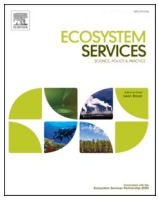
Ecosystem Services 79 (2026) 101847

Contents lists available at ScienceDirect

Ecosystem Services

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



Full Length Article

Exploring the disaster risk reduction and energy resilience benefits of coastal ecosystems and protected areas in Puerto Rico

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ARTICLE INFO

Keywords:
Coastal resilience
Protected areas
Energy infrastructure
Disaster risk reduction
Nature-based solutions
Climate adaptation
Small Island Developing States

ABSTRACT

Coastal hazards associated with sea-level rise and extreme events threaten people and energy infrastructure in Small Island Developing States. Coastal communities could benefit from conserving and restoring nearby ecosystems that mitigate hazard impacts such as coral reefs, mangrove forests, and seagrass beds. However, the intersection between nature-based coastal risk reduction, protected areas, and energy resilience is currently not well-understood. This study aims to address these gaps by exploring where protected and unprotected ecosystems reduce the risk of coastal hazards for people and energy infrastructure under future sea-level rise. Focusing on Puerto Rico, where Hurricane Maria destroyed the electrical grid in 2017, we used a spatial model to estimate an exposure index based on biophysical and oceanographic data. Our model shows that the number of people at highest hazard risk would nearly triple if coastal ecosystems were lost, and the number of electrical substations at highest risk would nearly quadruple. In total, ecosystems may reduce hazard exposure for over one third of the coastline under sea-level rise, and a majority of that mitigation is sustained by protected areas. By exploring where energy infrastructure within municipalities benefits from nature-based coastal risk reduction, our results suggest sites for new protected areas that could enhance energy resilience. Leveraging protected areas for disaster risk reduction and energy resilience reveals opportunities to engage new actors and institutions in broader conservation initiatives and nature-based solutions.

1. Introduction

Coastal hazards such as storms, flooding, erosion, and sea-level rise (SLR) pose a major threat to coastal communities and energy infrastructure worldwide (Genave et al., 2020; Schaeffer et al., 2012). Over time, the frequency and intensity of these hazards are increasing (IPCC, 2023). In the tropics, for example, hurricanes and other extreme storms have become more severe and costly in recent decades (Hallegatte, 2012). At the same time, rapid population growth and urban development in the coastal zone mean that many more people are becoming exposed to hazards (Neumann et al., 2015). The buildup of electrical infrastructure that supports growing populations necessitates strategies for disaster risk reduction now and in the future (Schaeffer et al., 2012).

To build long-term resilience, coastal communities are increasingly exploring natural and nature-based risk reduction approaches as an alternative or complement to gray infrastructure. Nature-based solutions utilize hazard mitigation and other regulating services provided by coastal habitats such as coral reefs and mangrove forests (Duarte et al., 2013; Spalding et al., 2014; TEEB, 2010). The physical formations of these ecosystems attenuate wind and wave energy before hazards reach the shore (Chang & Mori, 2021; Cunniff & Schwartz, 2015; Ferrario et al., 2014; Narayan et al., 2016). These hazards are intensifying in part due to SLR – a process that also threatens ecosystem health and the delivery of services (Temmerman et al., 2013). However, ideal sediment delivery conditions and unobstructed space may enable coral reefs, mangroves, seagrasses, and marshes to accrete vertically and/or migrate landward at a rate that outpaces SLR (Kirwan et al., 2016; Saunders et al., 2013; Temmerman et al., 2013; Woodroffe et al., 2016). Additionally, co-occurring habitats are more resilient to degradation because they reduce hazard risk for each other, helping to mitigate erosion and wave impacts on both natural and built infrastructure as sea levels rise (Guannel et al., 2016). Risk reduction strategies that leverage existing habitats are considered “low-” or “no-regrets” approaches because coastal ecosystems also provide a wide range of other services that

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https://doi.org/10.1016/j.ecoser.2026.101847
Received 6 March 2025; Received in revised form 27 February 2026; Accepted 26 March 2026
Available online 8 April 2026

sustain human well-being (Cheong et al., 2013; Mycoo & Donovan, 2017). Due to their co-benefits and cost-effectiveness, nature-based solutions for coastal resilience are gaining policy and investment momentum globally (UNEP, 2021).

Conservation and restoration of coastal ecosystems is necessary to maintain their hazard mitigation services amidst rapid degradation due to changing environmental conditions, urban development, and overharvesting globally (Convention on Biological Diversity, 2022; Duarte, 2009; Mycoo & Donovan, 2017; Spalding et al., 2014). One approach to curtail the impact of these anthropogenic pressures is to establish coastal and marine protected areas. Protected areas can enhance ecological recovery from long-term stressors and extreme events, including storms and flooding (Hernández-Delgado, 2024; Mellin et al., 2016; Roberts et al., 2017; Sullivan-Stack et al., 2022). However, only a few studies have explored the potential for ecosystems within protected areas to mitigate the impact of coastal hazards for human communities (Grorud-Colvert et al., 2021; Manes et al., 2023) – and the relevance of protected areas for infrastructure resilience remains a gap in the research. Furthermore, ecosystem-based risk reduction and other regulating services are underrepresented in the protected area literature compared to provisioning and cultural services (Arkema et al., 2024; Sala et al., 2021).

Protected areas for coastal risk reduction and energy resilience could be particularly beneficial in Small Island Developing States (SIDS). SIDS are vulnerable to coastal hazards due to their isolated nature and low accessibility; reliance on imported goods; limited natural and financial resources; and food, water, and energy insecurity (Genave et al., 2020; Thomas et al., 2020; UNDESA & UNDRR, 2022; Winters et al., 2022). SIDS also tend to have centralized electrical grids that depend on imported fossil fuels, which compounds disaster vulnerability (Dornan & Shah, 2016; Surroop et al., 2018). In Caribbean SIDS, damages from coastal hazards could exceed 20% of gross domestic product (GDP) by end-of-century (UN-OHRLLS, 2015). To minimize loss and damage for nearshore populations and infrastructure, cost-effective approaches to build coastal resilience are imperative (UNEP, 2014). These approaches are beginning to include nature-based solutions as set forth by the SIDS Accelerated Modalities of Action (SAMOA) Pathway, which also calls for expanded protected areas to sustain the delivery of ecosystem services (UN General Assembly, 2014). Many SIDS have vast, yet declining, coastal ecosystems that could support infrastructure resilience through conservation and restoration measures (Hay, 2013; Hernández-Delgado, 2024; Mercer et al., 2012).

The Commonwealth of Puerto Rico is a Caribbean SIDS that is vulnerable to both chronic and acute coastal hazards. This was demonstrated severely when Hurricane Maria destroyed the electrical grid and other critical infrastructure systems in 2017 (Gallucci, 2018; Kwasinski et al., 2019). When Hurricane Maria hit, Puerto Rico had one of the most centralized energy systems in the U.S., with nearly 98% of its electricity coming from imported fossil fuels. The territory had no local fossil fuel resources, concentrated power plants, aging grid infrastructure, and minimal renewable energy. The centralized and fragile grid was particularly vulnerable to the hurricane, leaving the majority of Puerto Rico without power for over six months (Bennett et al., 2021). The prolonged humanitarian crisis caused 4,645 deaths by one estimate and $90 billion in damages (Kishore et al., 2018; Storlazzi et al., 2021). This highlights the urgency to build disaster resilience that incorporates ecosystems, people, and infrastructure in Puerto Rico. Local residents understand the value of conserving mangroves and coral reefs for coastal risk reduction, but this ecosystem service is underrepresented in the protected areas documentation (Castro-Prieto et al., 2019; PRCZMP, 2018). Additionally, the scientific community has not yet evaluated the potential for habitats to reduce risk for critical energy infrastructure, which has major implications for coastal resilience in Puerto Rico and other energy-vulnerable SIDS.

Our study aims to identify where protected and unprotected ecosystems have potential to mitigate coastal hazards for people and energy infrastructure in Puerto Rico. We ask: (1) Where are people and energy infrastructure highly exposed to coastal hazards under sea-level rise in Puerto Rico? (2) Where do coastal ecosystems reduce the risk of coastal hazards for people and energy infrastructure and by how much? and (3) How could ecosystem-based risk reduction inform the siting of protected areas? To answer these research questions, we used the InVEST® Coastal Vulnerability model to generate a coastal hazard exposure index for Puerto Rico. The InVEST model is widely used in nature-based resilience studies to examine which coastal areas are at risk (Arkema et al., 2013; Cabral et al., 2017; Manes et al., 2023; Silver et al., 2019). We build off this literature by spatially linking hazard exposure data with energy infrastructure and protected areas data. The insights generated by our replicable approach help break down silos between disaster risk reduction, energy resilience, and conservation efforts. In the following sections, we explain the theory and data sources behind the model, report the results of the analysis for different scenarios and spatial scales, and discuss potential management implications. Our results illustrate where ecosystems with and without protected status have the potential to reduce coastal risk for communities and the energy infrastructure they depend upon.

2. Methods

To understand the role of ecosystems and protected areas in reducing risk to communities and energy infrastructure, we created a spatial model of exposure to coastal hazards that considers multiple habitat and sea-level rise (SLR) scenarios for Puerto Rico. We begin this section by describing the physical, ecological, and social features of Puerto Rico that influence vulnerability to coastal hazards. Next, we specify each input variable of the InVEST Coastal Vulnerability model and explain how our habitat degradation and SLR scenarios represent changing environmental and management conditions. Lastly, we combine population and energy infrastructure data with the coastal exposure results to assess the benefits of ecosystems for coastal risk reduction.

2.1. Study area

The physical geography of Puerto Rico influences its exposure to coastal hazards. Located in the eastern Caribbean Sea, Puerto Rico is an archipelago of four major islands and over one hundred minor islets. On the main island, the mountainous and forested interior terrain transitions into tall cliffs on the western coast and a lowland plain on the northern coast (Wagenheim et al., 2023). Small segments of the Puerto Rican coastline are rocky or armored, but most of the shore is sandy or vegetated (Barreto, 2017). The nearshore habitats of the archipelago include coral reefs, mangrove forests, wetlands, seagrass meadows, and algae beds (Fig. 1A, Fig. 1B, Fig. 1C) (Miller & Lugo, 2009). Despite the extensive coverage of these habitats, the coastline is still hazard prone; 60% of Puerto Rico's sandy beaches and dunes are undergoing erosion due to heightened SLR (Barreto, 2017). More extreme hazards such as hurricanes run through the main island from east to west, regularly harming both interior and coastal communities (Morelock et al., 2001).

Two-thirds of Puerto Rico's 3.29 million inhabitants live near the coastline (NOAA Office for Coastal Management, 2023; U.S. Census Bureau, 2021). With an urbanization rate of 94%, most of the energy infrastructure and economic development are concentrated in coastal cities such as the capital, San Juan, and Ponce (Fig. 1D) (Dobson et al., 2020; U.S. Census Bureau, 2021). Vulnerability to coastal hazards is compounded by Puerto Rico's poverty rate of 42% – over triple that of the United States (U.S. Census Bureau, 2021). Additionally, it is widely recognized that poor governance practices and disenfranchisement of the Puerto Rican people have led to perpetual economic hardship, energy insecurity, and unsustainable natural resource use (Cabán, 2019; Hernández-Delgado, 2024; Joseph et al., 2020; Winters et al., 2022).

Human activity has degraded ecosystems throughout Puerto Rico's history – wetlands in particular have receded to 5% of their original

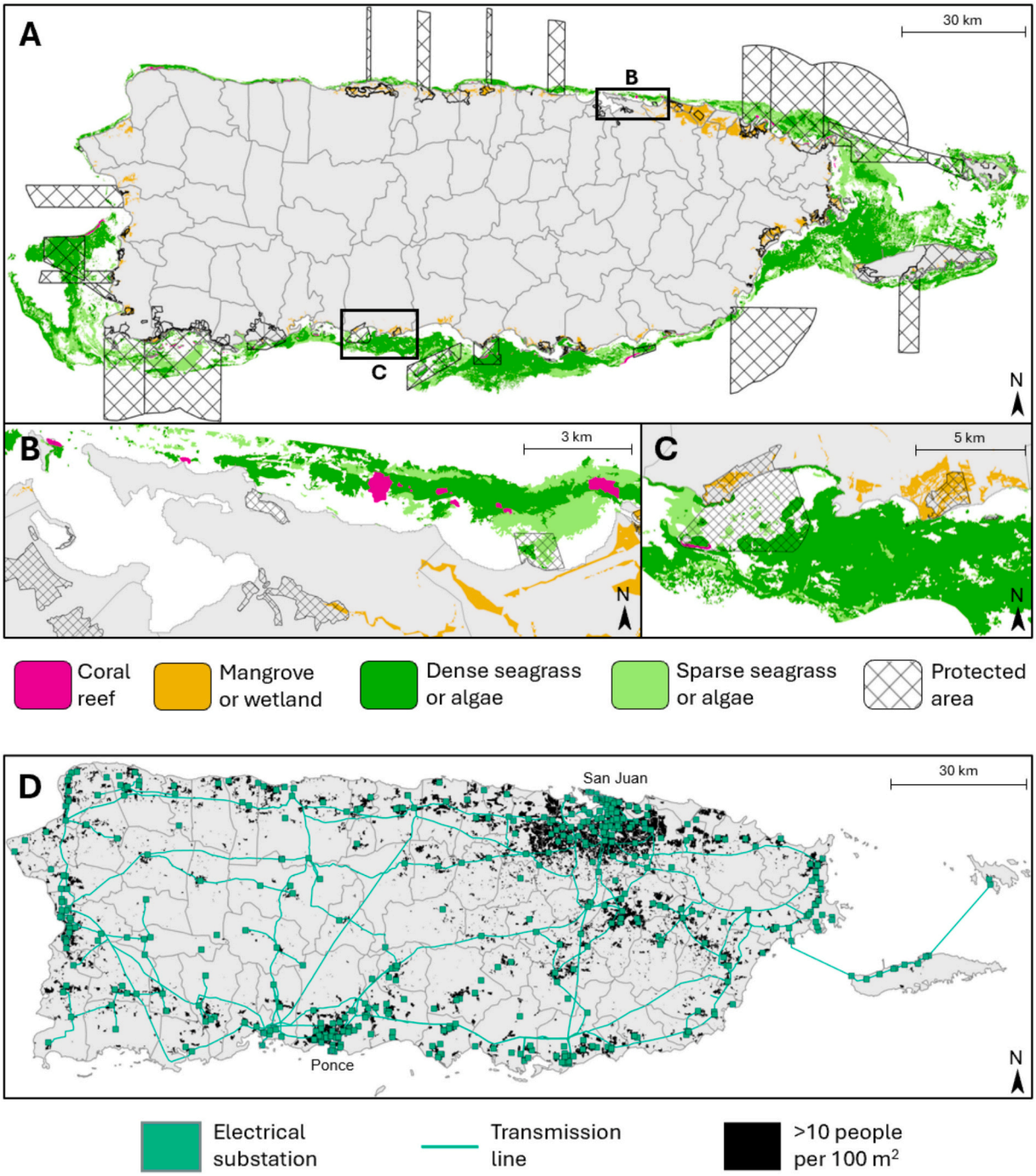


Fig. 1. Coastal and marine habitats of Puerto Rico that have potential to reduce exposure to coastal hazards **(A)**. Coastal and marine protected areas are also shown. Additional detail is shown for the San Juan metropolitan area **(B)** and Ponce **(C)**. Distribution of population and energy infrastructure **(D)**. Note: islands in the Mona Passage are not shown in **(A)** and **(D)**.

range due to agriculture, urban development, and SLR (Miller & Lugo, 2009). The expansion of cities, fishing, and tourism have also caused declines in Puerto Rico's seagrass and coral reef ecosystems (Hernández-Delgado and Ortiz-Flores, 2022; Miller and Lugo, 2009; NOAA Coral Reef Conservation Program, 2020). Widespread habitat degradation has resulted in a loss of critical ecosystem services including the mitigation of hazards, ultimately exacerbating climate vulnerability (PRCCC, 2022). In an effort to reverse degradation and sustain diverse ecosystem services and cultural resources, the Puerto Rico Department of Natural and Environmental Resources (DNER) established a network of 186 protected areas (Fig. 1A) (Castro-Prieto et al., 2019).

2.2. Modeling exposure

We used the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST®) Coastal Vulnerability model to quantify exposure to coastal hazards in Puerto Rico. InVEST is a free and open-source ecosystem services assessment tool developed by the Natural Capital Project (Natural Capital Project, 2024). The InVEST Coastal Vulnerability model has been used to analyze risk from coastal hazards in countries around the world at various spatial scales (Arkema et al., 2013; Cabral et al., 2017; Silver et al., 2019). The model uses seven spatial data layers – shoreline geomorphology, relief, habitats, SLR,

wind exposure, wave exposure, and storm surge potential (Fig. 2) – to estimate the exposure index (EI) for each coastline segment. This index-based approach builds on previous models by explicitly considering the role of ecosystems in coastal risk reduction (Silver et al., 2019). The model calculates exposure using the geometric mean shown in the equation below. R_i represents the rank of each model input on a 1-to-5 scale with 1 meaning "lowest exposure" and 5 meaning "highest exposure" (Natural Capital Project, 2024). All input variables are equally weighted, and the geometric mean reflects the nonlinear nature of real-world interaction effects between each variable. We set the model resolution to 250 m, so InVEST calculated the exposure index value for every 250 m of coastline. The exposure value for each coastline segment is relative to all other segments in the model and across the habitat and SLR scenarios.

$$EI = \left(R_{Geomorphology} R_{Relief} R_{Habitats} R_{Sea\ Level\ Rise} R_{Wind\ Exposure} R_{Wave\ Exposure} R_{Surge}\right)^{1/7}$$

To run the InVEST Coastal Vulnerability model for Puerto Rico, we collected spatial input layers and loaded them into the geographic information system software ArcGIS Pro (ESRI, 2022). We sourced each input layer from various national and global datasets – except for the Area of Interest and WaveWatch III layers (Table 1). We manually drew the Area of Interest polygon around the maritime boundary of Puerto Rico, and the WaveWatch III shapefile was automatically included in the InVEST download package. To prepare each layer in ArcGIS Pro for InVEST model runs, we adapted methods from the Allen Coral Atlas Coastal Vulnerability Tutorial Version 1.0 (Allen Coral Atlas, 2022). The rest of this section describes the data and methods we used to prepare each of the model inputs.

We selected habitats to include as model inputs based on the degree of coastal risk reduction provided by each habitat and the availability of habitat data for Puerto Rico. Each habitat was given a rank from 1 to 5 (Table 2). We chose the rank and protective distance of each habitat based on the InVEST User Guide recommendations as well as prior studies that ran the Coastal Vulnerability model in other regions (Arkema et al., 2013; Cabral et al., 2017; Silver et al., 2019; Natural Capital Project, 2024). Coral reefs, mangrove forests, and wetlands provide relatively more protection from erosion, inundation, and wind and wave energy through their stiff structure that can extend throughout the water column and above the surface of the water (Ferrario et al., 2014). Seagrass and algae provide relatively less but non-negligible protection through their flexible, low-lying shoots (McHenry et al., 2023; Natural Capital Project, 2024). Both of these habitats have extensive range along the continental shelf, and The Nature Conservancy dataset captures their spatial diversity by categorizing them into "sparse" and "dense" varieties (Fig. 1A) (Schill et al., 2021). For coastline segments that have more than one habitat, InVEST accounts for the protection services of all of them (Guannel et al., 2016; Natural Capital Project, 2024).

The geomorphology input variable indicates the susceptibility of the coastline segment to erosion and inundation from coastal hazards (Natural Capital Project, 2024). Like habitats, each shoreline type was assigned a rank based on the influence of the geomorphology on exposure (1 = least exposed and 5 = most exposed) (Table 3). Rocky cliffs and man-made structures such as seawalls are most resistant to erosion, and sand or gravel beaches are least resistant (Silver et al., 2019; Natural Capital Project, 2024).

InVEST calculates the relief variable using a digital elevation model (DEM) of the landmass (U.S. Geological Survey, 2018). Each coastline segment has an average elevation based on all elevation values in the DEM within the elevation averaging radius, which we set to 5000 m. To derive a rank, InVEST takes the distribution of average elevation above sea level across the entire coastline and separates percentiles into a 1-to-5 scale – lower elevation corresponds to higher rank and higher exposure (Silver et al., 2019; Natural Capital Project, 2024).

Wind and wave exposure were automatically calculated using the WaveWatch III dataset included within InVEST. These variables describe patterns of wind and wave speed and direction on each coastline segment. Higher wind and wave speeds lead to increased erosion and damage during coastal hazard events. The bathymetry layer is also used

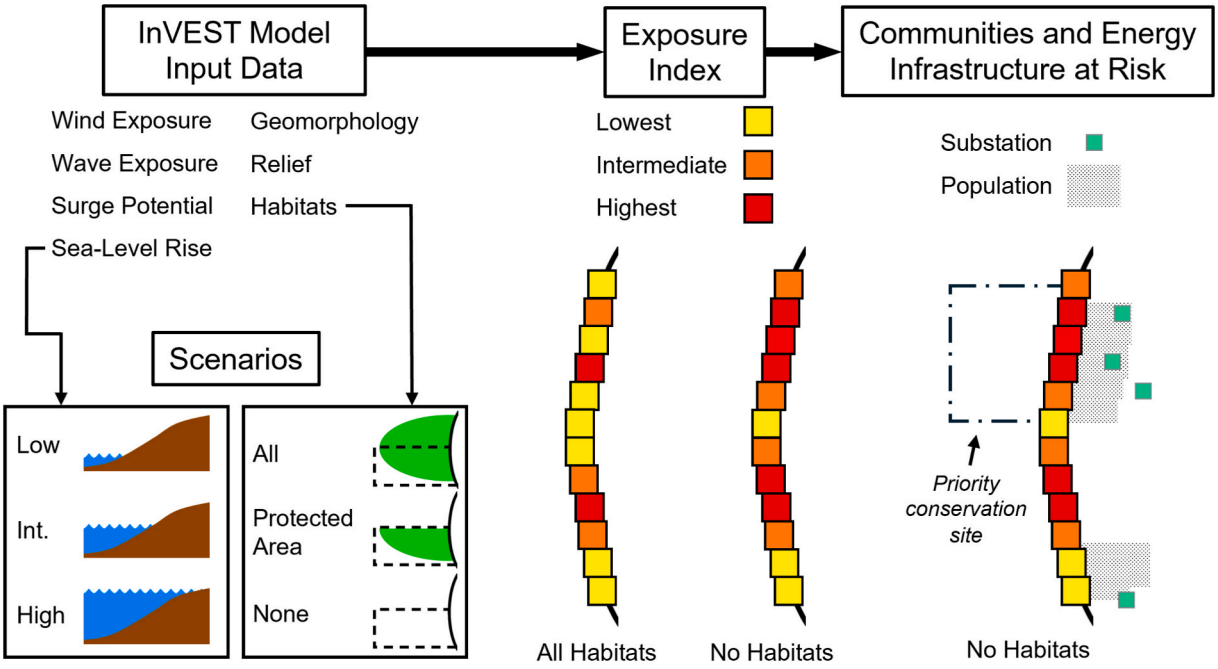


Fig. 2. Conceptual diagram showing the steps of the coastal exposure analysis. For every 250 m of coastline, the InVEST model calculates a rank from 1 to 5 for each of the seven input variables. We modified the habitat and sea-level rise layers to run the model under different scenarios, simulating future habitat degradation and environmental change (see Section 2.3). For each scenario, the model generates an exposure index by calculating the geometric mean of the seven input variables. The substations located within 2 km of a highly exposed coast and the inhabitants within 1 km are considered at greatest risk to coastal hazards. Priority sites for conservation are nearshore areas that become highly exposed when habitats are lost and have significant population and energy infrastructure near the coast.

Table 1
Source of each data layer

Input layer	File Type	Year	Source
Area of Interest	Shapefile	2022	Created for our analysis
Landmass	Shapefile	2022	Database of Global Administrative Areas (GADM, 2022)
Bathymetry	TIF (15 arc seconds)	2022	General Bathymetric Chart of the Oceans (GEBCO, 2022)
Relief	TIF (1 arc second)	2018	Digital Elevation Shuttle Radar Topography Mission (USGS, 2018)
Continental Shelf	Shapefile	2019	Ifremer Continental Margin Ecosystems (Marine Regions, 2019)
WaveWatch III	Shapefile	2009	Included in the InVEST download package (Natural Capital Project, 2024)
Habitats (coral, algae, seagrass)	Shapefile	2022	The Nature Conservancy Caribbean Marine Maps (Schill et al., 2021)
Habitats (mangrove, wetland)	Shapefile	2010	C-CAP Regional Land Cover (NOAA Office for Coastal Management, 2010)
Geomorphology	Shapefile	2000	Environmental Sensitivity Index (NOAA OR&R, 2000)
Population*	TIF (30 arc seconds)	2020	WorldPop Unconstrained Population Density (WorldPop, 2020)
Sea-level rise	Shapefile	2020	U.S. Army Corps of Engineers Sea Level Tracker (USACE, 2020)
Protected areas*	Shapefile	2018	U.S. Department of Agriculture, Protected Areas Conservation Action Team (PA-CAT, 2018)
Electrical substations*	Shapefile	2022	Homeland Infrastructure Foundation-Level Data (USDHS, 2022)
Transmission lines*	Shapefile	2022	Homeland Infrastructure Foundation-Level Data (USDHS, 2022)

Each layer in the InVEST analysis is listed along with their file type, year, and source. Layers marked with an (*) are not InVEST model inputs. The protected areas layer was used in the preparation of habitat input layers for one of the scenarios. Population and electrical substations were used in the subsequent analysis following the application of InVEST. The transmission lines visually demonstrate the connectivity of the electrical grid but were not a part of our calculations (Fig. 1D). Note that we accessed the Homeland Infrastructure Foundation-Level Data in 2022 when it was a public-facing portal. Now the substation data can be accessed through (NOAA Office for Coastal Management, 2026) and the transmission line data through (Climate Mapping for Resilience and Adaptation, 2026).

Table 2
Habitat ranks and protective distances

Habitat	Rank	Protection distance (m)
Coral	1	2000
Mangrove	1	2000
Wetland	2	1000
Dense seagrass	4	500
Sparse seagrass	4.25	400
Dense algae	4	500
Sparse algae	4.25	400

Each habitat layer was assigned a rank from 1 (major contribution to coastal risk reduction) to 5 (no contribution to coastal risk reduction) and a protection distance, which is the maximum distance it can be located from the coastline to provide protection (Natural Capital Project, 2024).

to determine the spatial variation of wave exposure in the model (GEBCO, 2022). InVEST calculates the rank for wind and wave exposure by separating the total distribution of values into percentiles using the same process as calculating relief rank (Silver et al., 2019; Natural Capital Project, 2024).

Storm surge is the temporary rise in sea level during a storm, causing increased coastal erosion and property damage. To calculate the storm surge potential rank on the same 1-to-5 scale as the other input variables, InVEST finds the distance between the landmass and continental shelf layers, with higher distances leading to higher storm surge and inundation. Every coastline segment has a storm surge rank – even those that are seemingly protected by nearby landmasses (Natural Capital Project, 2024).

Table 3
Geomorphology ranks

Geomorphology type	Rank
Exposed rocky cliffs	1
Exposed, solid man-made structures	1
Sheltered, solid man-made structures	2
Exposed wave-cut platforms in bedrock	2
Exposed scarps and steep slopes	2
Sheltered, vegetated low banks	3
Mangroves	4
Riprap	4
Sheltered rocky shores	4
Sand or gravel beaches	5

Each geomorphology type was assigned a rank based on its contribution to coastal risk reduction.

2.3. *Modeling future scenarios*

To evaluate the role of habitats in coastal risk reduction, we created three habitat scenarios that heuristically model varying degrees of degradation due to human activity (Fig. 2). The “All Habitats” scenario represents one extreme in which coastal habitats that exist today maintain their extent, quality, and hazard mitigation services into the future. It is important to note that this is not a best-case scenario as it is embedded in prior habitat destruction (Hernández-Delgado, 2024). Conversely, the “No Habitats” scenario represents the other extreme in which human development and ambient stressors cause further habitat degradation. In the “No Habitats” scenario, we assume ecosystems are too degraded to provide coastal resilience benefits. To model this, InVEST ignores the contents of the habitat layer and gives every coastline segment a habitat rank of 5 (Natural Capital Project, 2024). These two scenarios are common throughout the literature in the studies that use the InVEST Coastal Vulnerability model (Arkema et al., 2013; Cabral et al., 2017; Silver et al., 2019). While these scenarios represent extreme conditions that may not occur across the whole territory, they are very likely scenarios for any particular segment of coastline, especially due to local conditions determining where habitats are vulnerable to future SLR and where there is potential for adaptation (Cunniff & Schwartz, 2015; Temmerman et al., 2013). The habitat scenarios provide a method to assess the influence of ecosystem-based coastal risk reduction relative to the other variables in the model.

In addition to the “No Habitats” and “All Habitats” scenarios, we follow (Manes et al., 2023) and add a middle-ground scenario called “Protected Habitats,” in which only the habitats within current protected areas are assumed to provide risk reduction benefits. This scenario represents a future in which all habitats outside of protected areas have degraded, allowing us to explore the influence of protected areas on coastal risk reduction. To create the protected habitats layer, we clipped each habitat layer by separate boundaries of marine protected areas, terrestrial protected areas, important management areas, and karst buffer zones from the Puerto Rico DNER (Puerto Rico PA-CAT, 2018). Together, these three scenarios allow us to analyze how habitat presence affects coastal exposure and examine where protected areas have the potential to mitigate hazards.

We also generated three future SLR scenarios using the U.S. Army Corps of Engineers Sea Level Tracker tool (Fig. 2) (USACE, 2020). The tool combines local tide gauge data and the National Oceanic and Atmospheric Administration (NOAA) 2100 global SLR projections to

estimate the projected SLR of a specific area (Sweet et al., 2022). The San Juan tide gauge data generated 2100 SLR projections of 0.40 m, 1.06 m, and 2.10 m for the Low, Intermediate, and High SLR scenarios respectively – with no significant spatial variation in SLR around Puerto Rico (NOAA Tides & Currents, 2022). We assigned a SLR rank of 1 for Low, 3 for Intermediate, and 5 for High. To create the SLR input layer, we started with an empty copy of an initial exposure index output layer with points at every 250 m of coastline. Then, we added a column in the attribute table for SLR rank and re-ran the model with this layer. Due to limited predictive data on the effect of future SLR on Puerto Rico's ecosystems, interactions between SLR and habitat extent are not included in our scenario design. This is standard practice for incorporating SLR into the InVEST Coastal Vulnerability model (Arkema et al., 2013; Silver et al., 2019).

We ran the InVEST model for the three SLR scenarios and three habitat scenarios, resulting in nine total sets of coastal exposure data (Fig. 2). Each scenario represents a different combination of management and oceanographic changes. For example, local results for the "All Habitats, High SLR" scenario could represent successful conservation actions to help ecosystems persist under SLR in sites where persistence is possible (Epanchin-Niell et al., 2017; Woodroffe et al., 2016). In sites where habitats may fail to adapt to SLR conditions, the "No Habitats, High SLR" scenario gives an appropriate projection of relative hazard risk.

To compare relative exposure to coastal hazards across scenarios, we divided the distribution of exposure of all coastline segments into three groups following (Silver et al., 2019): lowest exposure at < 2.087 (bottom 25%), intermediate exposure at 2.087–2.844 (middle 25–50%), and highest exposure at > 2.845 (upper 50%). The highest exposure cutoff was used throughout our analysis to compare the amount of coastline most exposed to coastal hazards across the scenarios. Throughout this study, "highest risk" refers to exposure values in the upper 50% of the full distribution of exposure indices from all scenarios.

2.4. Assessing communities and energy infrastructure at risk

We used three variables to assess risk from coastal hazards in Puerto Rico: length of coastline, number of people, and number of electrical substations (Fig. 2). Each variable was analyzed in Microsoft Excel and RStudio using exported data from the layers in ArcGIS Pro. To estimate the length of coastline at highest risk, we took the sum of the number of coastline segments with exposure values > 2.845 (upper 50%) in each scenario. We calculated the number of people and substations highly exposed to coastal hazards both in the entire territory (Section 3.1) and in individual municipalities (Section 3.2). Territory-wide results explore general patterns of exposure under different scenarios across the coastline. Municipality-specific results highlight municipalities where people and energy infrastructure stand to benefit most from the risk reduction provided by habitats.

To estimate the number of people at highest risk, we loaded the WorldPop 2020 population density layer in the InVEST model (WorldPop, 2020). InVEST calculates the population density around each exposure point according to the population search radius that we set to 1 km. We divided these values by four to account for the scaling factor between the 250 m resolution of the exposure index and the resolution of the WorldPop layer (Silver et al., 2019; Natural Capital Project, 2024). We chose not to model population growth because Puerto Rico has a growth rate of 0.0% (U.S. Census Bureau, 2021).

To estimate the energy infrastructure at highest risk, we overlaid electrical substation data from the Homeland Infrastructure Foundation-Level Data in ArcGIS Pro (USDHS, 2022). We created Thiessen polygons for each exposure point and then spatially joined the substation layer. This step assigns an exposure value to each substation based on the nearest exposure point. We used these data to calculate how many substations within 2 km of the coast are highly exposed to coastal hazards in each scenario.

3. Results

In the first part of this section, we report the outputs of the InVEST Coastal Vulnerability model for the entire territory of Puerto Rico. We focus on the spatial distribution of risk, variation due to sea-level rise (SLR), and the potential for habitats to reduce risk to people and energy infrastructure. In the second part of this section, we analyze model outputs for individual municipalities of Puerto Rico. Our analysis identifies sites that could be prioritized for ecosystem-based risk reduction with a focus on benefits to energy infrastructure and coastal communities. For the San Juan metropolitan area and Ponce, we explore how urban protected areas could contribute to energy resilience.

3.1. Territory-scale risk

Exposure to coastal hazards varies considerably across the Puerto Rico coastline. With all habitats present, our modeled results indicate the highest relative exposure along the northeastern coast, south-central coast, and the northern coast of Vieques (Fig. 3A). This pattern is partly driven by storm surge potential – an important driver of exposure to coastal hazards on islands (Silver et al., 2019). Coastlines further from the continental shelf boundary tend to have higher storm surge potential and higher overall exposure, which is consistent with other studies that applied the InVEST model (Silver et al., 2019; Natural Capital Project, 2024).

The magnitude and spatial distribution of exposure also varies with presence of coral reefs, mangroves, wetlands, seagrasses, and algae that reduce the impact of hazards to varying degrees (Fig. 1A) (Table 1). With all habitats present under intermediate SLR, over 200 km of the coastline is highly exposed to hazards: approximately 20% of the total length (Fig. 3A, Fig. 4A). The extent of high-risk coastline increases to 340 km if we assume only habitats within protected areas are healthy enough to reduce risk from coastal hazards in the future and unprotected habitats have been degraded or lost (Fig. 3B, Fig. 4A). With complete loss of coastal ecosystems, our modeled results indicate over half of the coastline will be at highest risk (Fig. 3C, Fig. 4A).

The amount of people and energy infrastructure highly exposed to hazards increases significantly if habitats are degraded or lost (Fig. 4B, Fig. 4C). With intermediate SLR, if all habitats are present and intact, 13 substations and nearly ten thousand people are highly exposed (Fig. 4B, Fig. 4C). These numbers more than double if habitats outside protected areas are lost – and rise to 50 substations and more than 25,000 people if all habitats are lost (Fig. 4B, Fig. 4C). Across all habitat scenarios, higher SLR also leads to higher exposure, but this effect is nonlinear; the increase in risk from Low to Intermediate SLR is larger than the increase from Intermediate to High SLR (Fig. 4).

The relative importance of habitats for hazard risk reduction varies along the coastline (Fig. 5). Coastlines where habitats play a larger role in reducing risk represent candidate sites for new protected areas that could support the health of ecosystems that mitigate hazards. Nearly two-thirds of the coastal ecosystems in our model are currently protected, but protected areas do not always overlap with coastlines where ecosystems play a significant coastal risk reduction role (Fig. 1A, Fig. 5). Current protected areas are not necessarily the regions that supply the greatest hazard mitigation benefits. However, some places do have synergy between existing protected areas and ecosystem-based risk reduction, such as the east end of the northern coast (Fig. 5). When siting new protected areas for hazard mitigation, it is also important to consider whether human communities and infrastructure are located close enough to benefit (Tallis et al., 2015). Currently, there is little overlap between communities that have "demand" for the ecosystem service, such as large cities, and protected areas that preserve the "supply" of the service (Figs. 1, 5). In the following subsection, we examine ecosystem-based coastal risk reduction in individual municipalities to identify priority sites for protected areas that could enhance risk reduction for people and energy infrastructure.

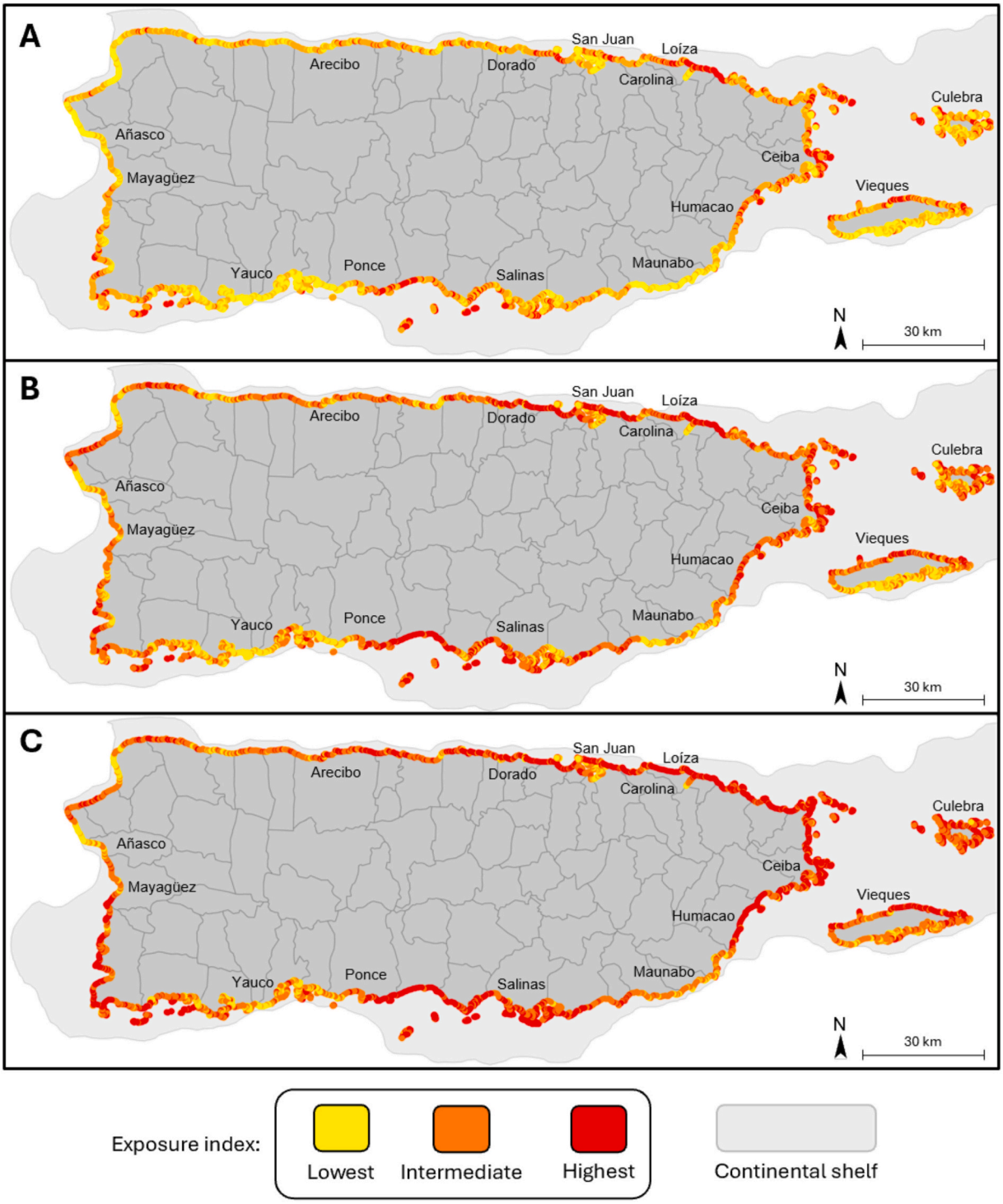


Fig. 3. Exposure to coastal hazards in Puerto Rico with all habitats present **(A)**, only habitats in existing protected areas present **(B)**, and no habitats present **(C)**. These exposure indices were generated under intermediate SLR. "Lowest exposure" is the bottom 25% of exposure index values from the full distribution of habitat and SLR scenarios (1.000 to 2.086), "intermediate exposure" is the middle 50% (2.087 to 2.844), and "highest exposure" is the top 25% (2.845 to 5.000).

3.2. Municipality-scale risk

Puerto Rico's 44 coastal municipalities differ in their exposure to coastal hazards and the extent to which habitats reduce risk to communities and infrastructure (Fig. 6). Across all municipalities, the proportion of people at highest risk with habitats present at intermediate SLR ranges from zero to nearly three-quarters of the population. Over one quarter of the municipalities in this scenario do not have any people at highest risk from coastal hazards (Fig. 6). However, if habitats were lost, the number of people highly exposed increases substantially. The most at-risk municipality becomes Humacao with 95% of its population highly exposed. Only Yauco, Maunabo, and Añasco continue to have zero people at highest risk without the coastal risk reduction potential of ecosystems (Fig. 6). In addition to population, we estimated the number of electrical substations at highest risk in each coastal municipality, which nearly quadruples if habitats were lost or degraded (Fig. 4C,

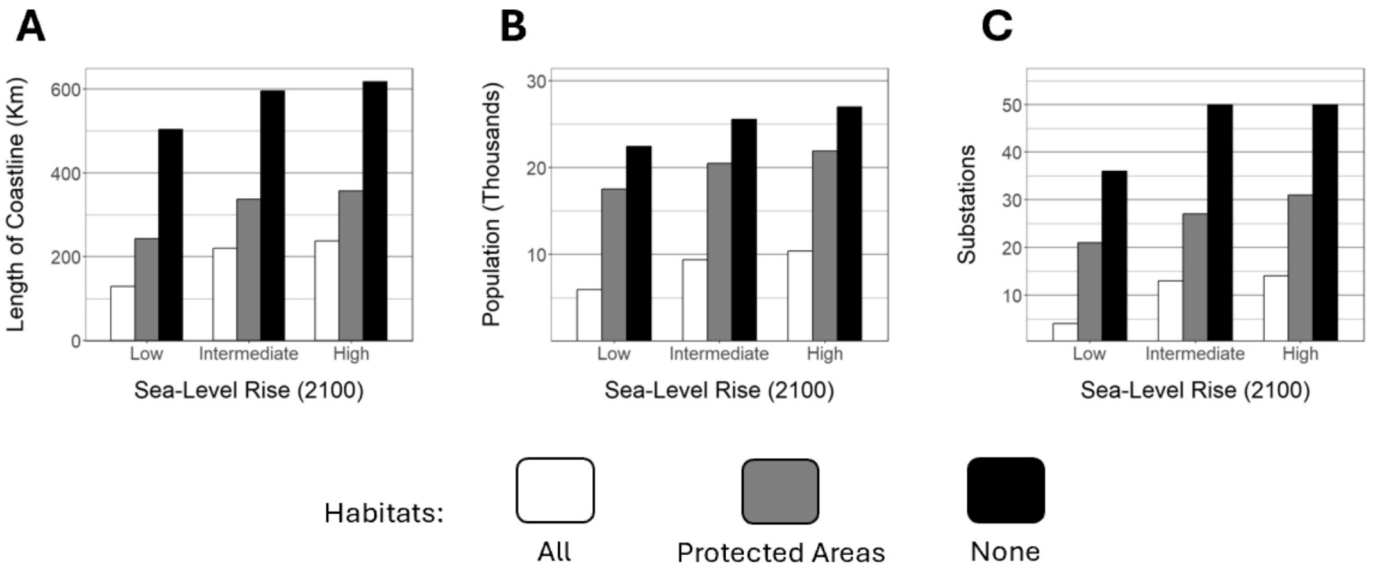


Fig. 4. Length of coastline **(A)**, number of people **(B)**, and number of electrical substations **(C)** that are highly exposed to coastal hazards (exposure > 2.844) under three habitat scenarios and three SLR scenarios.

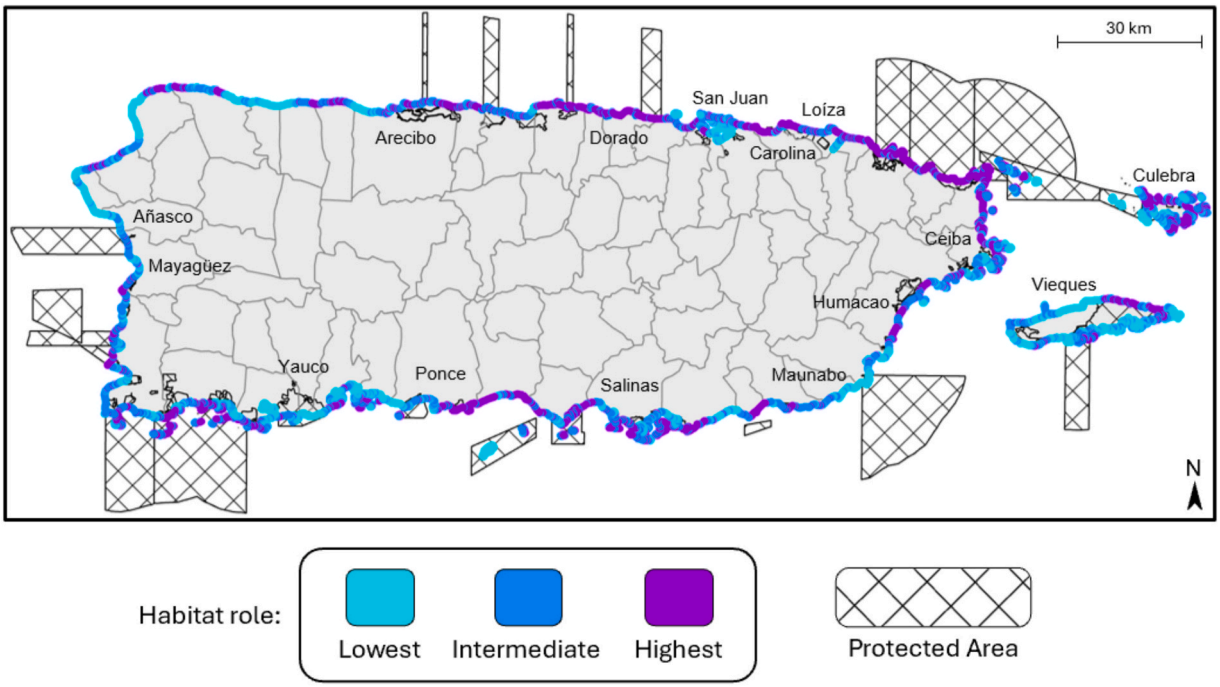
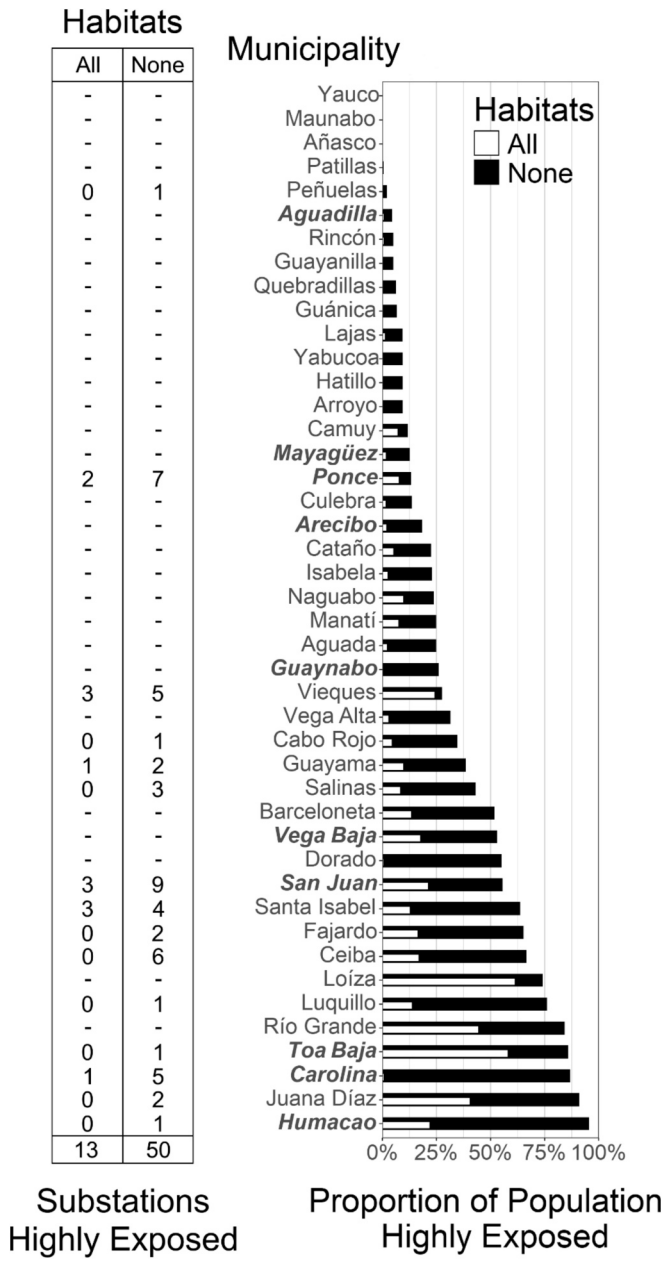


Fig. 5. Role of coastal and marine habitats in reducing exposure to coastal hazards. "Habitat role" equals the difference between exposure with no habitats present and exposure with all habitats present. "Lowest," "intermediate," and "highest" represent the three levels of habitat role calculated for intermediate SLR. Protected areas are overlaid to show which coastlines with a high habitat role value are currently protected and which are not. Note that even if a protected area covers a coastline with a low habitat role, it may still be important, as protected areas aim to achieve a variety of management goals in addition to risk reduction.

Fig. 6). Notably, every municipality with coastal electrical infrastructure has more substations highly exposed without the presence of habitats (Fig. 6).

Preserving ecosystem-based risk reduction is most important in municipalities that have extreme increases in exposure to coastal hazards if habitats are lost. In particular, the number of people at highest risk in Dorado and Carolina rises from < 1% with habitats to 54% and 86% without habitats respectively (Fig. 6). Both municipalities have coral reefs that buffer the populated and low-lying shoreline. Conversely, other municipalities such as Vieques and Loíza only have a marginal increase in risk if all habitats were lost, because population is concentrated near seagrass beds with less resistance to hazards (Fig. 6). The municipalities with the largest increases in highly exposed substations without habitats are San Juan, Ponce, Ceiba, Carolina, and Salinas (Fig. 6). These areas could be prioritized for energy resilience plans that incorporate ecosystem-based hazard mitigation.

The two municipalities with the largest number of substations at highest risk without habitats are San Juan and Ponce (Fig. 6). The San Juan metropolitan area is the largest population center in Puerto Rico – its coastline spans the municipalities of Cataño, Guaynabo, San Juan, and Carolina (Muñoz-Erickson et al., 2014). Under intermediate SLR, most of the metro area's coastline is either highly exposed to coastal



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-	-
3	9
3	4
0	2
0	6
-	-
0	1
-	-
0	1
1	5
0	2
0	1
13	50

Fig. 6. Number of substations and proportion of population highly exposed to hazards (exposure > 2.844) in each coastal municipality. Each row in the table corresponds to the adjacent municipality on the Y-axis of the bar graph. The bar graph is ordered by lowest to highest proportion of people at highest risk without habitats. The table considers substations within 2 km of the coastline and the bar graph considers population within 1 km of the coastline. Municipalities in ***bold italics*** have a total population size greater than 50,000. Note: these results were generated under intermediate SLR.

hazards with habitats present or becomes highly exposed if habitats were lost (Fig. 7A). A network of seagrass, algae, and coral along the northern shore helps to mitigate hazards for people and energy infrastructure, but only a small fraction of this ecosystem's extent is protected by the Isla Verde Reef Marine Reserve (Fig. 1B). This protected area conserves habitats that potentially reduce risk for the two easternmost substations at the SJU International Airport (Fig. 7A). Other substation and population clusters near segments marked as "additional shoreline at highest risk (w/out habitats)" are priority sites to conserve nearby ecosystems that reduce hazard risk for communities (Fig. 7A). New protected areas established on these coastlines could provide benefits to the greatest number of people and infrastructure.

Ponce is the central hub of energy infrastructure on the southern coast and a multitude of its substations become highly exposed to hazards if habitats were lost (Fig. 1D, Fig. 6, Fig 7B). Extensive patches of marine seagrass and algae, as well as coastal wetlands and mangroves, moderate the impacts of coastal hazards for the electrical grid in Ponce (Fig. 1C). A large portion of these habitats are protected by the Punta Cucharas Nature Reserve, which prohibits certain human activities and provides risk reduction ecosystem services in addition to its original purpose of biodiversity conservation (Fig. 7B) (Puerto Rico House Bill #3797, 2008). This protection benefits a large cluster of westernmost substations (Fig. 7B). On the eastern shore, Punta Cabullones is a nature reserve that was established in part to reduce storm surge by conserving mangroves and wetlands (Fig. 1C, Fig. 7B) (Rodríguez-Martínez & Soler-López, 2014). However, Ponce's substations are located away from Punta Cabullones and our model suggests they do not directly benefit from its hazard mitigation services (Fig. 7B). Conversely, the Port of Ponce has a cluster of substations that may become highly exposed to hazards if nearby habitats were lost, and these habitats are currently unprotected (Fig. 7B).

4. Discussion

We present a coastal hazard model for Puerto Rico that accounts for the risk reduction services provided by corals, mangroves, and seagrasses in the context of protected areas, sea-level rise (SLR), population, and energy infrastructure. Our modeled results show where coastal communities benefit from ecosystem-based risk reduction under future SLR (Fig. 3, Fig. 7). By identifying where habitats within and outside of protected areas mitigate hazards for electrical substations, our results suggest a potential link between ecological conservation and energy resilience (Fig. 6, Fig. 7). This is especially relevant because access to electricity is necessary for communities in SIDS to recover from disasters induced by coastal hazards (Winters et al., 2022). In Puerto Rico, interior communities rely on electricity that is generated in coastal areas and then delivered inland via transmission lines (Fig. 1D) (Kwasinski et al., 2019). Thus, the electrical grid serves to amplify the serviceshed of coastal ecosystems that reduce hazard risk, extending access to benefits to the entire territory – not just the coastal municipalities evaluated in our model (Ribot & Peluso, 2003; Tallis et al., 2015).

4.1. Advancing previous studies and frameworks for ecosystem services

Our analysis of energy infrastructure and protected areas advances previous assessments of coastal risk reduction provided by ecosystems. Prior studies have used the InVEST Coastal Vulnerability model to generate exposure indices and evaluate populations at risk under various habitat scenarios, but none have evaluated energy infrastructure at risk (Arkema et al., 2013; Cabral et al., 2017; Manes et al., 2023; Silver et al., 2019). Accounting for the electrical grid makes the model outputs more relevant to Puerto Rico and other energy-vulnerable SIDS (United Nations General Assembly, 2014; Winters et al., 2022). Another overlooked element is the potential role of protected area siting and management for nature-based coastal risk reduction. Our modeled scenarios demonstrate where protected areas could conserve or restore ecosystems that have the greatest potential to bolster disaster and energy resilience for coastal communities (Fig. 5, Fig. 7). In doing so, we contribute to an emerging effort to broaden the scope of protected area benefits beyond biodiversity, fisheries, and tourism to also include coastal risk reduction (Arkema et al., 2024; Grorud-Colvert et al., 2021).

In addition to filling gaps in the energy resilience and protected area literatures, our study advances specific elements within ecosystem service frameworks. For example, hazard mitigation is well-understood to be one of nature's benefits to people, but we expand on how this benefit contributes to human wellbeing by modeling the implications of coastal risk reduction for energy resilience (Díaz et al., 2015). Our results

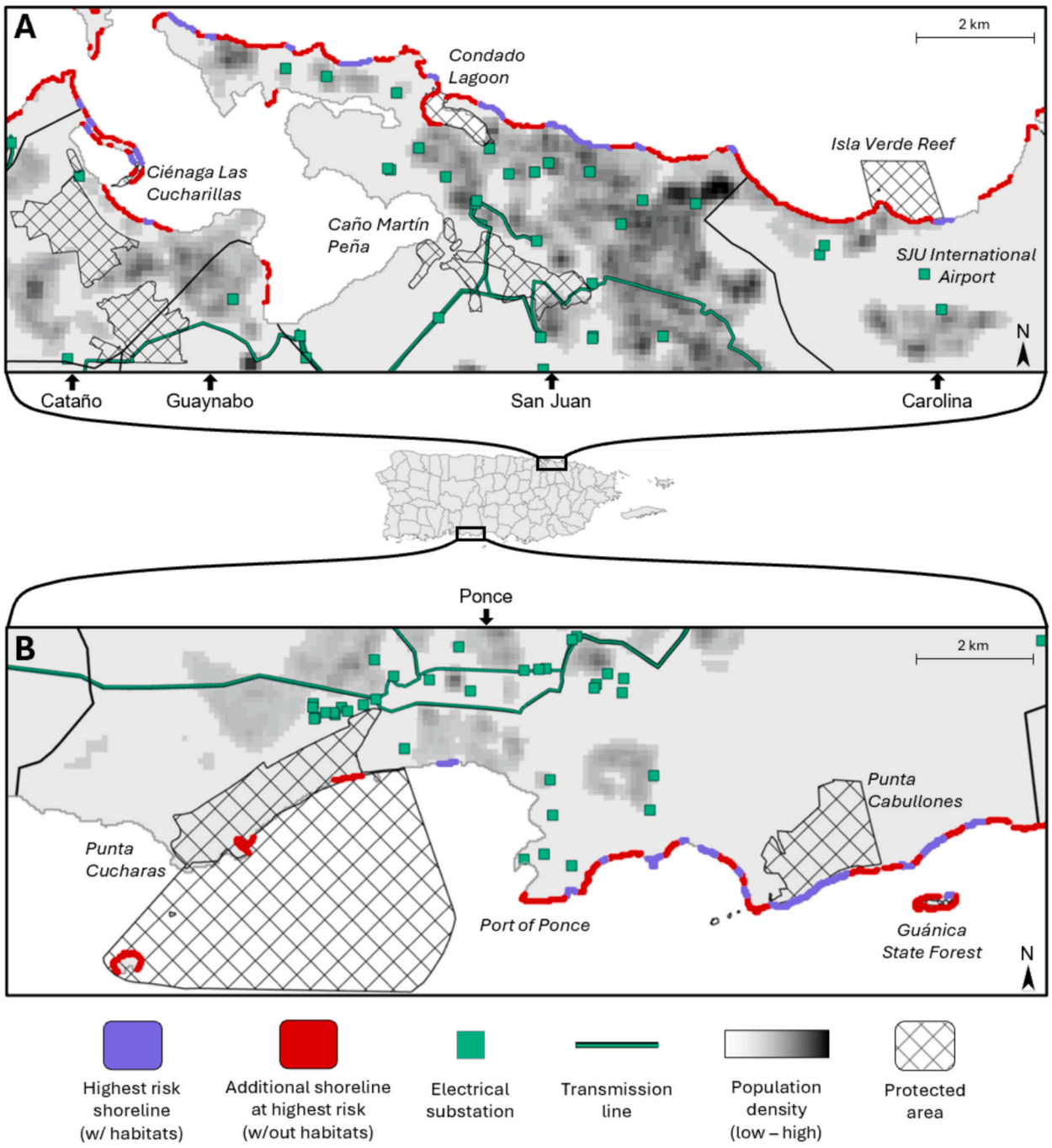

Fig. 7. Coastal hazard exposure, energy infrastructure, population, and protected areas in the San Juan Metropolitan Area **(A)** and Ponce **(B)** under intermediate SLR. The highest risk shoreline (exposure > 2.844) with habitats present and additional shoreline at highest risk without habitats are indicated following (Silver et al., 2019). Habitats reside both inside and outside of the protected areas (Fig. 1B, Fig. 1C). Municipality name labels are written with arrows below panel **(A)** and above panel **(B)**. Note: these maps only show the region next to the coast and not the entire metropolitan area.

suggest that hazard mitigation services provide several dimensions of value (TEEB, 2010). Specifically, we show where ecosystems have potential to offer economic value by reducing the risk of damages to as many as 37 substations in Puerto Rico (Fig. 4, Fig. 6). Nature-based coastal risk reduction also provides indirect social and ecological value – continued access to electricity helps alleviate poverty and enables people to pursue more sustainable livelihoods (Genave et al., 2020). Further, our analysis positions protected areas as a mechanism to maintain communities' access to hazard mitigation services if they are able to sustain ecosystem function over time (Ribot & Peluso, 2003). Future studies could evaluate how access to benefits is influenced by disparities in critical infrastructure coverage, zoning patterns, and other institutional factors (see Section 4.4) (Berbés-Blázquez et al., 2017; Tallis et al., 2015).

4.2. Management implications

Our approach could be used to generate spatial data that support the development of integrated land and ocean use plans that simultaneously build disaster resilience, balance stakeholder objectives, and safeguard ecosystem services (Delevaux et al., 2024). The implementation of such policies would require new collaborations between diverse sectors, such

as local and territorial government, renewable energy, tourism, fisheries, and shipping. In addition, participation from socially vulnerable populations can help inform where to site conservation or restoration projects to benefit communities most in need of coastal resilience (Grorud-Colvert et al., 2021; Mycoo and Donovan, 2017; PRCCC, 2022). Our methods of identifying priority locations for new protected areas could be combined with engagement practices and vulnerability assessments to fully account for trade-offs and community goals (Arkema et al., 2024; Sala et al., 2021; Seddon et al., 2020; Sullivan-Stack et al., 2022). This transdisciplinary work is especially important in coastal cities characterized by competing uses of the coastal zone, immense natural and built infrastructure exposed to hazards, and a dearth of protected areas that could reduce risk (Fig. 1, Fig. 7). In Puerto Rico and other SIDS, the decline of nature in and around cities presents an urgent opportunity for decision makers to conserve ecosystems and their disaster resilience benefits (Duarte et al., 2020; Hernández-Delgado, 2024; Mazor et al., 2021).

Protected areas managed for nature-based risk reduction and energy resilience could synergize multiple initiatives in Puerto Rico that are currently siloed. The Climate Change Act lists separate objectives for the protection of degraded habitats, mitigation of coastal hazards, and siting of renewable energy (Puerto Rico Climate Change Act, 2019). Our study connects these objectives by demonstrating the potential for habitats in protected areas to reduce risk for nearby communities and energy infrastructure (Fig. 5). We also identify infrastructure-dense municipalities that could benefit most from nature-based resilience strategies amidst the effort to transition to 100% renewable energy by 2050 (Fig. 6). The PR100 study highlights coastal hazard mitigation as a key element of energy resilience under future conditions, but it does not mention nature-based approaches (Baggu & Burton, 2024). The growing momentum for conservation and restoration in Puerto Rico – along with emergent research on nature-based coastal resilience – could be leveraged to support the development of renewable energy (Castro-Prieto et al., 2019; Dobson et al., 2020; FEMA, 2024).

As a relatively new approach, nature-based solutions for disaster risk reduction have several limitations that represent opportunities for further research (Arkema and Ruckelshaus, 2017; Bridges et al., 2021). These limitations include uncertainty about effectiveness due to trade-offs and site-specificity, slow growth rates of certain species, and vulnerability of ecosystems in protected areas to ambient stressors (Bates et al., 2019; Cunniff & Schwartz, 2015; Ruckelshaus et al., 2016; Seddon et al., 2020). In the case of SLR, an ambient stressor, protected habitats are more likely to adapt if the conserved area includes adjacent land that the habitats can migrate to without experiencing coastal squeeze from human development (Epanchin-Niell et al., 2017; Yu et al., 2019). It is also possible to develop SLR resistance by planting species that are more resilient to higher water levels or improving water quality around the protected area (Saunders et al., 2013; Woodroffe et al., 2016). However, these strategies do not fully eliminate the risk of SLR and other coastal hazards (Bates et al., 2019).

Our modeled results are useful for identifying sites where conservation or restoration could be appropriate for hazard mitigation, or where alternative strategies may be more suitable. For example, it may be necessary to build gray or hybrid infrastructure along a coastline that is already at highest risk when all habitats are intact because a protected area on its own may not provide any additional reduction in exposure (Fig. 7). By modeling the entire Puerto Rico coastline at a 250 m resolution, our study meets the demand for accessible hazard risk data that could help decision makers operationalize a variety of disaster resilience approaches while accounting for ecosystems, energy infrastructure, and people (Mycoo and Donovan, 2017; UNDRR, 2015).

4.3. Model limitations and opportunities

Our methodology to model nature-based coastal resilience in Puerto Rico comes with important limitations. First, our model does not consider social vulnerability indicators such as age or income when assessing exposure to coastal hazards. Second, our data sources for mangroves, wetlands, and geomorphology predate Hurricane Maria (Table 1). We encourage future studies to incorporate post-Maria data once it becomes available, as well as demographic data, to improve the accuracy of the exposure index and make the results more relevant to vulnerable communities (Cabral et al., 2017; Silver et al., 2019).

Third, the InVEST model makes several assumptions to simplify the hazard dynamics calculations. For example, it does not account for interaction effects between input variables and it underestimates exposure to severe storms (Natural Capital Project, 2024). Despite these assumptions, other studies for the United States and Mozambique validated the accuracy of the exposure index and found high agreement with observed hazard data (Arkema et al., 2013; Cabral et al., 2017). Fourth, we simplify the data requirements of our modeled scenarios by defining SLR as a standalone input variable that does not affect habitat extent, following (Arkema et al., 2013; Silver et al., 2019). Under high SLR, it is possible that nature-based resilience for people and energy infrastructure could be weakened if local conditions interfere with sediment accumulation or landward migration – or protected areas are not managed for SLR adaptation (Epanchin-Niell et al., 2017; Saunders et al., 2013; Woodroffe et al., 2016; Yu et al., 2019). Thus, the exposure values for the “All Habitats” and “Protected Habitats” scenarios may be underestimates (Fig. 4). Future studies could account for this interaction effect using tools such as Sea Level Affecting Marshes Model in conjunction with InVEST models (Reddy et al., 2016).

4.4. Questions for further research

Our study uses an ecosystem services approach to explore connections between nature-based risk reduction, protected areas, and energy resilience in Puerto Rico. We pose the following questions for future studies to build on our work and adapt the approach to specific disaster resilience and management contexts:

1. Where do coastal habitats reduce hazard exposure for other parts of the energy grid (fuel terminals, transmission lines, etc.) – or for other types of infrastructure (transportation, water, telecommunications, etc.)?
2. Where are human activities currently degrading or restoring habitats that provide coastal resilience for communities and energy infrastructure?
3. In potential sites for new protected areas, what tradeoffs exist between managing for hazard mitigation and other regulating services vs. provisioning and cultural services?
4. What social-ecological factors influence access to hazard mitigation services in urban areas?

5. Conclusion

This study explores the potential for ecosystems to reduce exposure to coastal hazards for both people and energy infrastructure in Puerto Rico. Our results reveal sites where infrastructure is co-located with coastal habitats that mitigate hazards, enabling decision makers to leverage nature-based solutions and protected areas to build resilience. These approaches could help Puerto Rico and other SIDS achieve cost-effective and co-beneficial disaster risk reduction under future SLR (UN DESA, 2022). By connecting conservation to disaster and energy resilience, we invite actors from new sectors to participate in the siting of protected areas, potentially broadening support for the effort to protect 30% of Earth’s lands and waters by 2030 (Convention on Biological Diversity, 2022). Further, protected areas that enhance hazard mitigation ecosystem services could contribute to multiple Sustainable Development Goals that converge on the patterns explored in our study, including but not limited to: No Poverty, Affordable and Clean Energy, Climate Action, and Life Below Water.

Meaningful engagement across sectors is critical for implementing ecosystem-based risk reduction, which has been shown by other studies that used the InVEST Coastal Vulnerability model in Belize and The Bahamas (Arkema & Ruckelshaus, 2017; Silver et al., 2019). In Puerto Rico, our study could serve as a starting point for similar cross-sectoral sustainable development projects. Researchers in other SIDS could also benefit from running the InVEST model, as this methodology is replicable even in data-limited areas. Our approach illustrates spatial relationships between ecosystems, protected areas, and energy infrastructure in coastal communities where it is increasingly urgent to explore opportunities for nature-based solutions to build resilience to natural hazards.

CRediT authorship contribution statement

Maxwell S. Perkins: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonathan D. Bakker:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Katie K. Arkema:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank our institutions for their support. This study was initiated as part of an internship for Maxwell Perkins at the Pacific Northwest National Laboratory, operated by Battelle Memorial Institute, for the United States Department of Energy under Contract DE-AC05-76RL01830. The study was completed through the University of Washington School of Environmental and Forest Sciences Departmental Honors Program and the Program on Climate Change Graduate Certificate in Climate Science (GCeCS). We thank Miriam Bertram for her advisership during the GCeCS and Jess Silver and the software team at the Natural Capital Project for their support in applying the InVEST Coastal Vulnerability Model. We also thank Elise Boos and Shon Zimmerman for their help with the spatial analysis. Lastly, we thank the student and faculty community at the University of Washington School of Marine and Environmental Affairs for their support and feedback throughout the project.

Data availability

The model outputs are available here: https://doi.org/10.17632/n4gzfjddz2.1.

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