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Global protection from tropical cyclones by coastal ecosystems—past, present, and under climate change

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Abstract

Coastal ecosystems have the potential to contribute to disaster risk reduction and adaptation to climate change. While previous studies have estimated the value of current coastal ecosystems for reducing coastal risk, there have been relatively few studies that look at changes in ecosystem service provision, in the past and under climate change. We employ the probabilistic, event-based CLImate ADAptation platform (CLIMADA) to quantify the protection from tropical cyclones (TCs) provided by coastal ecosystems, modeling the number of beneficiaries in the past and under future climate change. We also investigate the potential of nature-based solutions (NbS), such as mangrove restoration. We find that currently, one in five (21%) of all people impacted annually by TCs in the global low-elevation coastal zone is within the protection distance of coastal ecosystems. Over the last 30 years, the share of protected people has decreased by approximately 2%, due to ecosystem loss. With climate change, the average annual number of people impacted will increase by 40%. Simultaneously, the proportion of people protected by coastal ecosystems with climate change decreases due to changes in TC distribution (−1%). The importance of current coastal protection, and the potential for increasing protection by NbS, varies widely between countries. While the number of people protected globally only increases slightly with mangrove restoration, the share of people protected in individual countries can increase by up to 39%. Our findings provide a basis for NbS planning and adaptation policy, by highlighting areas which will be crucial for coastal protection services in a world altered by climate change.

1. Introduction

Communities in low-lying coastal areas are increasingly at risk of extreme sea level events such as tropical cyclone (TC) storm surges, often exacerbated both by sea-level rise due to climate change and non-climatic drivers, including historical population and settlement trends (Oppenheimer *et al* 2019). With climate change, models show an increase in both the intensity and frequency of TCs (Knutson *et al* 2020, Emanuel 2021, Bloemendaal *et al* 2022). Therefore, climate change will likely exacerbate TC risk across the globe (Lin *et al* 2012, Collins *et al* 2019). The projected changes necessitate large-scale adaptation efforts globally, especially in coastal areas which are not only exposed to direct wind damage but also damage from resulting storm surges.

Coastal ecosystems such as mangroves, coral reefs, seagrass, coastal forests, and salt marshes have the potential to reduce disaster risk (Arkema *et al* 2013, Spalding et al 2014a, Beck et al 2018, Chaplin-Kramer et al 2019, 2023, Reguero et al 2019, 2021, Selig et al 2019, Menéndez et al 2020, Costanza et al 2021, Tiggeloven et al 2022). Benefits derived from nature are often encompassed in concepts such as nature-based solutions (NbS), ecosystem-based disaster risk reduction, and ecosystem-based adaptation (IUCN 2016, Sudmeier-Rieux et al 2021, UNDRR 2021, Cooley et al 2022). The mechanisms by which these ecosystems reduce TC associated risks include the reduction of wind speed, water retention, acting as a barrier to prevent flooding, and attenuating wave height and energy (Wamsley et al 2010, Shepard et al 2011, Duarte et al 2013, Pinsky et al 2013, Ferrario et al 2014, Guannel et al 2016, Narayan et al 2016, Sudmeier-Rieux et al 2021, Jordan and Fröhle 2022).

At the same time, coastal ecosystems are negatively affected by anthropogenic habitat degradation (Oppenheimer et al 2019). Thus, protection and restoration measures have been proposed to maintain the protective function of coastal ecosystems (Beck et al 2018, Worthington and Spalding 2018, Cooley et al 2022, Tiggeloven et al 2022). To maintain or even increase nature's role in coastal protection requires knowledge about the location of potential beneficiaries in relation to both coastal risk and coastal ecosystems. It is also necessary to identify historical and potential future changes in the patterns and magnitude of nature's protective potential (Spalding et al 2014b, Ruckelshaus et al 2020). Probabilistic risk assessment can provide a nuanced picture of risk since it reflects not only the severity of potential impacts but also the probability of a coastal risk materializing (Aznar-Siguan and Bresch 2019). While previous studies have estimated the number of beneficiaries of risk reduction through coastal natural habitat, there have been few studies that looked at changes in global ecosystem service provision, historically and with climate change (Arkema et al 2013, Beck et al 2018, Selig et al 2019, Menéndez et al 2020, Burke and Spalding 2022, Chaplin-Kramer et al 2023).

Using a combination of ecosystem index data and probabilistic risk modeling, we aim to answer the question: how has coastal protection by ecosystems changed over time and how will it evolve with a change in TC hazard due to climate change? We explore this question based on both historical and potential future changes of coastal ecosystems, population, and climate. Thereby, we quantify how many people on average are annually protected by coastal ecosystems currently and in the past taking into consideration population and ecosystem change. Looking to the future, we interrogate how coastal protection by ecosystems may change with climatic changes and large-scale efforts in nature restoration.

2. Data and methods

2.1. Data

2.1.1. Population exposure

WorldPop is an annual gridded population data product, which uses ancillary data sources to downscale population counts to 1 km resolution (WorldPop 2018, Lloyd et al 2019). The datasets are spatio-temporally consistent, making WorldPop population data suitable for comparison between years, in contrast to some other available global population datasets (Lloyd et al 2019, Ruckelshaus et al 2020). Populations living in the low-elevation coastal zone, i.e. coastal areas less than 10 m above sea-level, are especially subject to coastal risk but are also closest to coastal ecosystems (Oppenheimer et al 2019). For the current baseline, we use population data from 2020, while for the historical analysis data from 2000 is used[10]. Using a digital elevation model (Earth Resources Observation And Science (EROS) Center 2017), at a resolution of 1 arcsecond, we confine the exposure dataset to the population living within 10 m elevation of sea level before integrating it into the CLIMADA (CLImate ADAptation) open-source probabilistic modeling platform, described in more detail in section 2.2.1.

2.1.2. Coastal ecosystem protective capacity

We overlay our population exposure with data from the InVEST Coastal Vulnerability Model, which produces an index-based assessment of coastal vulnerability based on several factors, including the presence of coastal habitats (Natural Capital Project 2019, 2022, Ruckelshaus et al 2020). Using a combination of terrestrial coastal land cover and offshore coastal habitat data as inputs, the model computes an ecosystem rank, to reflect the ecosystem-based protection of points along the coastline (UNEP-WCMC, Short FT 2005, Burke et al 2011, ESA CCI-LC 2017, Mcowen et al 2017, Bunting et al 2018, Natural Capital Project 2019). In addition to the spatial distribution of individual coastal habitats and their protective potential, this computation considers the vicinity of multiple habitats and their combined protective potential. Previous research has shown that a combination of vegetation types has an additive benefit, therefore mixed habitats receive a better ranking than individual habitat types (Guannel et al 2016, Natural Capital Project 2019). This yields a relative ranking of the protective potential of different combinations of coastal ecosystems, where a rank close to 1 corresponds to a very highly protective habitat, while a rank of 5 corresponds to no protective habitat (see table 1).

[10] Although the historical ecosystem data is from 1992, we use population data from 2000 as a proxy, since earlier WorldPop data is not available.

Table 1. Exemplary coastal ecosystems ranking table computed with the InVEST coastal vulnerability model (adapted from Natural Capital Project 2022).

Combination of coastal vegetation types	Ranking
None	5—None
Seagrass	4—Low
Saltmarsh/wetland	3—Medium
Saltmarsh/wetland seagrass	3—Medium
Reefs	2—High
Mangroves/coastal forest	2—High
Reefs seagrass	2—High
Mangroves/coastal forest seagrass	2—High
Reefs saltmarsh/wetland	2—High
Mangroves/coastal forest saltmarsh/wetland	2—High
Reefs mangroves/coastal forest	1—Very high
Reefs mangroves/coastal forest saltmarsh/wetland	1—Very high
Reefs mangroves/coastal forest saltmarsh/wetland seagrass	1—Very high

To integrate the ecosystem data obtained from the InVEST model into CLIMADA, population exposure points are matched with the ecosystem rank data within the maximum protection distance (2000 m), i.e. the radius within which coastal ecosystems are expected to serve a protective function (Natural Capital Project 2022) (for more information see supplementary material figure 1 and tables 1–3). Where multiple matches are possible, exposure points are assigned the best possible rank, following the reasoning that the vicinity of multiple coastal ecosystems has an additive benefit (Guannel *et al* 2016). This is calculated based on a historical habitat layer for 1992 and a current baseline layer for 2020, as well as a layer for the restoration scenario elaborated below.

2.1.3. Mangrove restoration scenario

To model how protection by coastal ecosystems may change in the future due to measures to restore nature, we use a mangrove restoration potential scenario. This is builds up on the Mangrove Restoration Potential map, the methodology of which is described by Worthington and Spalding (2018). In the scenario, all areas where mangroves have been recently lost (between 1996 and 2020) and which are assessed as having the potential to be restorable are converted back to mangrove habitat, excluding areas which have been converted to urban land use or have eroded into non-tidal open water (Worthington and Spalding 2018). To quantify the impact of mangrove restoration, we model the change in number of people protected from TCs by coastal ecosystems compared to current ecosystems.

2.1.4. Hazard data

We use hazard data from the Synthetic Tropical cyclOne geneRation Model (STORM) to probabilistically model TCs under both current and future climatic conditions (Bloemendaal *et al* 2020, 2022). STORM uses historical storm track data from the International Best Track Archive for Climate Stewardship and meteorological datasets from climate models to generate synthetic tracks for 10 000 years of TC activity by resampling tracks and intensities from the underlying dataset (Bloemendaal *et al* 2020, 2022). Thus, STORM contains many more events than the historical TC record, including low-probability events, which enables a more accurate assessment of the hazard, and consequently, the risk. The future hazard modeled by STORM is based on SSP585 over the period 2015–2050. This is a high-emission scenario, which is in line with historical cumulative emissions and current policies; however, the model authors highlight that the average climate conditions during that time period do not vary much between low- and high-emission scenarios (O'Neill *et al* 2016, Schwalm *et al* 2020, Bloemendaal *et al* 2022). In CLIMADA, the storm tracks are used to generate wind fields for each event using the Holland model (Holland 2008). We use TC wind speeds as a proxy for a variety of associated sub-hazards, including storm surge, heavy precipitation, and landslides.

2.2. Method

2.2.1. Impact and protection

This research uses the open-source probabilistic modeling platform CLIMADA to perform a TC risk assessment for populations in the vicinity of coastal ecosystems (Aznar-Siguan and Bresch 2019, Bresch and Aznar-Siguan 2021). Risk is defined as the probability of an event occurring multiplied by its severity and is obtained by combining the hazard (probabilistic TC set), exposure (population distributions), and vulnerability. Here we use a simplified vulnerability model and only count the number of people affected by every Saffir-Simpson TC scale value 1–5 to capture all potential ecosystem service beneficiaries (National Hurricane Center 2022). CLIMADA is spatially explicit, which means impact is measured by calculating which exposures (i.e. number of people) are located in an event's windfield. Hence, we obtain the severity, or impact, of each TC event in the probabilistic set as the number of people subject to a maximum wind speed of a given category. Subsequently, we compute the average annual impact, or risk, per exposure point by averaging over all events weighted by their annual occurrence probability. This thus covers yet differentiates regions that are regularly and rarely exposed to TCs.

Using a spatial overlay with InVEST coastal ecosystem data, we assess the absolute number and proportion of people simultaneously within the protection distance of coastal ecosystems, i.e. the radius within which coastal ecosystems have the potential to provide a protective service to coastal populations. The number of people protected by coastal ecosystems then corresponds to the sum of all impacted people that are within the protection distance of coastal ecosystems (see section 2.1.2). Thus, protection occurs if there is a non-zero probability of a TC at the given location, and population exposure within the protective distance of coastal ecosystems. Conversely, non-protection occurs if a population exposure is impacted outside the protective distance of any coastal ecosystem. The average number of people impacted annually can be aggregated across exposure points, for example to calculate the average number of people impacted in a certain region, or a given coastal ecosystem category, per year. The proportion of people protected (in %) refers to the fraction of people impacted within the protection distance of coastal ecosystems. Note, this is a proportion of the total number of people impacted (i.e., experience TCs and are at an elevation below 10 m above sea level), not a share of the total number of people in the exposure dataset.

2.2.2. Comparison across scenarios

We explore how the protection of people in the low-elevation coastal zone by coastal ecosystems evolves over time based on changes in the population distribution, the coastal ecosystems themselves, and the TC climatology. A baseline is established to reflect the current level of coastal protection through ecosystems based on ecosystem service and population data for 2020, as well as TC hazard data from the STORM model based on the current climatic conditions. We then quantify changes from the baseline: first, historical changes due to developments in population and ecosystems between 1992 and 2020 are investigated. Next, potential changes in impact and protection due to a changed hazard under climate change until 2050 are analyzed. Finally, the impact of mangrove restoration is assessed. Figure 1(a) shows protection in 1992 (historical), 2020 (baseline) and 2050 (future under climate change), while figure 1(b) shows how changes in the population distribution, the coastal ecosystems themselves, and the TC climatology affects the relative share of protected people. Below, we first discuss the geographical patterns of protection in the baseline (section 3.1), before further investigating historical and future changes, and the factors influencing these changes (sections 3.2–3.4).

3. Results

3.1. Current baseline

On average every year 14 million people benefit from protection from TCs by coastal ecosystems worldwide (see middle bar in figure 1(a)). This equates to one in five (21%) of all people in the low elevation coastal zone currently impacted by TC being within the protection distance of coastal ecosystems (see middle bar in figure 1(b)). To contextualize this annual average over a time period relevant for disaster risk management and adaptation planning, this means that over a time period of 50 years, the expected number of people protected globally would be 700 million. Of those protected, the highest numbers of people are seen for high levels of protection by coastal ecosystems and low wind speed categories (figure 1(a), supplementary material table 4).

Global scale absolute and relative numbers of people protected by coastal ecosystems only provide limited information, since the patterns and levels of protection are not evenly distributed. The highest number of people impacted are found in Eastern- and South-Eastern Asian countries (figure 2(a), table 2), due to a combination of high population density and exposure to high levels of TC hazards. Very high and high degrees of protection, as well as a complete lack of protection at individual population exposure points, can be found across global coastlines (figure 2(b)). However, the share of impacted population within coastal ecosystem protection distance differs considerably between geographical regions. For instance, the difference in the proportion of people protected between Southern Asia and the Caribbean, where the lowest and highest share can be found (8% and 53% respectively), is 45% (figure 3(a)). The highest absolute number of people protected from TC by coastal ecosystems are found in the Philippines, China, and Japan (table 2). However, the relative proportion of people protected is highest for countries in the Caribbean and Pacific Islands, where 69%–92% of the impacted people are within the protection distance of coastal ecosystems (table 2).

3.2. Past changes: population development and coastal ecosystem loss

Due to an increase in coastal population, the absolute number of people currently protected is 18% higher than 30 years ago (2.2 million more people protected annually) (see change from historical to current bar in figure 1(a)). However, the proportion protected decreases by approximately 2% between 1992 and 2020 (see change from historical to current bar in figure 1(b)). The decrease in the proportion of people protected is almost entirely due to coastal ecosystem loss (95% of the decrease), and to a lesser extent due to population change (3% of the decrease) (see change in proportion protected based on ecosystem and population change in figure 1(b)). Note

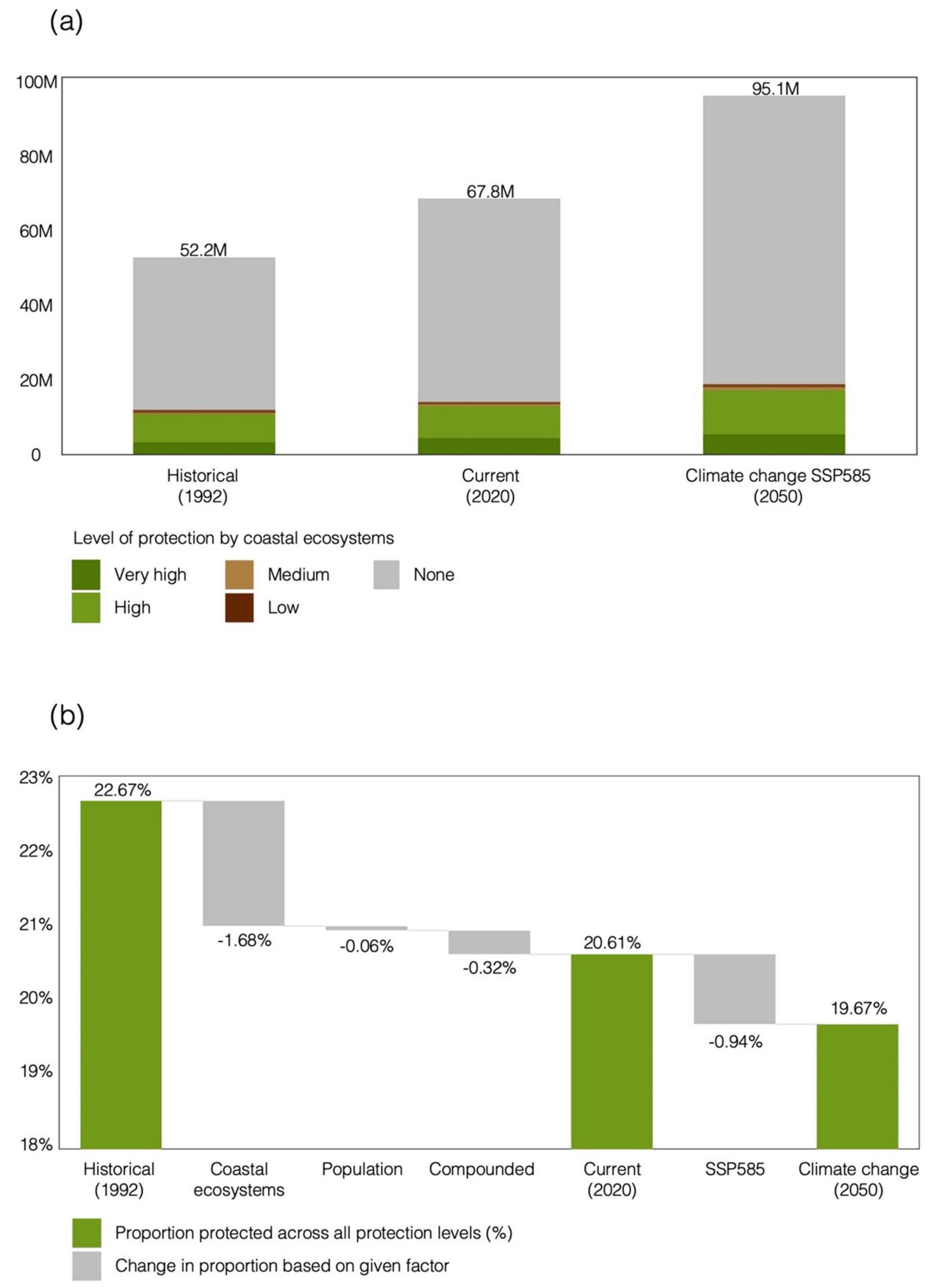

Figure 1. (a) Global total number of people impacted annually historically (1992), under the current climate (2020), and with climate change (SSP585 in 2050). The colors indicate the degree of protection by coastal ecosystems, while the gray color indicates non-protection. (b) The global proportion of people protected historically (1992), under the current climate (2020), and with climate change (SSP585 in 2050), and the different factors influencing these changes including loss of coastal ecosystems, population changes, compounding effects of the latter two, and climate change. Note that 'compounded' refers to the change in protection that occurs if coastal ecosystems and population exposure are varied simultaneously, i.e. in addition to the changes in protection based on the two factors individually.

that the change in the proportion protected when considering both ecosystem and population change is larger than the sum of these changes when varying each factor individually (see compounded change in figure 1(b)). This indicates that increases in population have occurred predominantly in areas where

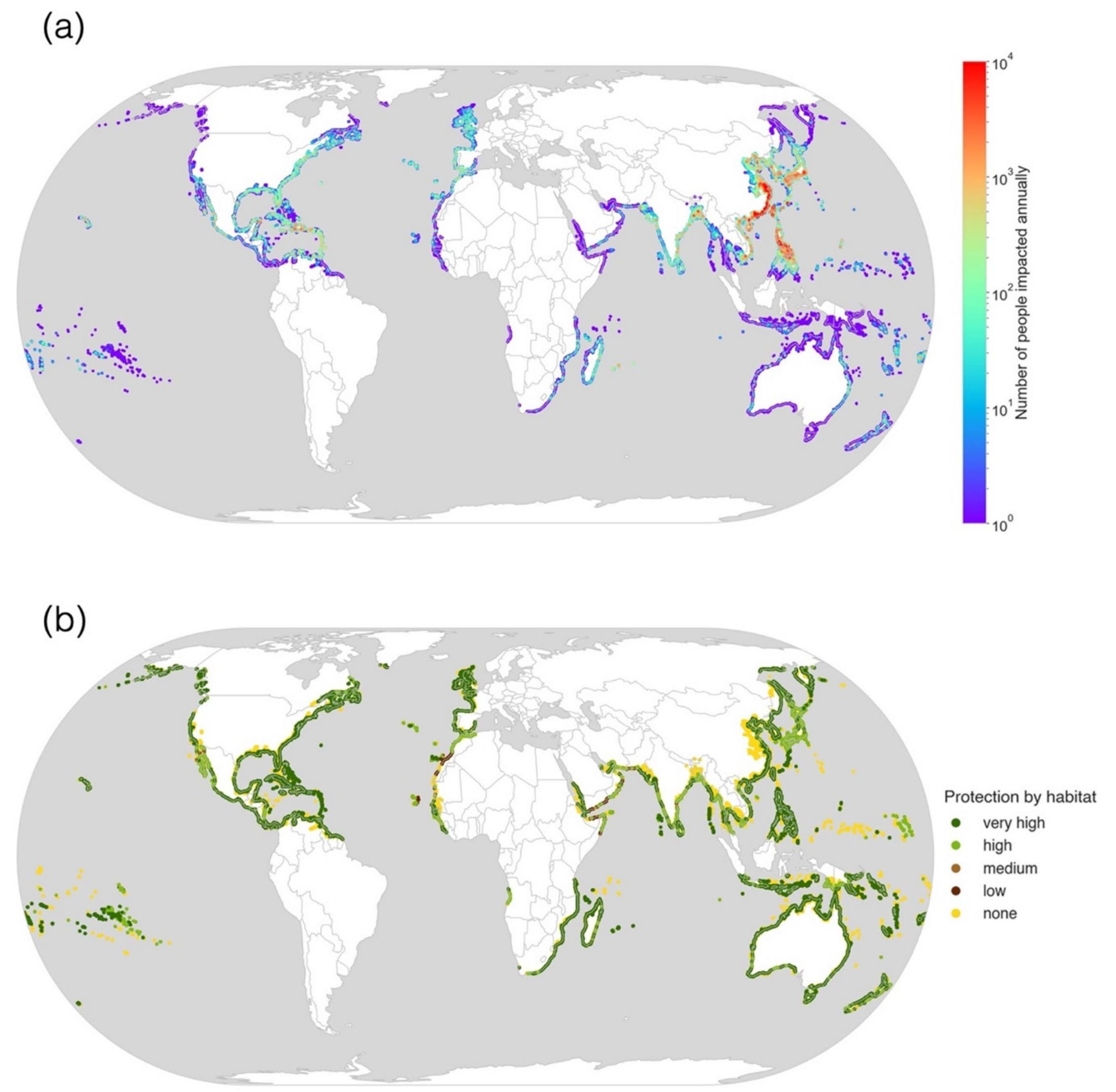

Figure 2. (a) Population in the low-elevation coastal zone impacted by tropical cyclones (TC) globally under current conditions. Each point represents an exposure point impacted by TC, while the color shows the number of people impacted per exposure point annually. Note the logarithmic scale. (b) Population in the low elevation coastal zone protected from TC by coastal ecosystems globally under current conditions. The color refers to the degree of protection by nearby coastal ecosystems. Note that only exposure points with a non-zero average annual impact are plotted, i.e. the coastal ecosystem protective rank is only mapped for points impacted by tropical cyclones.

coastal vegetation has been lost between 1992 and 2020. This combination of ecosystem and population changes compounds to an added decrease in protection (2% of the decrease).

This global view is differentiated further when considering regional changes. Between 1992 and 2020, all regions experience an increase in the annual number of people impacted and protected (compare top and bottom bars for each region in figure 3(b)). This increase in absolute numbers impacted and protected is due to a higher population exposure caused by population growth. However, protection in relative terms developed differently across regions, with a general decrease in the share of people protected over the last 30 years observed. The regions most affected by a loss of protection through coastal ecosystems are South America, Northern Africa, and Eastern Asia (decreases of 3%, 2%, and 2%) (figure 3(a)). While most regions experience a decrease in the share of people protected across any degree of protection, there are some exceptions. Only three regions, namely the Caribbean, Central America, and East Africa, experience an increase in the share of people protected in 2020 (figure 3(a)). This increase of the share protected is due to more people currently living in the vicinity of coastal ecosystems in 2020 compared to 1992, while decreases in protection due to coastal ecosystem loss overall are relatively minor in these regions (supplementary material table 5).

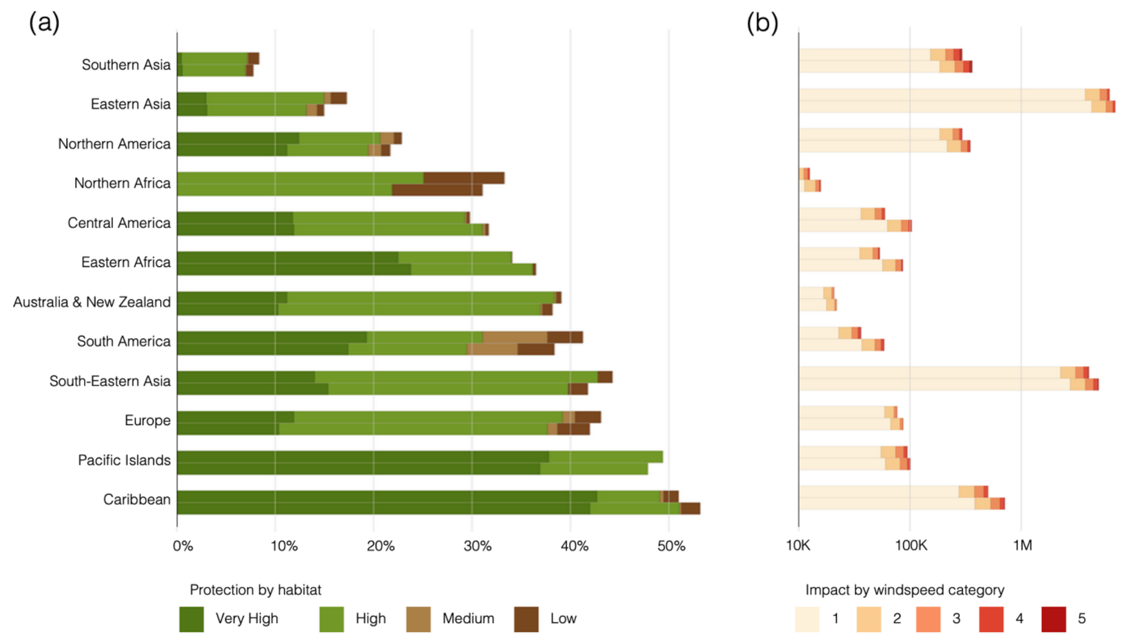

Figure 3. (a) Proportion of people protected (%) from tropical cyclones by coastal ecosystems across different regions. The colors indicated the degree of protection (very high to low). In both panels, the top bar shows the historical numbers (1992), while the bottom bar shows the current baseline numbers (2020). (b) Absolute number of people impacted annually per region. The colors show the Saffir-Simpson wind speed category. Note the log-scale on the x-axis.

Table 2. Highest ranking countries or areas in terms of the absolute number of people impacted annually, highest number of people protected, and the proportion of people protected. For each high-ranking country in one of these categories, the rank across the other categories is shown as well. The column 'Total number of people impacted annually' refers to the average number of people impacted by tropical cyclones per country each year. 'Number of people protected annually' gives the average number of people protected per country each year, while 'Proportion of people protected' shows the people protected as a share of people impacted per country.

Highest ranking countries for absolute and relative protection								
Total number of people impacted by tropical cyclones annually			Number of people protected annually			Proportion of people protected (%)		
1	China	30 M	1	Philippines	5 M	1	US Virgin Islands	92%
2	Japan	11 M	2	China	4 M	2	Saint Vincent and the Grenadines	84%
3	Philippines	9 M	3	Japan	2 M	3	Saint Kitts and Nevis	72%
4	Taiwan ROC	3 M	4	Hong Kong SAR	0.8 M	4	Hong Kong SAR	70%
5	Viet Nam	2 M	5	South Korea	0.5 M	5	Northern Mariana Islands	69%
…								
9	South Korea	1 M	6	Taiwan ROC	0.5 M	21	Philippines	51%
10	Hong Kong SAR	1 M	8	Viet Nam	0.3 M	38	South Korea	35%
53	Northern Mariana Islands	17 K	38	Saint Vincent and the Grenadines	13 K	52	Japan	15%
55	Saint Vincent and the Grenadines	16 K	40	US Virgin Islands	13 K	53	Taiwan ROC	15%
56	US Virgin Islands	14 K	42	Northern Mariana Islands	12 K	56	China	12%
59	Saint Kitts and Nevis	12 K	51	Saint Kitts and Nevis	8 K	57	Viet Nam	11%

3.3. Potential effect of climate change

With climate change, TC frequency and intensity are likely to change (Knutson *et al* 2020, Emanuel 2021, Bloemendaal *et al* 2022). Therefore, we expect to see changes in the number of people impacted by TC annually and protected by coastal ecosystems. We modeled the number of people impacted and protected under the SSP585 climate change scenario, while keeping population and ecosystem data constant at the 2020 baseline level.

We observe an increase in both the number of people impacted, as well as the number of people

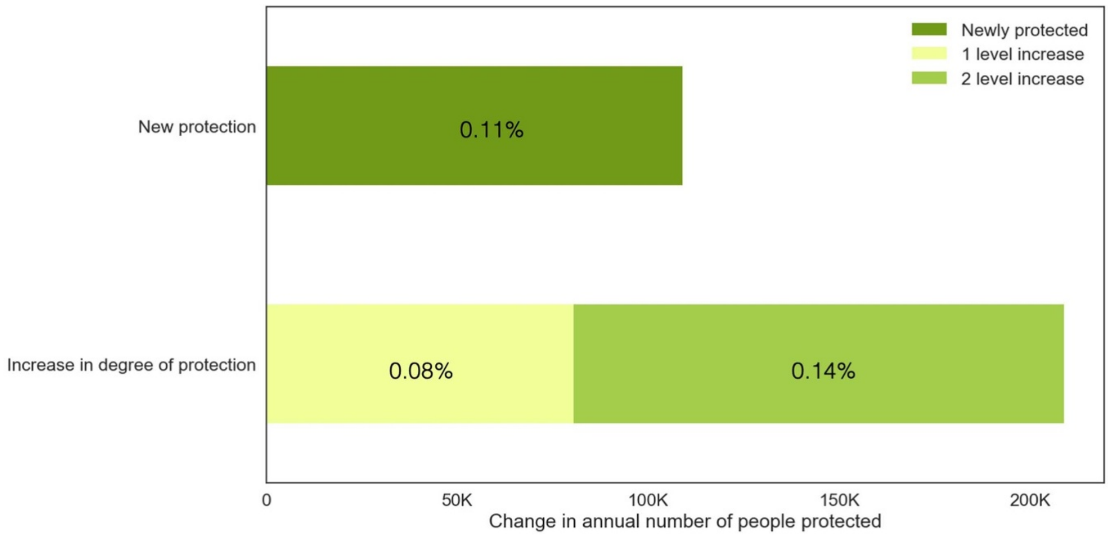

Figure 4. Global increases in the proportion of people protected for the mangrove restoration and reforestation scenarios. The top bar represents the increase in total protection, i.e. changes from non-protection in the baseline to protection under the restoration scenario. The lower bar represents the increase in the degree of protection for areas which already receive some level of protection in the baseline. The *x*-axis indicates the increases in absolute numbers of people protected annually, the percentages within the bar chart indicate the increase in the share of people protected. The increase in the degree of protection is higher than the total increase in protection, which indicates that the mangrove restoration scenario mainly causes an increase in the ranking of areas already receiving some degrees of protection.

protected. Currently, 67.8 million people in the global low-elevation coastal zone are potentially impacted by TC annually, 14.0 million of which are protected by coastal ecosystems (see middle bar in figure 1(a)). With climate change, the number impacted increases by 27 million (95 million impacted annually in total) (see right bar in figure 1(a)). This constitutes a 40% increase of the number of people impacted across all wind speed categories. However, the number of people protected increases less than the number impacted (34% higher compared to the baseline), resulting in a 1% decrease in the share of people protected compared to the baseline (compare middle and right bar in figure 1(b)). While this decrease in the share of people protected globally is relatively small, given the number of people impacted under climate change, this decrease corresponds to 1 million people every year. Annual average impacts serve as useful metrics for comparisons, but it is important to bear in mind that annual averages can obscure the magnitude of extreme events. For instance, with climate change, the global annual average number of people impacted by category 5 wind speeds (252 km h^{-1} or higher) is approximately 1 million people; however, ten times as many people may be impacted by a single event with a 150 year return period in the Western Pacific (see supplementary material figure 2). Thus, even small losses of average annual protection by coastal ecosystems can have very negative effects for individual events, since extreme events are becoming more likely with climate change.

3.4. Potential changes under nature protection and restoration scenarios

Under the mangrove restoration scenario and considering changes in TC due to climate change, every year 109 000 more people may be protected from TCs by coastal ecosystems respectively. The fraction of people protected would thereby increase by 0.1% (figure 4). It is noticeable that the increase in the degree of protection by coastal ecosystems is higher than switches from non-protection to protection (209 000 people annually, which corresponds to a relative protection increase of 0.2%, or 6.27 million over 30 years) (figure 4). This results from restoration occurring mostly in areas which already provide some level of protection rather than areas which are completely unprotected.

The global increase in protection is relatively minor compared to historical losses; however, mangroves are confined to low and mid latitudes. On a country-scale, much higher gains in the level of coastal ecosystem-based protection are discernable than globally. Based on the global observation that changes occur mostly in terms of shifts within levels of ecosystem-based protection, we look at increases in the fraction of people under very high protection, rather than changes from non-protection to protection (table 3). The highest country-level increase occurs for mangrove restoration in Bermuda (39% increase in the fraction under very high protection), although increases for other countries are in the low single digits (table 3). For countries with currently

Table 3. Country-level changes in very high protection under the mangrove restoration scenario with climate change (SSP585) in 2050. The five countries with the biggest changes are listed, both in terms of absolute and relative changes.

Countries with biggest changes in very high protection under mangrove restoration scenario				
Country	Number of people impacted annually	Baseline value under very high protection	NbS scenario value under very high protection	Difference between baseline and scenario
		Absolute change		
China	45.9 M	1.4 M	1.5 M	103.4 K
Philippines	11.0 M	2.1 M	2.2 M	35.9 K
Bermuda	8.2 K	3.5 K	6.6 K	3.2 K
Trinidad and Tobago	42.1 K	14.4 K	15.9 K	1.5 K
Barbados	30.1 K	9.8 K	11.3 K	1.5 K
		Relative change		
Bermuda	8.2 K	42.6%	81.3%	38.7%
Barbados	30.1 K	32.5%	37.4%	4.9%
Trinidad and Tobago	42.1 K	34.2%	37.7%	3.5%
Papua New Guinea	6.3 K	31.1%	32.3%	1.2%
Sri Lanka	30.3 K	6.7%	7.5%	0.8%

small mangrove extents, even minor increases in mangrove land cover can result in comparatively high increases in protection. Smaller countries and island states benefit especially.

4. Discussion

Globally, a minority (21%) of all people impacted by TCs in coastal areas are currently within the protection distance of coastal ecosystems. However, in certain countries, a large majority of impacted people are protected, which highlights the importance of coastal ecosystems, as well as the need for analyzing NbS across a variety of spatial scales. In terms of absolute numbers of people, highly populated countries in Eastern and South-Eastern Asia are the chief beneficiaries of the coastal protection from TCs of mangroves and coastal forests, coral reefs, sea grass, salt marshes and wetlands. However, in proportional terms, protection by coastal ecosystems is key for small island states and developing countries, especially in the Caribbean and Pacific Islands.

In this study, we use maximum sustained wind speed as a proxy for all TC sub-hazards (storm surges, heavy precipitations, floods, landslides, etc), and therefore cannot model the physical mechanisms (e.g. wave attenuation or water retention) through which coastal ecosystems reduce risk. Thus, the risk reduction reported here relies on the assumption that sub-hazard intensities (e.g. precipitation and surge wave heights) and the derived impacts are correlated to the maximum wind speed, which may not always be the case. This relationship should be treated with caution at local scales but is reasonable over large spatial extents and compatible with the resolution and sophistication of the ecosystem model. Hence, we modeled the ecosystem service in a semi-quantitative fashion only: the ecosystem risk reduction potential is a ranking score, and the hazard intensity is categorized into the Saffir-Simpson scale. Protection is provided as soon as a pixel is below 10 m elevation, is within 2 km of an ecosystem, and is hit by at least one TC of the probabilistic cyclone set. Our research therefore only focuses on areas affected by TCs, but coastal ecosystems may provide important coastal protection benefits in other areas as well. Since this study focuses on coastal protection as an ecosystem service, we did not consider grey or hard infrastructure options. However, it is important to bear in mind that unprotected people by our definition may still receive protection by this infrastructure, and that areas with low restoration potential may benefit from other protective measures.

Furthermore, both absolute and relative numbers of people protected are sensitive to choices e.g. with regards to the protective distance chosen (see supplementary material tables 1–3). While some studies have modeled hazard attenuation through coastal ecosystems for both cyclonic and non-cyclonic flooding more explicitly, they tend to focus more on economic damages averted, and to a lesser extent people protected (Beck *et al* 2018, Menéndez *et al* 2020, Tiggeloven *et al* 2022). Simultaneously, studies from a more human-centric or ecosystem service provision perspective frequently use non-probabilistic hazard indices (Arkema *et al* 2013, Chaplin-Kramer *et al* 2019, Selig *et al* 2019). Our research combines the strengths of both approaches by providing a probabilistic risk assessment for populations in proximity to coastal ecosystems. This is well suited for identifying spatial and temporal patterns in the protective function of coastal ecosystems at scale.

The historical decrease of relative protection by coastal ecosystems over the past 30 years caused by coastal ecosystem loss (figures 1(b) and 3) is concerning. Other studies have demonstrated the negative consequences of ecosystem loss for coastal protection, both for moderate changes in coastal vegetation and complete loss scenarios (Arkema *et al* 2013, Beck *et al* 2018, Menéndez *et al* 2020, Tiggeloven *et al* 2022). Our findings complement these perspectives by (i) identifying where the decrease in protection has occurred historically, and (ii) quantifying the magnitude of changes, as well as the relative effects of population and ecosystem changes. Previous research has shown that coastal areas are subject to both increases in population and ecosystem degradation, and that both factors play a role in increasing coastal disaster risk (Oppenheimer *et al* 2019, Cooley *et al* 2022). We further find that ecosystem loss is the main factor, but there are strong regional variations across the globe.

The increase in the absolute number of people protected, due to an exacerbated hazard under climate change, which results in a higher number of people impacted, can give the impression that protection by coastal ecosystems is increasing (figure 1(a)). However, the projected TCs will predominantly affect areas which are currently unprotected by coastal ecosystems. Hence, the proportion of people protected by coastal ecosystems is decreasing, even though the overall increase in TC frequency leads to more people being protected. It is concerning that a decrease in relative protection is observed due to changes in TC activity alone, since extrapolating historical coastal ecosystem losses as well as population growth would lead to an even more pronounced reduction in coastal protection through ecosystems. In addition, the STORM model only considers climate change in the intensity and frequency of TCs. Hence, coastal risk aggravating factors such as sea-level rise or erosion are not included. These, along with potential adverse effects of higher storm frequencies on the coastal ecosystems, are likely to further increase the risk and thus the need for coastal ecosystem protection (Beck *et al* 2018, Schuerch *et al* 2018, Cooley *et al* 2022).

As a possible adaptation measure, we considered the potential for mangrove restoration (Narayan *et al* 2016, Worthington and Spalding 2018, Menéndez *et al* 2020, Rana *et al* 2022). However, at the global scale changes from non-protection to protection are fairly small. Thus, NbS should not be seen as a silver bullet for disaster risk and climate adaptation. Yet, the potential for offsetting some of the decreases in protection due to historical habitat loss should not be underestimated. Not all areas are equally suitable for mangrove restoration, with the most urbanized areas being the least suited both from an ecological and from a socio-economic point of view (Worthington and Spalding 2018). Areas where coastal ecosystems already protect a high share of the coastal population are of interest (e.g. in small island states and developing countries), as well as areas where nature's protective value has been degraded in the recent past. Note that we specifically considered restoration which implies that areas that never had ecosystem protection cannot be targeted. Our scenario focuses on mangroves as they give the highest level of protection, provide a wide range of other co-benefits, and restoration is already ongoing in a number of countries (Spalding *et al* 2014b, Worthington and Spalding 2018, Das *et al* 2022, Gerona-Daga and Salmo 2022). This does not mean that restoration efforts for other coastal ecosystems such as seagrass, saltmarsh or wetlands are not of value. Indeed, it suffices to look at the historical decrease in protection due to ecosystem losses to realize their potential if restored. Overall, our analysis of both the past and future changes in protection underpin the necessity of global ecosystem preservation and restoration efforts for meeting adaptation goals in a changing climate also highlighted in previous studies (Spalding *et al* 2014b, Beck *et al* 2018, Tiggeloven *et al* 2022). Simultaneously, we must caution that the effects of the TCs and the changing climate on the coastal ecosystems themselves, which were not considered here, might jeopardize the NbS adaptation efforts. This may lead to an overestimation of the areas considered to be restorable under climate change. Future research can attempt to model these multi-directional interactions of coastal risk, climate change, and coastal ecosystems.

5. Conclusions

Through the integration of index-based ecosystem data and probabilistic risk modeling, we identify patterns of coastal protection in relation to cyclone risk at different spatial and temporal scales. Our findings show how ecosystem-based coastal protection has reduced over the last 30 years due to ecosystem and population change, as well how it may change over the next 30 years based on climatic changes and potential nature protection and restoration activities. Our results provide insights on the contribution NbS can make to climate change adaptation globally, and how benefits are distributed across different countries. Currently, one in five people (21%) impacted by TCs in the low elevation coastal zone experience some level of protection from coastal ecosystems, such as coral reefs, mangroves, coastal forests, seagrass, salt marshes and wetlands. This share has decreased by 2% over the last 30 years mainly due to coastal ecosystem degradation and would be even more distinct without the simultaneous increase of coastal population in protected areas. With climate change and current population, 40% more people will be impacted by TCs annually, yet the share of annually protected people decreases by 1%, which amounts to 31.5 million over 30 years. The potential to increase coastal protection by restoring nature is not distributed evenly across the globe, but very high in smaller countries and island states. Our analysis can support prioritization of areas for more localized assessments of the applicability of NbS for disaster risk reduction and climate change adaptation.

Data availability statement

The data that support the findings of this study are openly available at the following DOI: 10.3929/ethz-b-000626330.

Code is available under https://github.com/CLIMADA-project/climada_papers/tree/main/202305_coastal_ecosystems_TC (Hülsen 2023a, 2023b).

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References

Arkema K K, Guannel G, Verutes G, Wood S A, Guerry A, Ruckelshaus M, Kareiva P, Lacayo M and Silver J M 2013 Coastal habitats shield people and property from sea-level rise and storms *Nat. Clim. Change* **3** 913–8

Aznar-Siguan G and Bresch D N 2019 CLIMADA v1: a global weather and climate risk assessment platform *Geosci. Model Dev.* **12** 3085–97

Beck M W, Losada I J, Menéndez P, Reguero B G, Díaz-Simal P and Fernández F 2018 The global flood protection savings provided by coral reefs *Nat. Commun.* **9** 2186

Bloemendaal N *et al* 2022 A globally consistent local-scale assessment of future tropical cyclone risk *Sci. Adv.* **8** eabm8438

Bloemendaal N, Haigh I D, de Moel H, Muis S, Haarsma R J and Aerts J C J H 2020 Generation of a global synthetic tropical cyclone hazard dataset using STORM *Sci. Data* **7** 40

Bresch D N and Aznar-Siguan G 2021 CLIMADA v1.4.1: towards a globally consistent adaptation options appraisal tool *Geosci. Model Dev.* **14** 351–63

Bunting P, Rosenqvist A, Lucas R, Rebelo L-M, Hilarides L, Thomas N, Hardy A, Itoh T, Shimada M and Finlayson C 2018 The global mangrove watch—a new 2010 global baseline of mangrove extent *Remote Sens.* **10** 1669

Burke L, Reytar K, Spalding M and Perry A 2011 *Reefs at Risk Revisited* (World Resources Institute)

Burke L and Spalding M 2022 Shoreline protection by the world's coral reefs: mapping the benefits to people, assets, and infrastructure *Mar. Policy* **146** 105311

Chaplin-Kramer R *et al* 2019 Global modeling of nature's contributions to people *Science* **366** 255–8

Chaplin-Kramer R *et al* 2023 Mapping the planet's critical natural assets *Nat. Ecol. Evol.* **7** 51–61

Collins M *et al* 2019 SPM6 extremes, abrupt changes and managing risks p 68

Cooley S *et al* 2022 Ocean and coastal ecosystems and their services *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H-O Pörtner, D C Roberts, M M B Tignor, E S Poloczanska, K Mintenbeck, A Alegría, M Craig, S Langsdorf, S Löschke, V Möller, A Okem and B Rama (Cambridge University Press)

Costanza R *et al* 2021 The global value of coastal wetlands for storm protection *Glob. Environ. Change* **70** 102328

Das S C, Das S and Tah J 2022 Mangrove ecosystems and their services *Mangroves: Biodiversity, Livelihoods and Conservation* ed S C Das, E C Ashton and T Pullaiah (Springer) pp 139–52

Duarte C M, Losada I J, Hendriks I E, Mazarrasa I and Marbà N 2013 The role of coastal plant communities for climate change mitigation and adaptation *Nat. Clim. Change* **3** 961–8

Earth Resources Observation and Science (EROS) Center 2017 Shuttle radar topography mission (SRTM) void filled USGS (https://doi.org/10.5066/F7F76B1X)

Emanuel K 2021 Response of global tropical cyclone activity to increasing CO_2: results from downscaling CMIP6 models *J. Clim.* **34** 57–70

ESA CCI-LC 2017 ESA/CCI viewer (available at: http://maps.elie.ucl.ac.be/CCI/viewer/download.php) (Accessed 14 October 2022)

Ferrario F, Beck M W, Storlazzi C D, Micheli F, Shepard C C and Airoldi L 2014 The effectiveness of coral reefs for coastal hazard risk reduction and adaptation *Nat. Commun.* **5** 3794

Gerona-Daga M E B and Salmo S G 2022 A systematic review of mangrove restoration studies in Southeast Asia: challenges and opportunities for the United Nation's Decade on Ecosystem Restoration *Front. Mar. Sci.* **9** 1865

Guannel G, Arkema K, Ruggiero P and Verutes G 2016 The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience *PLoS One* **11** e0158094

Holland G 2008 A revised hurricane pressure–wind *Model. Mon. Weather Rev.* **136** 3432–45

Hülsen S 2023a Global protection from tropical cyclones by coastal ecosystems - past, present, and under climate change research data (ETH Research Collection) (https://doi.org/10.3929/ethz-b-000626330)

Hülsen S 2023b Global protection from tropical cyclones by coastal ecosystems - past, present, and under climate change Code (GitHub) (available at: https://github.com/CLIMADA-project/climada_papers/tree/main/202305_coastal_ecosystems_TC)

IUCN 2016 WCC-2016-Res-069: defining nature-based solutions *World Conservation Congress (Hawai'i, 2016)* (available at: https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_069_EN.pdf)

Jordan P and Fröhle P 2022 Bridging the gap between coastal engineering and nature conservation? *J. Coast. Conserv.* **26** 4
Knutson T *et al* 2020 Tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming *Bull. Am. Meteorol. Soc.* **101** E303–22
Lin N, Emanuel K, Oppenheimer M and Vanmarcke E 2012 Physically based assessment of hurricane surge threat under climate change *Nat. Clim. Change* **2** 462–7
Lloyd C T *et al* 2019 Global spatio-temporally harmonised datasets for producing high-resolution gridded population distribution datasets *Big Earth Data* **3** 108–39
Mcowen C *et al* 2017 A global map of saltmarshes *Biodivers. Data J.* **5** e11764
Menéndez P, Losada I J, Torres-Ortega S, Narayan S and Beck M W 2020 The global flood protection benefits of mangroves *Sci. Rep.* **10** 4404
Narayan S, Beck M W, Reguero B G, Losada I J, van Wesenbeeck B, Pontee N, Sanchirico J N, Ingram J C, Lange G-M and Burks-Copes K A 2016 The effectiveness, costs and coastal protection benefits of natural and nature-based defences *PLoS One* **11** e0154735
National Hurricane Center 2022 Saffir-Simpson hurricane wind scale (available at: www.nhc.noaa.gov/aboutsshws.php) (Accessed 30 August 2022)
Natural Capital Project 2019 InVEST (Natural Capital Project) (available at: https://naturalcapitalproject.stanford.edu/software/invest) (Accessed 8 April 2022)
Natural Capital Project 2022 InVEST 3.13.0.post6+ug.g6b07b42 user's guide (Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, and Stockholm Resilience Centre) (available at: http://releases.naturalcapitalproject.org/invest-userguide/latest/en/coastal_vulnerability.html) (Accessed 8 March 2023)
O'Neill B C *et al* 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 *Geosci. Model Dev.* **9** 3461–82
Oppenheimer M, Glavovic B C, Hinkel J and van de Wal R, 2019 Sea level rise and implications for low-lying islands *Coasts and Communities IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (Intergovernmental Panel on Climate Change)
Pinsky M L, Guannel G and Arkema K K 2013 Quantifying wave attenuation to inform coastal habitat conservation *Ecosphere* **4** art95
Rana A, Zhu Q, Detken A, Whalley K and Castet C 2022 Strengthening climate-resilient development and transformation in Viet Nam *Clim. Change* **170** 4
Reguero B G, Secaira F, Toimil A, Escudero M, Díaz-Simal P, Beck M W, Silva R, Storlazzi C and Losada I J 2019 The risk reduction benefits of the Mesoamerican Reef in Mexico *Front. Earth Sci.* **7** 125
Reguero B G, Storlazzi C D, Gibbs A E, Shope J B, Cole A D, Cumming K A and Beck M W 2021 The value of US coral reefs for flood risk reduction *Nat. Sustain.* **4** 688–98
Ruckelshaus M, Reguero B G, Arkema K, Compeán R G, Weekes K, Bailey A and Silver J 2020 Harnessing new data technologies for nature-based solutions in assessing and managing risk in coastal zones *Int. J. Disaster Risk Reduct.* **51** 101795
Schuerch M *et al* 2018 Future response of global coastal wetlands to sea-level rise *Nature* **561** 231–4
Schwalm C R, Glendon S and Duffy P B 2020 RCP8.5 tracks cumulative CO_2 emissions *Proc. Natl Acad. Sci* **117** 19656–7
Selig E R *et al* 2019 Mapping global human dependence on marine ecosystems *Conserv. Lett.* **12** e12617
Shepard C C, Crain C M and Beck M W 2011 The protective role of coastal marshes: a systematic review and meta-analysis *PLoS One* **6** e27374
Spalding M D *et al* 2014a Coastal ecosystems: a critical element of risk reduction *Conserv. Lett.* **7** 293–301
Spalding M D, Ruffo S, Lacambra C, Meliane I, Hale L Z, Shepard C C and Beck M W 2014b The role of ecosystems in coastal protection: adapting to climate change and coastal hazards *Ocean Coast. Manage.* **90** 50–57
Sudmeier-Rieux K *et al* 2021 Scientific evidence for ecosystem-based disaster risk reduction *Nat. Sustain.* **4** 803–10
Tiggeloven T, de Moel H, van Zelst V T M, van Wesenbeeck B K, Winsemius H C, Eilander D and Ward P J 2022 The benefits of coastal adaptation through conservation of foreshore vegetation *J. Flood Risk Manage.* **15** e12790
UNDRR 2021 *Nature-Based Solutions for Disaster Risk Reduction* (United Nations Office for Disaster Risk Reduction)
UNEP-WCMC, Short FT 2005 *Global Distribution of Seagrasses* (https://doi.org/10.34892/X6R3-D211)
Wamsley T V, Cialone M A, Smith J M, Atkinson J H and Rosati J D 2010 The potential of wetlands in reducing storm surge *Ocean Eng.* **1** 59–68
WorldPop 2018 Global 1km population *WorldPop Hub* (https://doi.org/10.5258/SOTON/WP00647)
Worthington T and Spalding M 2018 Mangrove restoration potential: a global map highlighting a critical opportunity *Report* (https://doi.org/10.17863/CAM.39153)