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Estimating and Mapping Natural Hazards and Risk Reduction Provided by Coastal Ecosystems

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Abstract

We present two case studies in which coastal vulnerability modeling was used to quantify the role those coastal ecosystems play in reducing risk to coastal communities now and with future sea-level rise. These analyses were used to inform post-disaster reconstruction and coastal resilience building efforts as well as climate change adaptation strategies. Our goal is to quantify the role that coastal habitat plays in reducing risk to people and shoreline under current conditions and with future sea level rise (SLR). With SLR, we find that the extent of shoreline most exposed to coastal hazards would more than double, and the total population would nearly triple in The Bahamas. Similarly, the population living along high-risk shorelines increases by over 10x if habitat is lost and sea level rise is accounted for in the Mesoamerican Reef.

Keywords: Disaster risk reduction, coastal ecosystems, sea level rise, climate change.

JEL Codes: C63, Q20, Q54

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Introduction

To stimulate widespread uptake and implementation of nature-based coastal protection strategies, decision-makers need approaches and tools that can synthesize physical, demographic and ecological data to identify in a spatially explicit manner where ecosystems matter to vulnerable communities, and evaluate alternatives in a timely manner. Risk reduction benefits provided by coastal habitats have been measured in a variety of ways. These include employing process-based predictive modeling using expected damage functions to assist in cost-benefit analysis for protective interventions (this approach is used by U.S. Federal Emergency Management Agency's HAZUS software) (Barbier et al. 2015). Other approaches include measuring protective benefits as capitalized into housing values using hedonic analysis (Dundas 2017), asking people their willingness to pay for protection services using stated preference surveys (Landry et al. 2011), or using basic regression analysis as a means of relating the presence of coastal habitats to reduced flood damage (Danielsen et al. 2005, Costanza et al. 2008, Das and Vincent 2009, Boutwell and Westra 2016).

Although all these approaches can be used for decision support, they are data intensive, generally relying on existing data on the physical drivers of storm risk, geospatial information on exposed people and infrastructure, or extensive primary data collection. Data requirements notwithstanding, these approaches may also require significant expertise to run (i.e. complex wave models may take months to parameterize correctly by a coastal engineer), which can make it more difficult for staff in organizations with limited capacity to quickly iterate scenarios and consider in quantitative terms the competing goals and preferences of a broad group of stakeholders. What is needed to inform decisions are transparent, repeatable, and accessible tools and open-source data for resource-poor nations to identify where ecosystems matter most for people (UNDRR 2019).

The InVEST Coastal Vulnerability model is a decision support tool that uses an index-based approach to understand the relative risk of communities to coastal hazards and identifies where habitats have the greatest potential for providing coastal protection (Arkema et al 2013, Langridge et al 2014, Hopper and Meixler 2016, Cabral et al 2017, Silver et al. 2019, Sharp et al 2020). The model builds on previous similar indices that account for biophysical and climatic components governing exposure to flooding and inundation from coastal hazards (e.g. Gornitz 1990, Cooper and McLaughlin 1998, Hammar-Klose and Thieler 2001), by explicitly considering the role of ecosystems in providing coastal protection and incorporating information about people, property and other relevant metrics in the framing of risk. The model is designed to be very accessible; it produces robust results using relatively coarse, often globally available data inputs, the methodology is transparent and the model outputs are easy to interpret, and running the model requires basic GIS skills but no other specialized training.

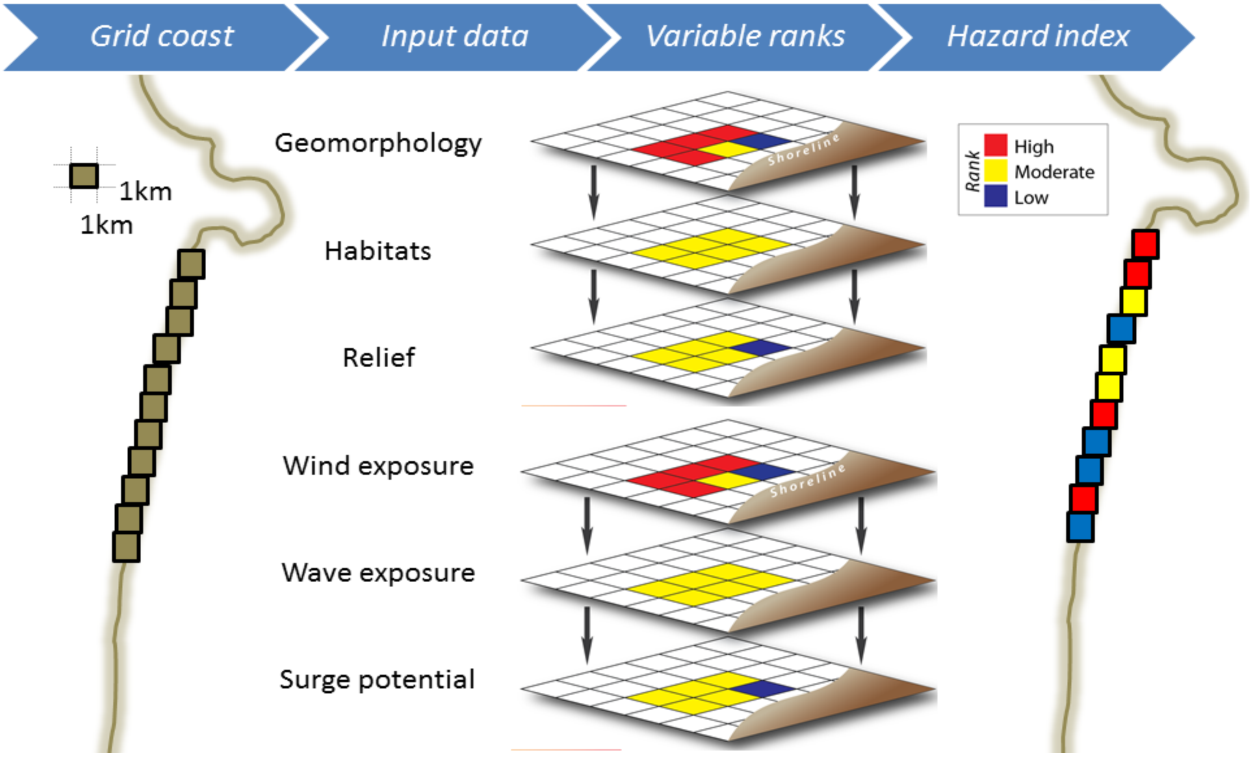
Objectives of this study

Here we present two case studies in which the coastal vulnerability model was used to quantify the role that coastal ecosystems play in reducing risk to coastal communities now and with future sea-level rise. The first case study is a national-scale coastal hazard and social vulnerability analysis for The Bahamas conducted in 2017, which focuses on addressing three fundamental questions that decision-makers often consider when implementing nature-based coastal protection: 1) where are people at risk from coastal hazards in The Bahamas? 2) how might sea-level rise (SLR) change the distribution of risk across the country? and 3) where are coastal and marine ecosystems providing protection currently, and under future SLR for the most socially vulnerable populations? This analysis was used to inform post-disaster reconstruction and coastal resilience building efforts following the 2015 and 2016 hurricane seasons, including the development of an IDB-funded Climate-Resilient Coastal Management and Infrastructure Program (Lemay et al 2017 and see Bahamas in the section below).

The second case study is an ongoing collaboration with the World Wildlife Fund, national and local governments, and marine protected area (MPA) managers in Mexico, Belize, Honduras and Guatemala to integrate climate projections into MPA planning and ICZM in the Mesoamerican Reef (MAR). With support from the International Climate Initiative (IKI), the project involves developing a portfolio of climate adaptation strategies for each country and using an optimization approach to target restoration and conservation for the greatest returns on investment in key ecosystems services (see Belize in the section below). The research questions driving this work are the same as those in The Bahamas hazard analysis above, but this work asks another question as well which is where should climate adaptation strategies be targeted to produce the greatest returns on investment for coastal risk reduction and other critical ecosystem services in the MAR (https://www.wwfca.org/en/smartcoastsmar/).

Approach and methods

The coastal vulnerability model quantifies the relative exposure of a given stretch of shoreline to flooding and erosion based on the following variables: the diversity and extent of coastal and marine ecosystems, coastal elevation, exposure to waves and wind, shoreline geomorphology, storm surge potential, and sea-level rise. For each coastal segment in a given area of interest, the length of which is designated by the user, input variables are assigned ranks from lowest exposure (rank=1), to highest exposure (rank=5) based on a combination of absolute and relative rankings of modeled and observed data. The final coastal hazard index is the geometric mean of the ranked variables (where R=rank, and all variables given equal weighting) (Figure 1).



$$HazardIndex = \left(R_{Habitats} R_{ShorlineType} R_{Relief} R_{Waves} R_{Wind} R_{SurgePotential}\right)^{1/6}$$

Figure 1. Conceptual diagram for the InVEST Coastal Vulnerability model.

Data inputs for the coastal vulnerability model are generally a mixture of local and global spatial datasets (Table 1). For example, global datasets such as NOAA's WaveWatch III model (Tolman 2009) provide the coverage and resolution necessary for the model to calculate wind and wave statistics anywhere in the world. A global map of the continental shelf margin can be used to compute the storm surge variable, for which the distance from the shoreline to the shelf edge is used as a proxy for storm surge potential. Other input data, such as habitat footprints and demographic data benefit from the use of more local high-resolution datasets where available. However, good globally available datasets exist (for warm water coral reefs, for example (Millenium Coral Reef Map), and global population (Lloyd et al. 2017)) for places in which local data do not exist.

Table 1. Data inputs for the Coastal Vulnerability model leverage a number of global and regional datasets. In some cases local or national data may be needed, or represent the best available.

Model Input	Year	Extent	Resolution	Source
Natural Habitats	variable	Local - Global	variable	Global and regional datasets exist for some marine and coastal ecosystems, such as the Millennium Coral Reef Map (Coral Reef), Allen Coral Atlas (Coral Reef, Seagrass and Macroalgae), Global Mangrove Watch (Mangrove), and others. In other cases, national or subnational data might be used to map the location of dunes, coastal forests, kelp forests, etc.
Relief	2014	Global	90m	Shuttle Radar Topography Mission Digital Elevation Model
Wind & Wave Exposure	2005-2010	Global	50km	National Oceanographic and Atmospheric Administration WaveWatch III model
Shoreline Geomorphology	variable	Local	vector	Often produced for the area of interest through a combination of existing datasets and digitized aerial imagery

Surge Potential	2005	Global	vector	Continental Margins Ecosystem (COMARGE) effort in conjunction with the Census of Marine Life
Sea Level Rise	variable	Global		Sea-level rise rates are monitored across the world. The Permanent Service for Marine Sea Level Rise (https://www.psmsl.org/) curates a global collection of tide gauges.
Population	2020	Global	100m	World Pop (https://www.worldpop.org/)

A primary goal of both case studies was to quantify the role that habitat plays in reducing risk to people and shoreline under current conditions and with future sea level rise (SLR). To do this we evaluated scenarios of habitat loss and SLR. To quantify habitat role, we considered two heuristic scenarios, a 'with habitat' scenario that accounts for the protection provided by the current distribution of coastal and nearshore habitats throughout the country, and a 'without habitat' scenario where habitat is assumed to be lost, and no longer provide protection. The 'without habitat' scenario is intended to evaluate where and to what extent habitats are providing protection to people, and is not intended to represent an actual reflection of the future. In the MAR we also considered a third habitat scenario in which habitat within the MPA network was removed in a 'without MPA habitat' scenario.

To model SLR we compared the relative exposure to coastal hazards under current sea levels against one future policy-relevant SLR scenario (2040 in The Bahamas and 2050 in the MAR). In both the MAR and The Bahamas, the spatial heterogeneity of relative sea level rise rates did not produce significant regional difference in anticipated net rise for our time horizons, instead we focused on the relative change between current and future scenarios assuming uniform rates of SLR across the entirety of study areas. To estimate the relative change in sea-level between timesteps, we used the projected SLR curve for the highest RCP scenario (2 m rise by 2100) depicted in Figure ES 1 of Parris et al. (2012) for The Bahamas, and downscaled modeled SLR data provided by Columbia University and the NASA collaboration ADVANCE for the MAR to assign SLR ranks for future scenarios. For example, in The Bahamas this was done as follows: using the Parris et al. RCP curves we divided the net rise (cm) from the start of the curve (1992) to the end (2100) into quantiles as follows: 0-40 cm rise corresponded to a rank of "1", 41-80 cm "2", 81-120 cm "3", 121-160 cm "4", and 161-200 cm a rank of "5". Using the curve, we estimated the net rise at the current timestep (2015) within the first quantile (~10 cm) and assigned a rank of "1". The projected rise for 2040 (our planning horizon) was ~40 cm and was assigned a rank of "2". Ranks for the MAR used a similar approach in this case the 25th percentile SLR for 2050 was assigned a rank of "3" and the 75th percentile a rank of "4". This is a simple approach to reflect the increased exposure to coastal hazards anticipated as sea-levels rise.

Results

In this section we report on key findings from The Bahamas national hazard analysis and the Mesoamerican Reef climate adaptation work. In both case studies, the results are focused on explaining the spatial distribution of risk, the drivers of risk, and the potential for coastal and nearshore ecosystems to provide protection to people now and with future SLR.

The Bahamas

Modeled results indicate that nearly one fifth of the coastline and nearly two in ten Bahamians are currently at highest risk of exposure to coastal hazards (Figure 7). With SLR, we found that the extent of shoreline most exposed to coastal hazards would more than double, and the total population would nearly triple (with more than 10% of the population, >40,000 people, living in highest risk areas) (Figure 7). Storm surge potential was a key driver of risk in The Bahamas; wide continental shelves like off the north coast of Grand Bahama and west coast of Abaco contributed to particularly high risk of exposure to hazards relative to the rest of the country. In addition to surge potential, low elevations and soft, erodible sediments are key factors driving risk on islands with large proportions of exposed shoreline.

Coastal and nearshore ecosystems occur along almost the entire coastline of The Bahamas, often with multiple habitats fronting sections of shoreline (e.g. coral reef backed by seagrass and mangrove). Our results suggest that if these habitats are lost, even under current sea-levels, the length of shoreline highly exposed to hazard throughout the country would quadruple (Figure 2). With habitat loss and modeled SLR, the length of shoreline at highest exposure increases five-fold (Figure 2), putting an estimated quarter of the population at highest risk. These results highlight the important role ecosystems may be playing in providing coastal protection now and in the future.

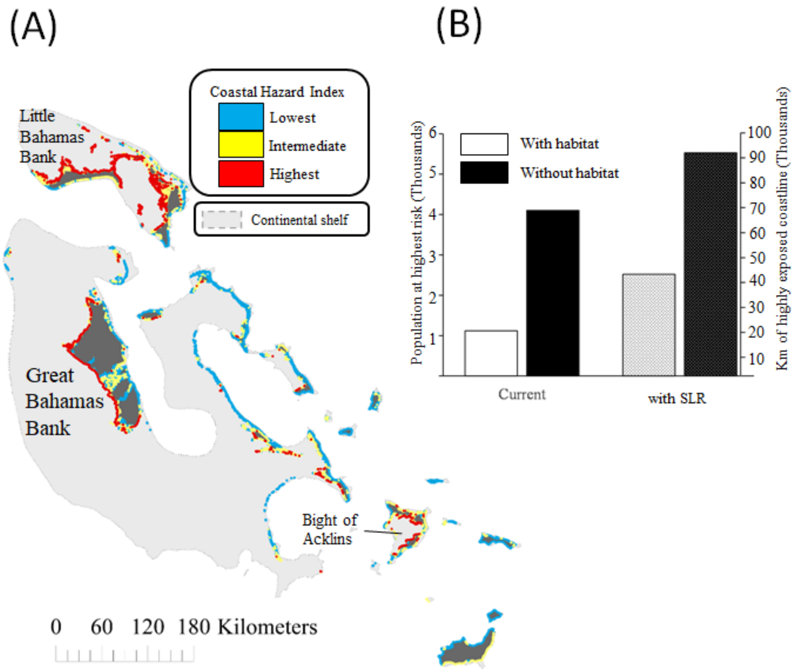


Figure 2. (A) Relative exposure to coastal hazards for The Bahamas. Storm surge is a key driver of exposure for The Bahamas and this is reflected in the modeled results. The greater the distance from land to the edge of the continental shelf (in grey), the greater the potential for exposure to storm surge. (B) Length of highly exposed coastline and number of people at the highest risk with and without coastal and nearshore habitats, currently and with future SLR. Results are represented using the same set of bars for both metrics because on the national scale these variables are highly correlated (from Silver et al. 2019).

At an island-scale, we found that ecosystems provide coastal protection for islands where exposure is inherently high due to other factors (elevation, storm surge potential, etc.), and are equally important for maintaining low exposure of other islands. For example, Grand Bahama has the greatest extent of highly exposed shoreline of any island in The Bahamas (almost half of the island is at highest risk). However, Grand Bahama also benefits from coastal protection along >300 km of the island's coastline by extensive seagrass beds, coral reef, mangrove, and coastal coppice forests (Figure 3). Our results suggest that if these habitats are lost, almost the entirety of Grand Bahama would be highly exposed relative to the rest of the country.

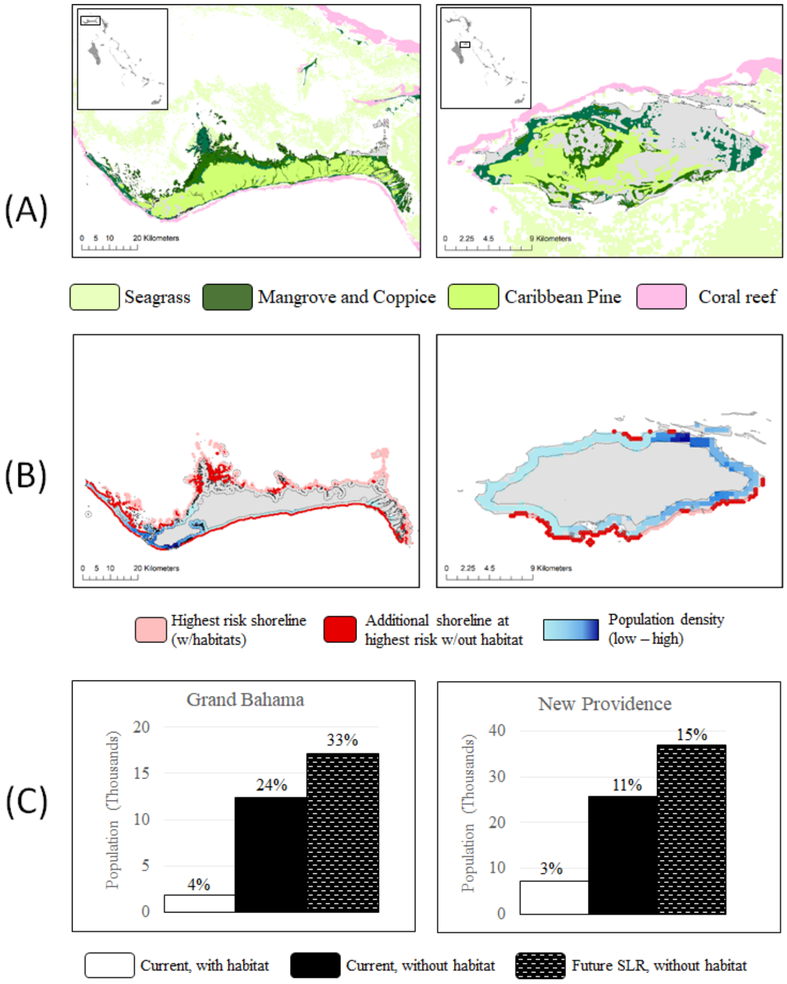


Figure 3. Coastal and marine ecosystems on Grand Bahama and New Providence Islands (A) provide protection for people who, if those habitats were lost, would be living along the highest risk shoreline (B). Population within a 1km inland coastal hazard zone is indicated with a dashed line. Bar charts in (C) show the total number of people and the percentage of the total island population at highest risk in each scenario (with habitat and current sea-levels, without habitat and current sea-levels, and without habitat and SLR) (from Silver et al. 2019).

Mesoamerican Reef

Coastal and marine ecosystems currently reduce risk for nearly 100,000 people across the MAR who would otherwise be at highest risk of exposure to coastal hazards. If SLR (75th percentile,

2050) is accounted for, the role of coastal and marine ecosystems in reducing risk becomes even more important, protecting an estimated ~200,000 people who would otherwise be at the highest risk of exposure to coastal hazards (Figure 4).

If all habitat is lost, an estimated 20% of the MAR shoreline will be at the highest risk of exposure to coastal hazards, increasing to an estimated 60% of the shoreline if SLR is accounted for as well. The population living along high risk shorelines increases by over 10x if habitat is lost and sea level rise is accounted for (this assumes 2020 populations).

The marine protected areas across the MAR reduces risk for an estimated 5,000 people currently, and again, when SLR is accounted for the importance of this network increases, protecting approximately 22,000 people who would otherwise be at the highest risk of exposure to coastal hazards. Another interesting finding is that the importance of the MPAs for coastal risk reduction varies substantially among countries in the MAR. In Belize, where the MPAs are offshore, they provide less protection to coastal communities than in Mexico or Honduras where the MPAs are multiple use areas and include coastal communities. This finding highlights the importance of management of multi-use MPAs for coastal risk reduction benefits and the opportunity in Belize to consider siting MPAs near populated areas.

Relative to the MAR region as a whole, it is notable that the majority of the high risk shoreline in the current scenario is along the northern coast of the Yucatán Peninsula. This is driven by a higher potential for storm surge, lower coastal relief, the presence of erodible shoreline and the lack of significant coral reef - a key coastal habitat present in the majority of the other MAR areas. This suggests an important role for mangrove and coastal forest along the Yucatan coast in providing critical coastal protection.

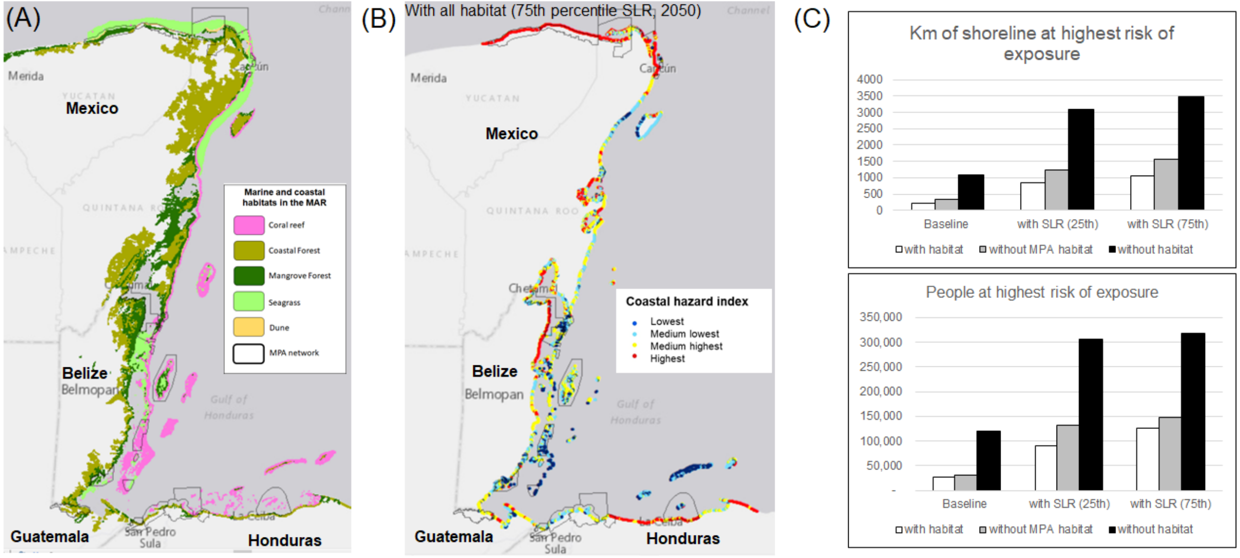


Figure 4. (A) Coastal and marine ecosystems in the Mesoamerican Reef region. (B) Relative exposure to coastal hazards for the MAR under a scenario that accounts for 2050 sea level rise. (C) Kilometers of shoreline and number of people at highest risk of exposure to coastal hazards under different scenarios.

Implications and utility of index-based approaches

The transparency of modeled inputs and outputs, and the ability to quickly test different climate and development scenarios make the InVEST Coastal Vulnerability model an effective tool to engage with stakeholders and communicate with scientists and non-scientists alike (Arkema et al. 2013, Langridge et al. 2014, Hopper and Meixler 2016, Cabral et al. 2017, Arkema et al. 2017, OPM 2017, Silver et al. 2019). Despite the methodological simplicity and known limitations of the modeling approach, several studies have found good correspondence between areas of high risk, as estimated by the coastal vulnerability model and empirical data on impacts from coastal hazards (Arkema et al. 2013, Cabral et al. 2017, Silver et al. 2019). These comparisons in general indicate that the coastal vulnerability model is a robust approach which can be applied even in data-scarce areas to help decision-makers understand where nature-based solutions may be feasible in their region under different conditions.

Opportunities for future work

Advances in the accuracy and availability of spatially explicit data on the distribution, health, and morphology of natural habitats represents a large opportunity for future work that could greatly increase the sensitivity of the Coastal Vulnerability model. Data on natural habitats are often outdated, incomplete, and/or are lacking key information about health status and basic morphology (e.g. canopy height, density, degradation, fragmentation) all of which affect the ability of these ecosystems to provide coastal protection. Increases in the wide-spread availability of high-quality habitat data using remote sensing techniques would greatly improve the power of the Coastal Vulnerability model as a tool for effective ICZM and DRM (Ruckelshaus et al. 2020).

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