, J.E. Cinner, C. Mora, C.C. Hicks, E. Maire, M. Puotinen, W. J. Skirving, M. Adjeroud, G. Ahmadia, R. Arthur, A.G. Bauman, M. Beger, M. L. Berumen, L. Bigot, J. Bouwmeester, A. Brenier, T.C.L. Bridge, E. Brown, S. J. Campbell, S. Cannon, B. Cauvin, C.A. Chen, J. Claudet, V. Denis, S. Donner, N. Estradivari, D.A. Fadli, D. Feary, H. Fenner, E.C. Fox, A. Franklin, J. Friedlander, C. Gilmour, J. Goiran, J.-P.A. Guest, A.S. Hobbs, P. Hoey, S. Houk, S.D. Johnson, M. Jupiter, C.-Y. Kayal, J. Kuo, M.A.C. Lamb, J. Lee, N. Low, E. Muthiga, Y. Muttaqin, K.L. Nand, O. Nash, J.M. Nedlic, S. Pandolfi, V. Pardede, L. Patankar, L. Penin, Z. Ribas-Deulofeu, T.E. Richards, Ku.S.Rodgers Roberts, C.D.M. Safuan, E. Sala, G. Shedrawi, T.M. Sin, P. Smallhorn-West, J.E. Smith, B. Sommer, P. D. Steinberg, M. Sutthacheep, C.H.J. Tan, G.J. Williams, S. Wilson, T. Yeemin, J. F. Bruno, M.-J. Fortin, M. Krkosek, D. Mouillot, Social–environmental drivers inform strategic management of coral reefs in the Anthropocene, Nat. Ecol. Evol. (2019), https://doi.org/10.1038/s41559-019-0953-8.

[38] N.A.J. Graham, S. Jennings, M.A. MacNeil, D. Mouillot, S.K. Wilson, Predicting climate-driven regime shifts versus rebound potential in coral reefs, Nature 518 (7537) (2015) 94–97, https://doi.org/10.1038/nature14140.

[39] M. Spalding, I. Meliane, N. Bennett, P. Dearden, P. Patil, R. Brumbaugh, Building towards the marine conservation end-game: consolidating the role of MPAs in a future ocean, Aquat. Conserv.: Mar. Freshw. Ecosyst. (2016), https://doi.org/10.1002/aqc.2686.

[40] S.L. Wear, Battling a common enemy: joining forces in the fight against sewage pollution, Bioscience 69 (5) (2019) 360–367, https://doi.org/10.1093/biosci/biz025.

[41] C. Zepeda-Centeno, I. Mariño-Tapia, E. McLeod, R. Rodríguez-Martínez, L. Alvarez-Filip, A.T. Banaszak, M. Escudero-Castillo, R. Silva-Casarín, E. Mendoza-Baldwin, M. Beck, E. Shaver, Guidance Document for Reef Management and Restoration to Improve Coastal Protection: Recommendations for global applications based on lessons learned in Mexico, The Nature Conservancy, Mexico, 2018.

[42] C. Sheppard, D.J. Dixon, M. Gourlay, A. Sheppard, R.A. Payet, Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles, Estuar. Coast. Shelf Sci. 64 (2005) 223–234, https://doi.org/10.1016/j.ecss.2005.02.016.

[43] 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 (2015) 6407–6415, https://doi.org/10.1002/2015GL064861.

[44] C. Villanoy, L. David, O. Cabrera, M. Atrigenio, F. Siringan, P. Aliño, M. Villaluz, Coral reef ecosystems protect shore from high-energy waves under climate change scenarios, Clim. Change 112 (2) (2012) 493–505, https://doi.org/10.1007/s10584-012-0399-3.

[45] K.L. Cramer, J.B.C. Jackson, M.K. Donovan, B.J. Greenstein, C.A. Korpanty, G. M. Cook, J.M. Pandolfi, Widespread loss of Caribbean acroporid corals was underway before coral bleaching and disease outbreaks, Sci. Adv. 6 (17) (2020) eaax9395, https://doi.org/10.1126/sciadv.aax9395.

[46] M. Montefalcone, C. Morri, C.N. Bianchi, Influence of local pressures on Maldivian coral reef resilience following repeated bleaching events, and recovery perspectives, Front. Mar. Sci. 7 (587) (2020), https://doi.org/10.3389/fmars.2020.00587.

[47] T.R. McClanahan, Changes in coral sensitivity to thermal anomalies, Mar. Ecol. Prog. Ser. 570 (2017) 71–85, https://doi.org/10.3354/meps12150.

[48] B.G. Reguero, C.D. Storlazzi, A.E. Gibbs, J.B. Shope, A.D. Cole, K.A. Cumming, M. W. Beck, The value of US coral reefs for flood risk reduction, Nat. Sustain. 4 (8) (2021) 688–698, https://doi.org/10.1038/s41893-021-00706-6.

[49] C.M. Roberts, C.J. McLean, G.R. Allen, J.P. Hawkins, D.E. McAllister, C. Mittermeier, F. Schueler, M. Spalding, J.E.N. Veron, F. Wells, C. Vynne, T. Werner, Marine biodiversity hotspots and conservation priorities for tropical reefs, Science 295 (2002) 1280–1284, https://doi.org/10.1126/science.1067728.

[50] E.R. Selig, W.R. Turner, S. Troëng, B.P. Wallace, B.S. Halpern, K. Kaschner, B. G. Lascelles, K.E. Carpenter, R.A. Mittermeier, Global priorities for marine biodiversity conservation, PLoS One 9 (1) (2014), e82898, https://doi.org/10.1371/journal.pone.0082898.

[51] M.D. Spalding, L. Burke, S. Wood, J. Ashpole, J. Hutchison, Pz Ermgassen, Mapping the global value and distribution of coral reef tourism, Mar. Policy 82 (2017) 104–113, https://doi.org/10.1016/j.marpol.2017.05.014.