Mapping Ecological Priorities and Human Impacts to Support Land-Sea Management of Puerto Rico's Northeast Marine Corridor

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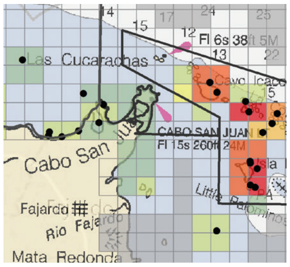

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About This Document

This report describes a spatial characterization conducted to support the development of an integrated management plan for Puerto Rico’s Northeast Marine Corridor. The Northeast Marine Corridor is a large, land-sea reserve network, making it unique in the region for both its size and the integrated land-sea geographical scope. Here we map and model ecological priorities and threats to support managers with risk assessment and prioritization of management actions. The best available data, including local expert knowledge of special ecological places and threats, were compiled to map key marine features, important habitat types and marine species of concern. Ecological priority areas were identified and ranked based on the number of ecologically important attributes across the region and analyzed relative to the distribution of threats and stressors to help managers identify and prioritize areas of concern. The methods and data used for spatial prioritization are described in this report and resultant maps showing ecological priorities and potential stressors are provided. The approach was implemented through a partnership between NOAA National Centers for Coastal Ocean Science and Puerto Rico’s Department of Natural and Environmental Resources, or Departamento de Recursos Naturales y Ambientales, with funding from NOAA's Coral Reef Conservation Program.

SINOPSIS

A continuación se describe un estudio espacial realizado para sustentar el desarrollo del plan integrado de manejo para del Corredor Marino Noreste en Puerto Rico. Corredor Marino Noreste es una vasta red de ecosistemas terrestres y costeros/marinos, característica propia de la extensa región y por su alcance geográfico de zona costera. Para ayudar a los manejadores y los planificadores en las evaluaciones de riesgos y determinar las prioridades de manejo, se presenta en este documento un mapa acompañado de un modelo de las prioridades y las amenazas ecológicas. Se compilaron datos fiables disponibles, incluyendo el conocimiento de expertos locales sobre lugares de interés y que pudieran estar amenazados o en riesgo ecológico. Una vez identificados, se procedió a trabajar el mapa que incluyera las características marinas principales, los tipos de hábitat importantes y las especies marinas de interés. Las áreas de prioridad ecológica de la región estudiada fueron identificadas y clasificadas en función del número de atributos de importancia ecológica. La mismas se analizaron con respecto a la distribución de las amenazas y los factores de estrés con el propósito de ayudar a los manejadores/especialistas a identificar y determinar las prioridades en las áreas de interés. Los métodos y los datos utilizados para la priorización espacial son descritos en este informe junto a los mapas desarrollados que demuestran las áreas de prioridad ecológica y los posibles factores de estrés. Esta iniciativa se implementó a través de una colaboración entre los Centros Nacionales para la Ciencia Oceánica Costera de la NOAA y el Departamento de Recursos Naturales y Ambientales de Puerto Rico (DRNA) con fondos del Programa de Conservación de Arrecifes Coralinos de la NOAA.

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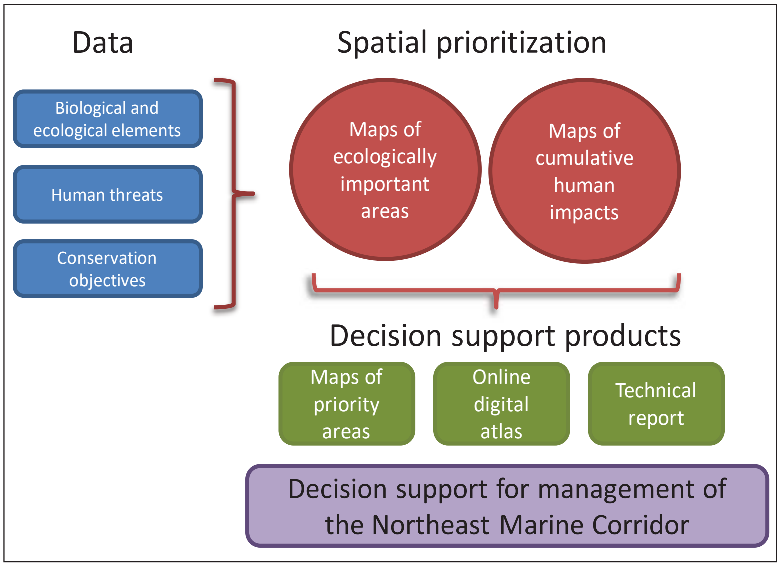
Executive Summary

The Northeast Marine Corridor is a unique land-sea reserve network that is important to the Commonwealth of Puerto Rico and the Nation because of its relatively high biodiversity and provision of valuable ecosystem services in comparison to other regions in Puerto Rico. It is widely acknowledged, however, that a combination of coastal development, agriculture, storms, fishing and other stressors have contributed to a decline in coral reef condition in northeast Puerto Rico, even within established marine reserves. The need to identify important ecological areas and prioritize those most vulnerable to existing threats for short-term management actions is crucial for Puerto Rico's Department of Natural and Environmental Resources (DNER), or Departamento de Recursos Naturales y Ambientales, and National Oceanic and Atmospheric Administration (NOAA). To successfully manage such a geographically broad and diverse region, a framework for prioritizing management actions is essential. To directly address this management challenge, NOAA National Centers for Coastal Ocean Science (NCCOS) compiled and analyzed a wide range of biophysical data, qualitative human use information, and knowledge from local experts to spatially characterize ecological resources and stressors and thereby identify areas of special concern.

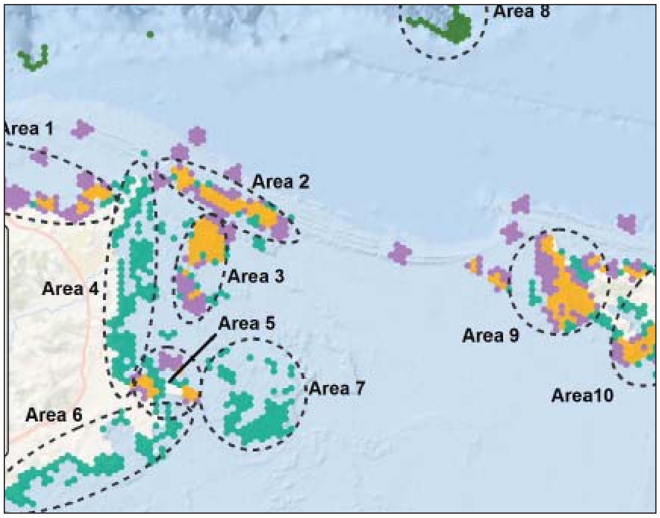


Structure of the spatial characterization.

Primary objectives were to address the following questions:

- What and where are the ecological priority areas?
- Where do multiple ecological priorities co-occur in space?
- Which human impacts threaten priority areas?
- At which locations are ecological priorities most threatened?

The maps of ecologically important areas and human impacts provided by this project result from integration and evaluation of local knowledge from scientific experts and resource managers with a long history of working in the region and analysis and modeling of biological and ecological monitoring data. Each analysis identifies special places in Puerto Rico's northeast region using different data, assumptions and processes. Integration and comparison of different techniques for identifying priority areas is the focus of Chapter 3. Together, the maps highlight special areas from local expert knowledge, empirical measurements and spatial models, and are less-sensitive to data gaps, analytical assumptions and uncertainties related to data quality.



Identification of priority areas.

Eleven areas of special ecological interest were identified (Chapter 3): Nearshore northeast coast near Luquillo, La Cordillera, Isla Palominos, Eastern coast of Puerto Rico, Isla Piñeros, Southeast coast of Puerto Rico, Bajo Chinchorro del Sur, Offshore canyons, Western Culebra, Eastern Culebra, and Bajos Grampus.

A geographic decision support system was used to assess areas with greatest ecological importance and those most threatened by cumulative human impacts. The Marxan tool was used to support spatial planning by identifying spaces that meet biological and ecological management objectives. Applying human impacts as a prioritization criteria was also explored (Appendix C).

The analyses presented in this report are dependent on where data exists, and as such our analyses have spatial and thematic gaps. These gaps include: the distribution of the most diverse and economically important coral reefs and locations of threatened coral species and deep water corals; population status of invasive species, such as lionfish and the seagrass *Halophila stipulacea*; and spatial information on human use patterns. Information addressing these gaps in knowledge are all urgently required.

In addition, very little is known about ecological connectivity of coral and fish larvae and the places that are most important as spawning and nursery habitat for commercially and recreationally important marine animals. Knowledge gaps also exist for a range of stressors, such as turbidity, nutrients and contaminants and thermal stress which causes coral bleaching.

RESUMEN EJECUTIVO

Corredor Marino Noreste es una red de ecosistemas terrestres y costeros/marinos única reconocida por el Estado Libre Asociado de Puerto Rico y el gobierno federal por su extraordinaria riqueza natural de alta biodiversidad y la provisión de servicios ecosistémicos valiosos. No obstante, se sabe a ciencia cierta que una combinación de factores ha contribuido al deterioro de los arrecifes coralinos del noreste de Puerto Rico, aún dentro de las reservas marinas ya establecidas. Sin embargo, es ampliamente reconocido que la combinación del desarrollo costero, agricultura, tormentas, pesca y otros factores de estrés han contribuido a debilitar la condicion de los arrecifes de coral en el noreste de Puerto Rico, incluso dentro de las reservas marinas establecidas. Es de prioridad para el Departamento de Puerto Rico de Recursos Naturales y Ambientales y la NOAA, identificar y priorizar las áreas ecológicas importantes y altamente vulnerables además de evaluar las amenazas que las acechan. El manejo de dicha zona geográfica amplia y diversa requiere un marco donde se establezca las acciones prioritarias de manejo. Para enfrentar directamente este desafío con un plan de manejo adecuado y en apoyo al desarrollo de un plan de manejo con la información amplia y completa, es que se lleva a cabo este proyecto de caracterización espacial por los Centros Nacionales de Ciencia de las Costas Oceánicas (NOAA-NCCOS por sus siglas en inglés). Su diseño recopila y analiza una amplia gama de información, incluyendo el conocimiento de expertos locales e identifica y caracteriza las áreas de un interés especial.

Las siguientes preguntas a bordan los objetivos principales:

- ¿Cuáles son y dónde están las áreas de prioridad ecológica?
- ¿Dónde ocurren simultáneamente múltiples prioridades ecológicas en el espacio?
- ¿Cuál impacto humano amenaza las áreas de prioridad?
- ¿En qué lugares están las prioridades ecológicas más amenazadas?

Este proyecto proporciona los mapas desarrollados de áreas de importancia ecológica e impactos humanos para ser utilizados en un proceso integrado y comparativo de evaluación donde se utiliza el conocimiento de expertos locales y los datos y modelos de monitoreo biológico y ecológico. Cada análisis identifica lugares especiales en la región noreste de Puerto Rico utilizando diferentes datos, premisas y procesos. La integración y la comparación de las diferentes técnicas usadas para la identificación de áreas de prioridad es el foco central de la Sección 3. En conjunto, los mapas destacan áreas especiales para el conocimiento de expertos locales, mediciones empíricas y modelos espaciales, y son menos sensibles a la falta de datos, a los supuestos de los análisis e incertidumbres relacionadas con la calidad de datos.

Se identificaron once áreas de especial interés ecológico (Sección 3), basado en el conocimiento experto y datos biofísicos que incluye los siguientes: zona costera noroeste cerca de Luquillo, La Cordillera, Isla Palominos localizada en la costa este de Puerto Rico, Isla Piñeros localizada en la costa sudeste de Puerto Rico, Bajo Chinchorro del Sur, cañones submarinos, este y oeste de Culebra y Grampus Bajos.

Un sistema de apoyo en la toma de decisiones geográficas fue utilizado para evaluar zonas de mayor importancia ecológica y las más amenazadas por los impactos acumulativos de origen humano. La herramienta Marxan fue utilizada para proporcionar ayuda en la planificación espacial para identificar áreas que alcancen unos objetivos biológicos y ecológicos para el manejo. También se exploró la aplicación de los impactos humanos como criterio de priorización (Apéndice C).

Los análisis presentados en este documento son dependientes de dónde existan datos, y como tales nuestros análisis tienen lagunas espaciales y temáticas. Esas lagunas incluyen: la distribución de los arrecifes coralinos más diversos y de gran importancia económica y el estado de poblaciones de especies invasoras como el pez león y la hierba marina *Halophila stipulacea*; y la información espacial sobre los patrones de uso humano. Información dirigida hacia esas lagunas de conocimiento es requerida con gran urgencia.

Además, se sabe muy poco sobre la conectividad ecológica de las larvas de coral y peces, y sobre los lugares que son más importantes como hábitat de cría y vivero para animales marinos de importancia comercial y recreativa. También existen lagunas de conocimiento para una serie de estresores, tales como turbidez, nutrientes y contaminantes y el estrés térmico que causa el blanqueamiento del coral.

Chapter 1: Background and objectives

The Northeast Marine Corridor is a large land-sea reserve network that is unique in the region for both its size and its integration of connected landscapes and seascapes. The region's marine areas are used for a wide range of human activities, such as commercial and recreational boating, diving, fishing, and tourism. The area supports more than 50 critical, rare, endemic and endangered species, including several marine species listed under the U.S. Endangered Species Act (ESA; e.g., West Indian manatee [*Trichechus manatus*]; sea turtles; *Acropora* corals; Nassau grouper [*Epinephelus striatus*]). Consequently, the area is a culturally and economically important resource, valuable to the Commonwealth of Puerto Rico and the Nation because of its high biodiversity and valuable ecosystem services. In 2010, The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Conservation Program (CRCP), guided by Puerto Rico's coastal managers and coral reef scientific experts, voted the Northeast Reserves and Culebra region as one of the most important sites for coral reef conservation in Puerto Rico (NOAA CRCP, 2010). This evaluation was based on the biological value of the area, as well as its relatively high risk from multiple stressors. More recently, in 2015, the national importance of the area was recognized by its designation as a NOAA Habitat Focus Area under the NOAA Habitat Blueprint initiative (https://www.habitatblueprint.noaa.gov/).

The sustainable management and protection of the region's special places, habitats and species has long been a priority for resource managers and environmental planners in Puerto Rico. The establishment of marine reserves within the northeast region began in 1975 when the Conservation Trust of Puerto Rico acquired the land area of the Cabezas de San Juan to conserve a bioluminescent lagoon and historic Spanish lighthouse (Figure 1). The reserve was later extended from shore out to nine nautical miles to protect the surrounding marine habitats. In 1980, the Puerto Rico Planning Board created the Reserva Natural Arrecifes de la Cordillera, and in 1991 developed a management plan to protect this chain of ecologically significant limestone cays which extend seaward from the Reserva Natural Cabezas de San Juan. Puerto Rico's Department of Natural and Environmental Resources (DNER), or Departamento de Recursos Naturales y Ambientales, updated this management plan in 2007. In the 1990s, community groups proposed the Reserva Natural Corredor Ecologico del Noreste (between Luquillo and Fajardo) which was finally signed into law in 2013 (Figure 2). In 1999, Reserva Natural Canal Luis Peña was created. The designation effort was catalyzed by the Culebra Fisher's Association, community members, local groups, and the scientific community. The RN Canal Luis Peña was designated as a no fishing zone in 1999 and a management plan was developed and approved in September 2008.

Figure 1. Cape San Juan Light within the Las Cabezas de San Juan Nature Reserve.

The northeast region currently has approximately 122 special conservation areas of interest identified by DNER, including 10 special beaches; 35 special habitat areas (upland and lowland for threatened and endangered species); 46 critical wildlife areas (birds and reptiles); 11 conservation priority areas; and 20 protected areas, including natural reserves, state forests and wildlife refuges (Figure 3). Six marine and coastal Natural Reserves exist within the new Northeast Marine Corridor (Figure 2), including: four multiple-use reserves (Reserva Natural [RN] Río Espíritu Santo, RN Las Cabezas de San Juan, RN Arrecifes de La Cordillera and the new RN Corredor Ecológico Noreste units), and one no-take reserve (RN Canal Luis Peña).

Background and Objectives

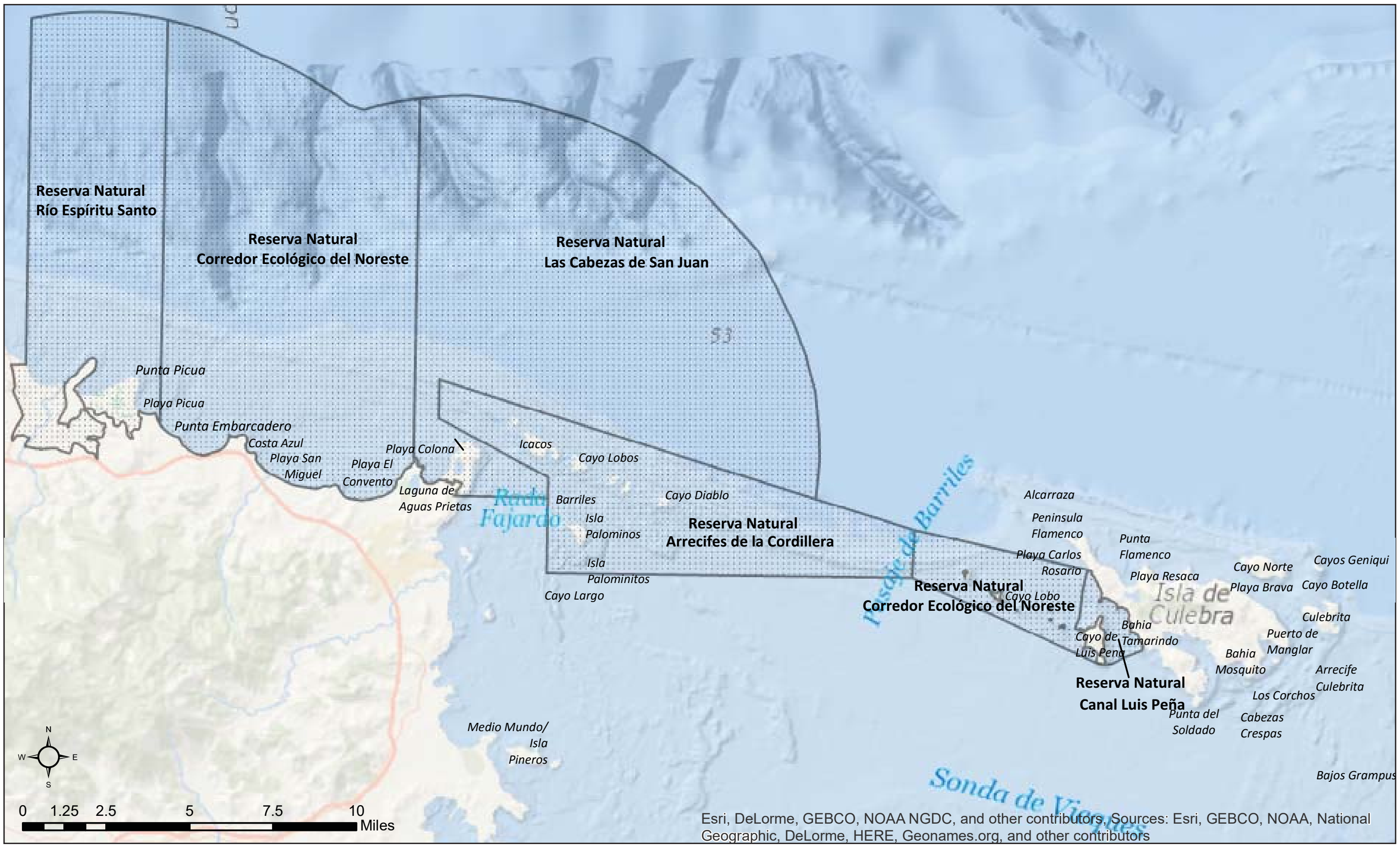


Figure 2. Place names for islands, bays, cays and marine protected areas (MPAs) in northeast Puerto Rico.

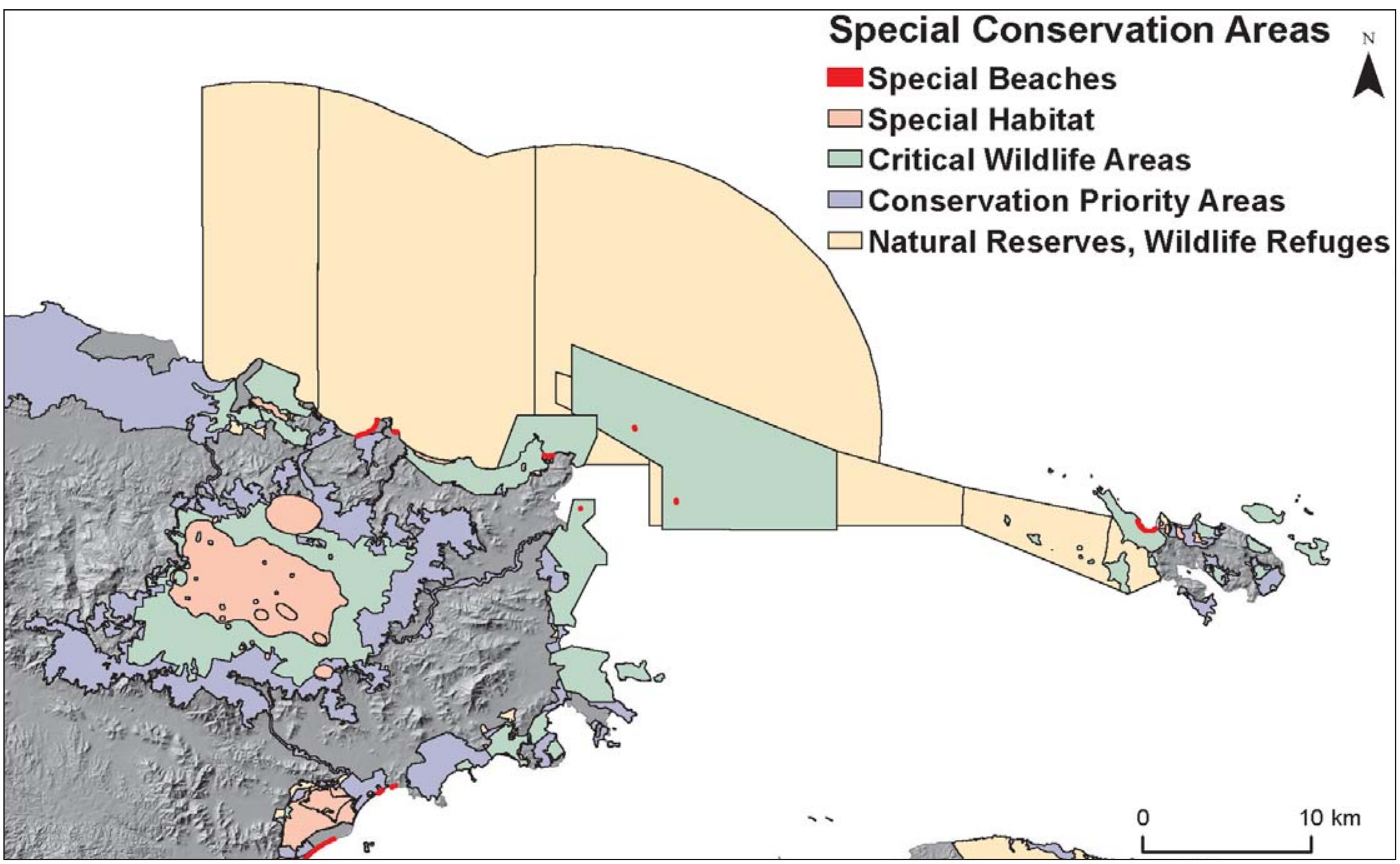


Figure 3. Areas of special conservation interest for northeast Puerto Rico including special beaches, habitat, critical wildlife habitat, conservation priority areas and marine and coastal protected areas (e.g., natural reserves).

Background and Objectives

These special conservation areas along with the five reserves provide a basis for implementing directed management actions to target select human activities and protect specific natural resources on relatively small spatial scales. However, they do not adequately consider ecological connectivity among the reserves nor address the need for integrated management of living resources outside their boundaries and over the broader spatial scale of northeast Puerto Rico. On March 1st, 2016, the new Northeast Marine Corridor boundaries were approved by the Puerto Rico Planning Board. With assistance from NOAA, this new land-sea management area is being designed by DNER to connect the marine component of the reserves between northeast Puerto Rico and Culebra Island and to provide comprehensive and integrated management of important ecological resources in the region.

NOAA's National Ocean Service's (NOS) National Centers for Coastal Ocean Science (NCCOS), as long-term partners of the DNER, were funded in 2012 to support DNER's development of an information-based spatial management plan for the proposed reserve network. During the planning stages of this project, local stakeholders, resource managers, and research scientists held workshops to identify management concerns, priorities, and short- and long-term goals for the reserves network. The working groups discussed and listed important ecological information on the distribution of marine habitats and living resources and key data gaps needing to be addressed for successful implementation and management of the reserves. Using the results from the scoping meetings, partners worked together to design and execute five components of the project:

1. *Create a Management Steering Committee* (MSC): to establish a shared vision and management approach among management stakeholders.
2. *Conduct Social Science*: to better understand human use values in the region.
3. *Develop Hydrodynamic Flow Models*: to model water circulation patterns and wave energy to help understand the hydrodynamic connectivity and the dispersion of plants, animals and energy within the region.
4. *Conduct Spatial Ecological Characterization:* to compile, evaluate and synthesize existing and newly acquired geospatial data to support spatial planning, identify ecologically important areas, prioritization of management actions and risk assessment. The data will be communicated through an interpretative report and an online map-based decision support tool.
5. *Conduct in-situ biological characterizations:* to identify candidate coral reefs sites suitable as part of a permanent long-term monitoring program.

It was recognized that comprehensive, detailed and reliable spatial data is central to modern marine management and is required to support effective decision-making in the management of a multi-use protected area. Few maps existed to describe the spatial distribution of important places, species and human activities across the region. The need to identify and prioritize important ecological areas and to evaluate threats to those important and vulnerable places is a high priority for DNER. To directly address this data requirement, the NCCOS spatial characterization project was designed to compile and analyze a wide range of information, including local expert knowledge, to identify and characterize areas of special ecological concern. The intention was to make spatial data accessible to managers and the community to support the design of efficient strategies to protect, maintain and enhance the quality of the ecosystem for current and future generations. New data collections were also required to support the spatial characterization, such as the mapping of bathymetry and the creation of a new benthic habitat map (Project page: https://coastalscience.noaa.gov/projects/detail?key=258). Although the marine environment was the primary focus, data on landscape use in the watersheds adjacent to the marine portion of the project area were also integrated into the project.

Background and Objectives

The primary objectives of this spatial characterization are:

Objective 1: Compile a comprehensive spatial database to characterize the ecosystem and provide a robust data-driven foundation for the development of an effective management plan;

Objective 2: Integrate socioeconomic, physical oceanographic, biological and seafloor habitat patterns to identify ecological priority areas and examine the overlap with human uses to map and evaluate areas of potential concern;

Objective 3: Build an online map tool to support marine protected area (MPA) managers with ecosystem-based decision-making and to increase community awareness of the broader regional ecosystem.

This report addresses the first two objectives of the spatial characterization project and contributes the required data for Objective 3.

General Approach

The general approach for this project centered on a logical stepwise data synthesis process following the NCCOS Biogeographic Assessment Framework (BAF; Caldow et al., 2015). The framework was designed to guide data synthesis in marine spatial planning and consists of four sequential steps: Planning, Data Evaluation, Ecosystem Characterization and Management Applications (Figure 4). The merits of the framework approach were that direct dialogue and information sharing with managers was a core process and important for the evaluation of spatial data quality. This collaborative information sharing partnership was critical to achieving Objective 1.

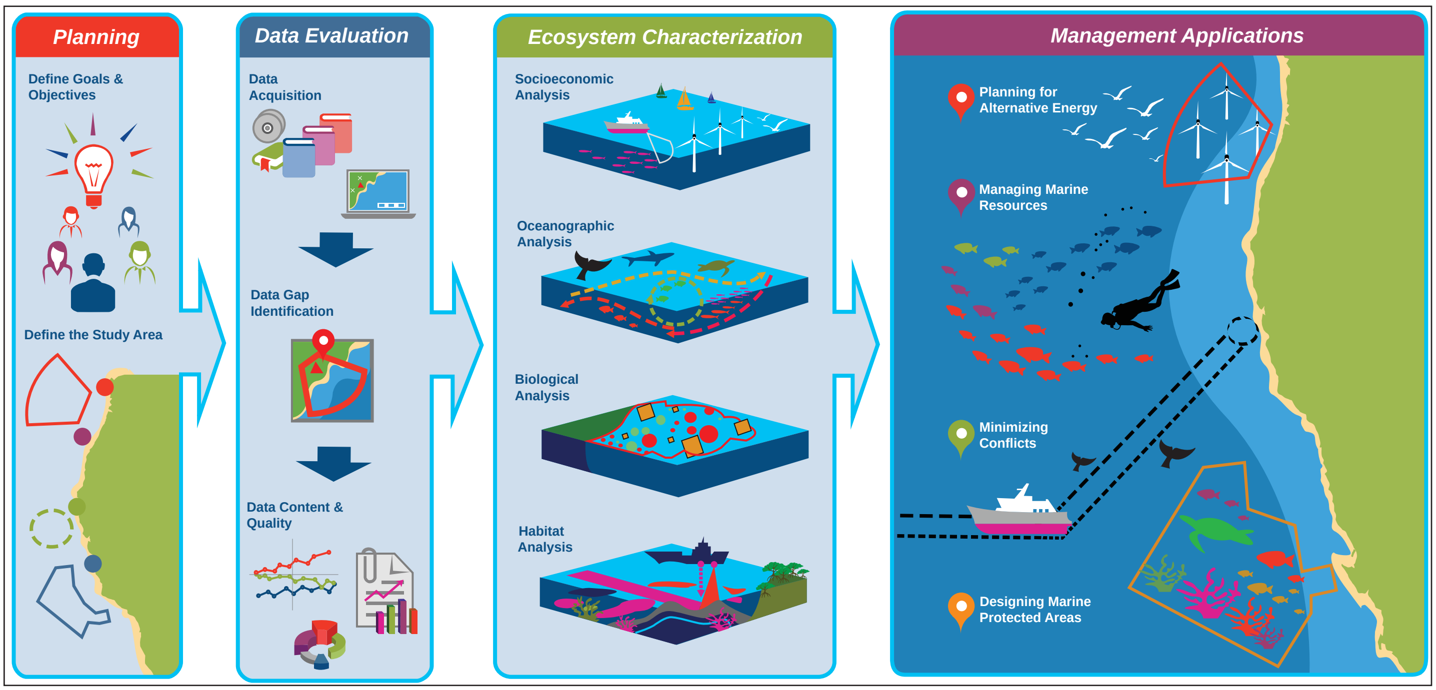


Figure 4. Logical steps in the Biogeographic Assessment Framework (BAF) approach designed to support robust and spatially explicit synthesis of spatial information for spatial management.

1.1 PRIORITIZATION IN MARINE MANAGEMENT

Objective 2 of the spatial characterization required a synthesis of biophysical and socioeconomic data in order to identify priority ecological areas and areas of concern. Identifying priority areas allows natural resource managers to focus effort on places that are of the greatest ecological value or in greatest need of protection (Myers et al., 2000). Identifying ecological “hotspots” along with areas of intense human use and impacts can help managers set conservation priorities for a range of objectives, including biodiversity conservation, fisheries management and MPA designation and management. Using a combination of data-driven, systematic methods and expert-driven methods is ideal for the prioritization process, as it allows for greater local participation and captures additional knowledge that may not be inherent in the systematically collected biophysical data (Maddock and Samways, 2000). This information can be derived from both biophysical data collected in the region, and through expert knowledge, which may incorporate emergent knowledge from many years of observations and ecosystem change. To help address data gaps, we recognized that academic and government scientists are knowledgeable about the underwater world in the project region that extends beyond information that was published or was publicly available. In this project, we used participatory mapping techniques to collect spatial information (Section 2.1) on important areas and threats. This information was then integrated with information from modeled and field data (see Chapter 3 for data integration). Figure 5 shows how the data products were developed through the spatial characterization process. This was accomplished through: 1) providing information for the development of a management plan; 2) an online map viewer; and 3) future strategic planning, such as addressing threats, optimizing MPA design and monitoring for adaptive management. To explore additional spatial design scenarios in marine planning, we also applied data on the distribution of biological and ecological elements together with threats and stressors. We employed a spatial decision support tool (Marxan software: http://marxan.net/) which managers can use to identify a network of places that meet resource management targets for the minimum area. Marxan software has the flexibility to support participatory planning processes and to help identify outcomes acceptable to multiple stakeholders. The results we provide are exploratory and examine just a few scenarios, although many more could be constructed to support complex multi-stakeholder decision making. As with other decision support software, Marxan's role is intended to support decision-making. It rarely provides a final network of conservation priorities because results must be fine-tuned to consider the full range of political, socio-economic and practical factors. The five Marxan scenarios developed here (Appendix C) represent some of the potential for systematic support of spatial decision making.

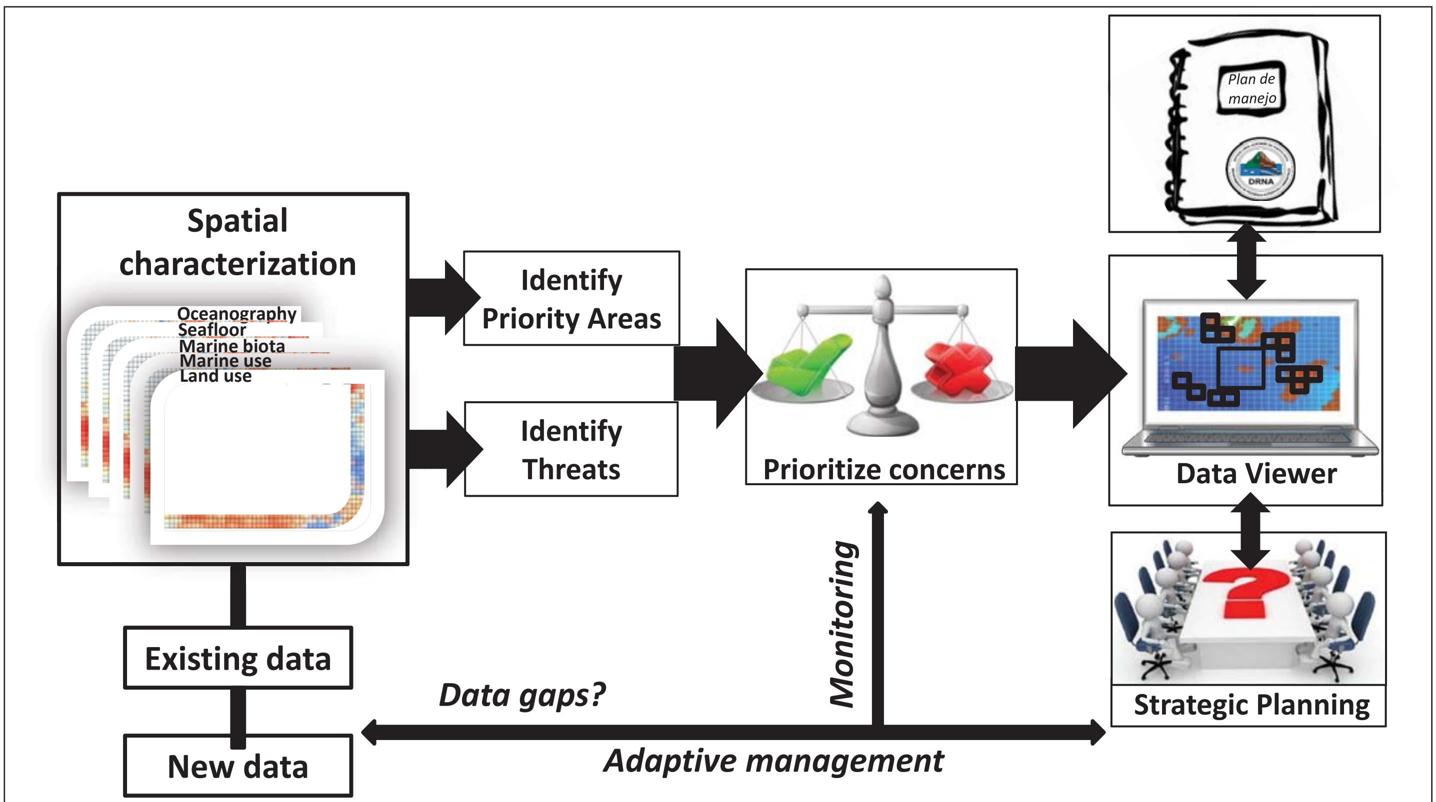


Figure 5. Spatial prioritization of ecological attributes and potential threats leading to decision support products.

Background and Objectives

1.2 PROJECT AREA AND IMPORTANT BIOLOGICAL AND ECOLOGICAL ELEMENTS

Puerto Rico is located on the geological feature known as the Puerto Rican Bank, which includes the U.S. Virgin Island (USVI) and the British Virgin Islands on the eastern end of the Greater Antilles. Puerto Rico is the fourth largest Caribbean island (9,000 km^2) populated by 3.5 million people, including a number of smaller islands, the largest of which are Vieques (population 8,950), Culebra (population 1,806) and Mona Island (no permanent inhabitants; 2015 Census data http://factfinder.census.gov/). The project area for the Northeast Marine Corridor includes the following municipalities which have all experienced declining populations since 2010: Río Grande (2015 population 51,725), Luquillo (19,004), Fajardo (33,102), Ceiba (12,218), Naguabo (26,632) and Culebra (1,818).

Northeast Puerto Rico (including Culebra) is home to many different terrestrial and marine habitats, ranging from the tropical rainforest in the mountains (e.g., El Yunque National Forest) to rich coastal areas with forests and wetlands, isolated beaches, coral reefs, extensive seagrass beds and a chain of island cays (Figure 6). Caribbean coral reef habitats provide a rich source of food and refuge for a high diversity of juvenile and adult organisms, and also provide valuable ecosystem services to people, including shoreline protection, fisheries replenishment, recreation, and tourism (Waddell and Clarke, 2008). Due to extensive coral reef ecosystems, the northeast region, was identified as a priority for coral reef management and conservation in Puerto Rico by the community of coral reef managers convened by CRCP in 2010 (NOAA CRCP, 2010). Coral reef ecosystems of the northeast region, and specifically the status of coral reefs in the RN Arrecifes de La Cordillera, are described by Hernández-Delgado et al. (2009). See Hernández-Delgado (2003) and Hernández-Delgado (2010) for information on coral reefs and environmental change around Culebra. Deeper water (mesophotic) coral reefs also exist beyond 30 m water depth, and although little is known about the ecology of these reefs, recent NOAA surveys (Kågesten et al., 2015) indicate that areas of high coral cover exist in the project area and support ecologically and economically important marine fauna.

Figure 6. Vulnerable species and habitats of the northeast region.

The region supports a year-round population of West Indian Manatee (*Trichechus manatus*), which is protected under the ESA and the U.S. Marine Mammal Protection Act. On January 8, 2016, the U.S. Fish & Wildlife Service (USFWS) proposed to reclassify the species as threatened from a previous classification of endangered due to decreased threats and successful conservation actions. Manatee are also included within the United Nations Protocol Concerning Specially Protected Areas and Wildlife (SPAW) which call for the development of general guidelines and criteria for the management and recovery of endangered and threatened species of regional concern. Primary threats to the manatee include habitat loss and fragmentation of seagrass beds, their main food source, entanglements in fishing gear and collisions with boats. The Caribbean Stranding Network reported 121 manatee deaths from 1990 to 2006 (UNEP, 2010), however, the population is thought to be recovering based on survey data that has estimated the island's population between 150 and 360 individuals (Mignucci-Giannoni, 2005). USFWS aerial surveys conducted in 2011 estimated the minimum population at 178 animals (USFWS, 2014).

The beaches, seagrass beds and coral reefs are also habitat for five ESA listed sea turtles: Leatherback (*Dermochelys coriacea*), Hawksbill (*Eretmochelys imbricata*), Green (*Chelonia mydas*), Kemp's Ridley (*Lepidochelys kempii*); and Loggerhead (*Caretta carett a*), which are considered to be threatened by coastal development and impacted by light pollution. Other endangered species in the region include five species of cetacean (blue [*Balaenoptera musculus*], fi n [*Balaenoptera physalus*], humpback [*Megaptera novaeangliae*], sei [*Balaenoptera borealis*] and sperm [*Physeter macrocephalus*] whales), with very little known about their distributions representing a major knowledge gap. Many species of seabird use the sand cays and islands as nesting places, as well as the mainland island coastal habitats. Surveys by the USFWS indicate that at least five bird species (Audubon's shearwater [*Puffinus lherminieri*]; White-tailed tropicbird [*Phaethon lepturus*]; Brown booby [*Sula leucogaster*]; Red-footed booby [*Sula sula*]) are in need of immediate management att ention due to recent declines; one species (Masked booby [*Sula dactylatra*]) is in need of critical recovery, and a further three species (Roseate tern [*Sterna dougallii*]; Red-billed tropicbird [*Phaethon aethereus*]; Brown noddy [*Anous stolidus*]) need management att ention (Saliva, 2009; Nytch et al.; 2015). The chain of islands extending across the Northeast Marine Corridor from Fajardo across the La Cordillera towards and including Culebra, and the coastal areas of the east of Puerto Rico, have been designated as an Important Bird Area by BirdLife International, and Areas of Conservation Priority for Birds by the Puerto Rico Natural Heritage Program of DNER.

Queen conch (*Lobatus gigas* - formerly *Strombus gigas*) is also an important species of conservation concern in the northeast region, with declining fishery landings. The Queen conch is associated with seagrass beds, but is also found over coral reefs and is a popular food item in Puerto Rico. The fishery is managed by the Caribbean Fishery Management Council. The Queen Conch Resources Fishery Management Plan of Puerto Rico and the USVI (CFMC, 1996) established a management program that is intended to rebuild conch resources in waters surrounding Puerto Rico. Fish spawning areas (FSAs) are essential fish habitat for many species of importance to the commercial and recreational fishery and are highly vulnerable to heavy fishing pressure. Local fisher knowledge, made available through participatory mapping, has identified more than 50 geographically distinct locations for fish spawning areas across the northeast project area (Ojeda-Serrano et al., 2007).

Queen conch, Lobatus gigas*, in Puerto Rico.*

Much of the Northeast Marine Corridor region is designated as Critical Habitat for elkhorn (*Acropora palmata*) and staghorn (*Acropora cervicornis*) corals. Critical habitat is defined by NOAA as specific areas within the geographical area occupied by the species at the time of listing, if they contain the physical or biological features essential to conservation, and those features may require special management considerations or protection. The region has high coral cover relative to other regions of Puerto Rico, with all seven corals listed as "Threatened" on the Endangered Species List (*A. palmata*, *A. cervicornis*, *Dendrogyra cylindrus*, *Mycetophyllia ferox*, *Orbicella annularis*, *Orbicella faveolata* and *Orbicella franksi*; 79 FR 53852; September 10, 2014). Multiple local and global stressors, several of which are documented in this report, have resulted in region-wide declines in live scleractinian coral cover (García-Sais et al., 2008).

Background and Objectives

1.2.1 Seafloor and marine habitats of northeast Puerto Rico

The first phase of the spatial characterization project involved developing and refining existing data on seafloor characteristics and marine habitats. Bathymetric and benthic habitat maps were produced by NCCOS scientists to support the overall management of the region. The benthic habitat map covers 744 km^2 of shallow-water habitats at a high spatial resolution (the smallest habitat features mapped are 10 x 10 m) and includes 250 km of shoreline for the regions 210 islands and rock outcrops (Figure 7). The habitat map was generated using a combination of semi-automated classification and visual interpretation techniques of remote sensing imagery (WV-2 satellite imagery collected 2011-2013, hydrographic data collected 1900-2012 and aerial photos collected 2007-2010) and underwater videos (2013-2014). It represents the first digital map that describes nearly 100% of the seafloor (including coastal mangroves) in the project area. This work updates previous NOAA maps generated by Kendall et al. (2001), which covered only 22% of the newly mapped region. The classification scheme used to map the coral habitats in northeast Puerto Rico and Culebra Island identifies benthic communities based on six primary coral reef ecosystem attributes: 1) geographic zone, 2) geomorphological structure, 3) percent hardbottom, 4) topographic complexity, 5) major biological cover, and 6) live coral cover. Habitat features are described by varying levels of detail, so users can depict the level of detail that best suits their research or management needs (Kågesten et al., 2015).

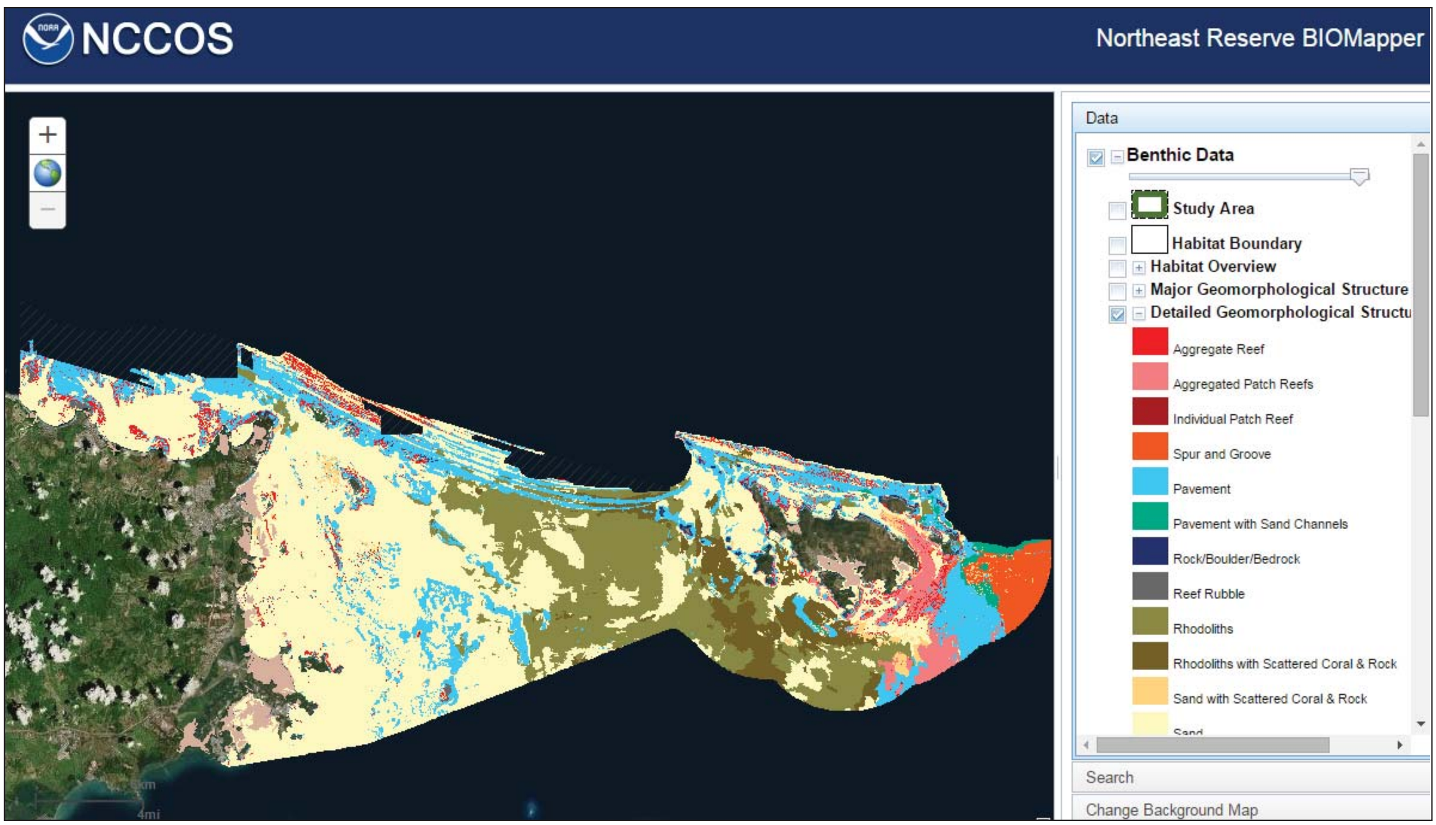


Figure 7. Online map viewer for NOAA benthic habitat map of northeast Puerto Rico and Culebra. http://maps.coastalscience.noaa.gov/biomapper/biomapper.html?id=prne

Softbottom, mainly consisting of sand and rhodoliths (encrusting marine red algae that form hard nodules), dominated the benthic habitats and covered 75% of the mapped area. Hardbottom habitats covered 25% and were dominated by pavement and coral reefs. Algae was the dominant biological cover for both hard and softbottom areas (57%), followed by seagrass beds (17%) and mangroves (4%). Half of all the hardbottom areas had live coral cover greater than 10%, however, habitats dominated by live corals were rare (covering only 0.2% of the mapped area) since a majority of the hardbottom areas were dominated by algae. Live coral cover varied across the region; reefs with relatively high amounts of live coral cover were found outside of existing MPA boundaries east of Culebra Island, and south of the northeast Reserves in the strait between Puerto Rico and Vieques Island, while reefs with low coral cover were identified along the north coast of Puerto Rico. A digital version (Figure 7) of the map along with a report detailing the methods and accuracy assessment can be found at: https://data.noaa.gov/dataset/northeast-puerto-rico-and-culebra-island-bathymetry-model-noaa-tiff-image

The shallow-water (0-35 m) seafloor of the project area has been modeled and mapped by integrating soundings from several different sources (1900-2013), including high-resolution coastal Light Detection and Ranging (LiDAR), single-beam and multi-beam sonar, and historical lead line soundings. In order to combine the many different data sources and densities, the model consists of three different resolutions (4 m, 20 m and 100 m). These data provide spatially continuous and accurate information on water depth and the three-dimensional surface morphology, including complexity of the seafloor. These data can be found at: https://data.noaa.gov/dataset/northeast-puerto-rico-and-culebra-island-bathymetry-model-noaa-tiff-image.

Deeper water reef shelf, banks, steep slopes and canyons of the project area were mapped using multi-beam sonar in 2012 and 2013. The survey missions also collected underwater video and photographs creating a significant library of information on this previously un-surveyed region, including sightings of deep water groupers, snappers and an invasive lionfish recorded at 193 m depth (Figure 8).

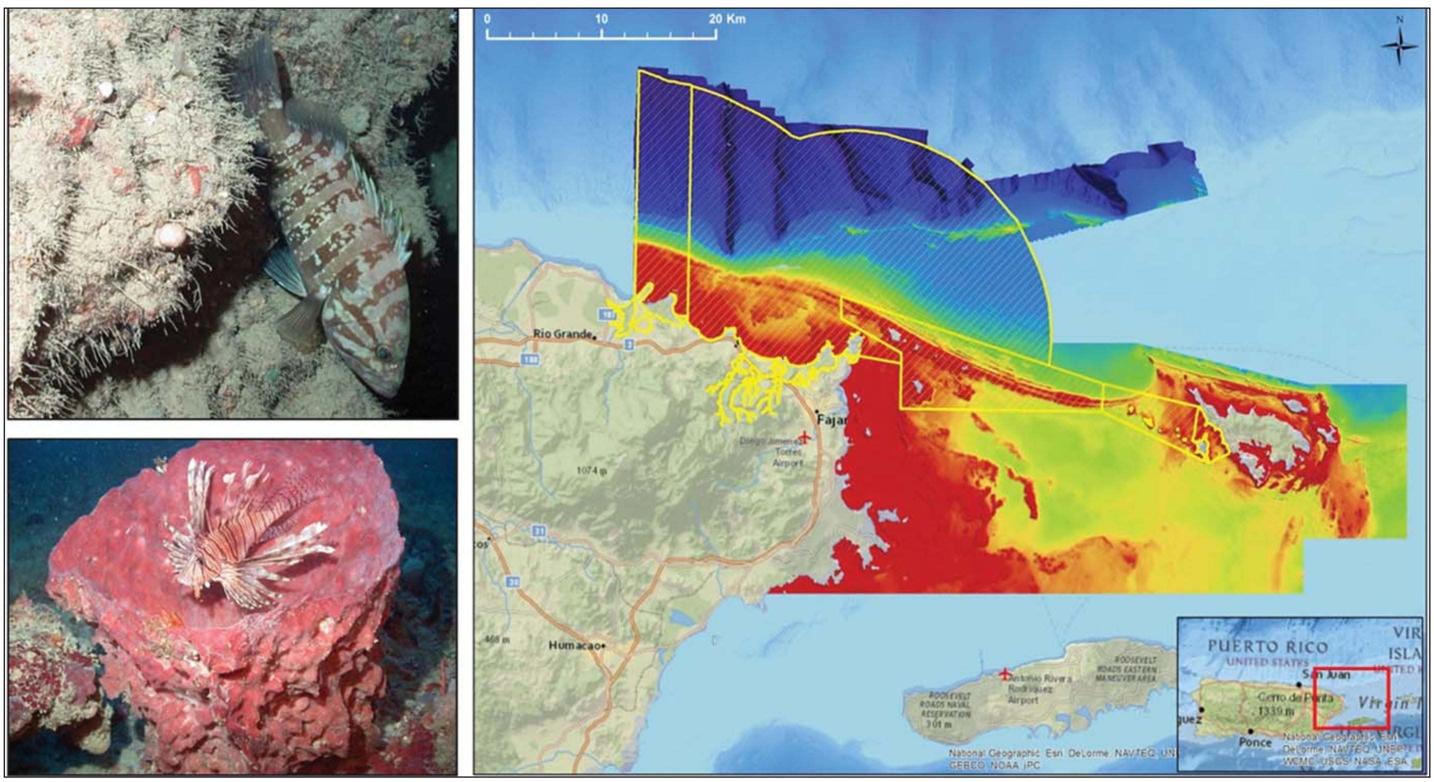


*Figure 8. High resolution bathymetry for the northeast Puerto Rico project area. Fish species, misty grouper (*Hyporthodus mystacinus*) and red lionfish (*Pterois volitans*), observed during 60 dives using remotely operated vehicle.*

1.3 THREATS TO ECOSYSTEM SUSTAINABILITY

The second component of the spatial characterization identified existing and potential threats to the sustainability of ecosystems in the region. The marine and coastal ecosystems of the northeast Puerto Rico region support local livelihoods through a productive fishery and substantial tourism economy, which is under increasing pressure from multiple environmental stressors. Land-based sources of pollution, climate change, and overfishing have been identified by CRCP as threats that adversely impact the health and longevity of ecosystems in the region. These threats are described in the following sections. Additional threats and stressors covering a broader range of human activities were modeled for this project, and are described in Section 2.2 and Appendices A and B.

Background and Objectives

It is widely acknowledged that the combination of coastal development, agriculture, climate change, storms and fishing among others have contributed to a decline in coral reef condition in Puerto Rico (García-Sais et al., 2008; Larsen and Webb, 2009; Ramos-Scharrón et al., 2015). Even within established Natural Reserves, including RN Río Espíritu Santo, RN Cabezas de San Juan and RN Arrecifes de La Cordillera, signs of severe environmental degradation have been observed (Hernández-Delgado and Sabat, 2000). The northeast Puerto Rico Habitat Focus Area working group identified several primary threats to the marine ecosystem of the project area, including: runoff of land-based sources of pollution and sedimentation from non-point sources and from rivers and streams; recreational activities that are causing impacts to fragile natural resources; and commercial and illegal and excessive fishing threatening resource sustainability and economic livelihoods. The working group highlighted the need for greater efforts to protect and restore coral reefs, including through transplantation of live corals from coral farms followed by monitoring efforts to track the performance of restoration and protection efforts. In addition, a need was identified for the provision of community tools to support habitat protection and community resilience.

Sediment plume in the northeast region of Puerto Rico.

1.3.1 Land-based sources of pollution

Between 1830 and 1950, much of northeastern Puerto Rico was cleared for agriculture, with runoff estimated to have increased by 50% and sediment supply to the river channels increased by more than an order of magnitude (Clark and Wilcock, 2000). More recently, urbanization and re-forestation have reduced sedimentation, but high rates of runoff have continued. Consequently, the coastal waters in the northeast region receive a large influx of sediment, pollutants and nutrients from eroding land and developed coastal area, and are also subject to wave induced re-suspension of seafloor sediment deposits. This has led to deteriorating water quality which has been considered to negatively impact coral reef condition and increase susceptibility to thermal stress from global warming (Warne et al., 2005; Ramos-Scharrón et al., 2015). The watersheds of the northeast region receive the islands highest mean precipitation (Figure 9). Extreme rainfall events also create high volume discharge of sediments and nutrients into nearshore waters (Figure 10). Streamflow gaging stations used to characterize water and sediment discharge to coastal waters estimate that from 1990 to 2000, rivers in eastern Puerto Rico contributed an average of between 51,000 to 180,000 metric tonnes of suspended sediments to coastal waters per year (Warne et al., 2005). The major rivers impacting the regions water quality are the Río Espíritu Santo (22 km^2), Río Mameyes (35 km^2), and Río Fajardo (39 km^2). The greatest mean runoff has been estimated for the Río Espíritu Santo with 4,060 mm per year between 1990 and 2000. The waters around Culebra are similarly affected by runoff, but to a lesser extent due to its geography and smaller population (Warne et al., 2005). The two most critical local stressors in Culebra are sewage from poor treatment facilities and sediment runoff from unpaved roads and bare soils, which are currently being addressed through a NOAA-funded community watershed action plan for water quality and coral reefs (Sturm et al., 2014).

Between 1936 and 2004, the watersheds of the northeast region experienced major changes including reforestation of former cane fields and a ten-fold increase in urban areas (Ramos-Scharrón et al., 2015). Between 1977 and 1999, urban spaces doubled in northeast Puerto Rico and increased by 16% between 1991 and 2003. Overall population trends were characterized by suburbanization of the rural landscape. For example, from 1990 to 2000, population increased markedly in 92 barrios (300-6,800 new inhabitants), with 9% of barrios classified as urban, 77% as suburban, and 14% as rural (Figure 11; Gould et al., 2012).

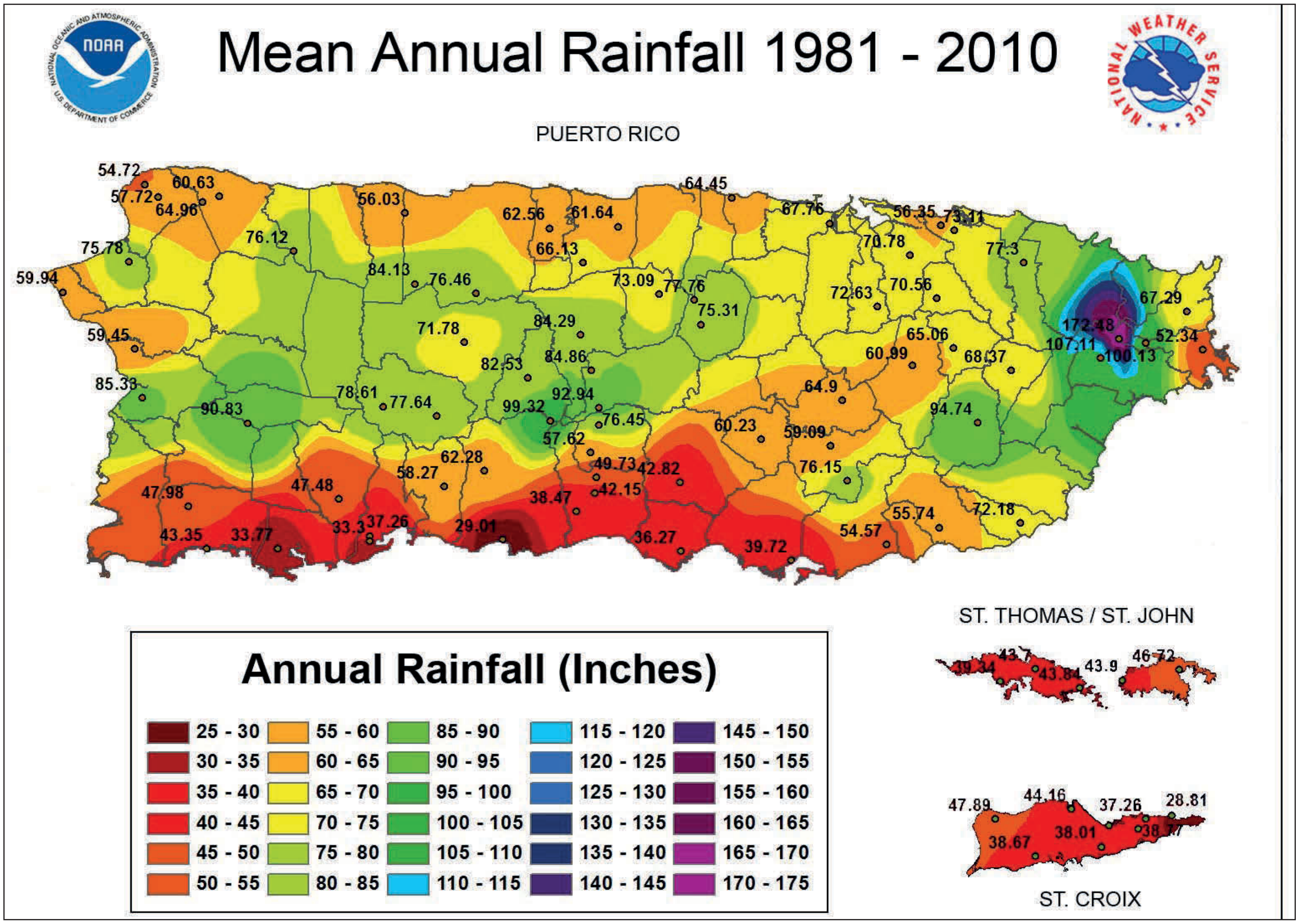


Figure 9. Mean annual precipitation showing high rainfall in the watersheds of the northeast region. Source: NOAA National Weather Service, Southern Region. www.srh.noaa.gov

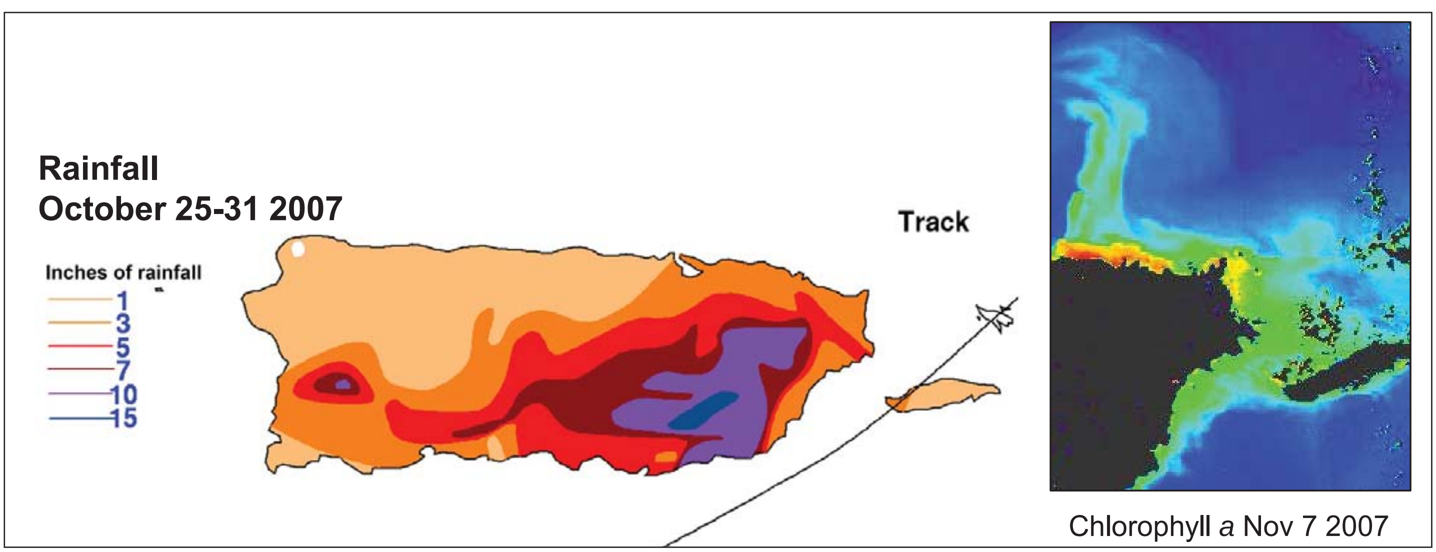


Figure 10. Tropical Storm Noel dropped heavy rainfall across Puerto Rico for several days, leaving grounds saturated and causing surface runoff. Precipitation peaked at 17.23 inches (437.6 mm) at Carite Lake, southeast Puerto Rico. Plumes of phytoplankton detected by ocean color satellite from space approximately one week later showing the impact of river outflow and runoff in the coastal zone. Source: NOAA NWS/Weather Prediction Center and NOAA NOS/NCCOS.

Background and Objectives

In the Río Fajardo watershed, high-density urban areas increased from less than 1% in 1936 to 7.7% in 2004 and industrial and commercial areas increased 10-fold. Ramos-Scharrón et al. (2015) estimated that although forests covered 54% of the watershed by 2004, the surface runoff potential was still considerably greater than background levels due to the expansion of urban areas (Figure 12). Puerto Rico now has some of the highest population and road densities in the Caribbean. According to Gould et al. (2012), the loss of natural land cover in the coastal areas highlight the need to protect the coastal hills and plains and the matrix of habitats that include the mangrove forests and river systems of the coastal area. Detailed land cover in 2003 has been provided by the Puerto Rico Gap Analysis Project (PRGAP) and is available online (Gould et al., 2007). See Murphy and Stallard (2012) for descriptions of land cover change, vegetation and geology in northeast Puerto Rico.

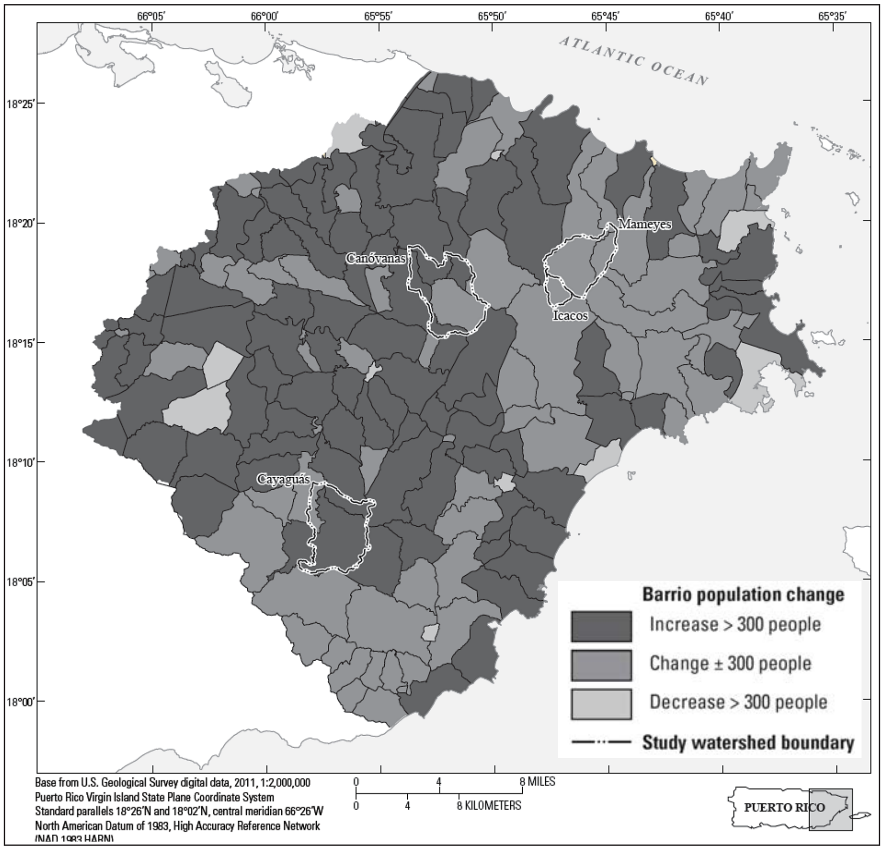


Figure 11. Population change in eastern Puerto Rico between 1990-2000. Adapted from Gould et al. (2012).

However, in more recent years, the populations of most principalities have declined most likely due to economic migration to the continental U.S., with as yet unknown implications for land use change and marine water quality.

Figure 13 shows a multi-year (2003-2011) synthesis or climatology representing relative exposure of coral reefs to turbidity derived from runoff and re-suspension of sediments. The turbidity data are from the MERIS (Medium Resolution Imaging Spectrometer) ocean color satellite. The climatology was created by computing the 90% quantile value (i.e., the mean of the highest values) for all the MERIS images in a year, across all years. To identify coral reefs at different levels of exposure, the presence of hardbottom habitat with corals is shown on the same map (Figure 13).

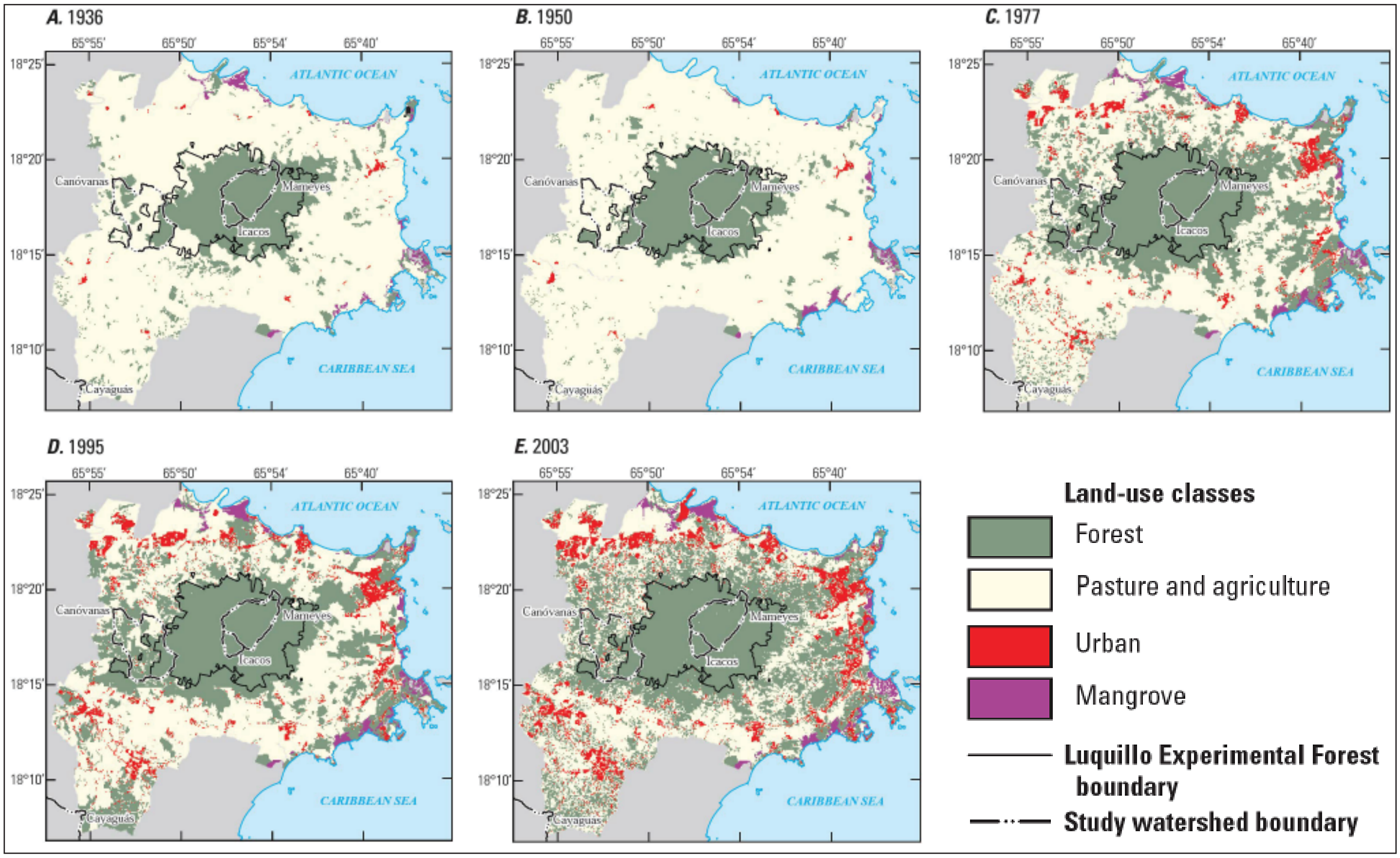


Figure 12. Trends in forest, pasture and agriculture, urban, and mangrove extent, 1936-2003 in eastern Puerto Rico. Source: Murphy and Stallard (2012).

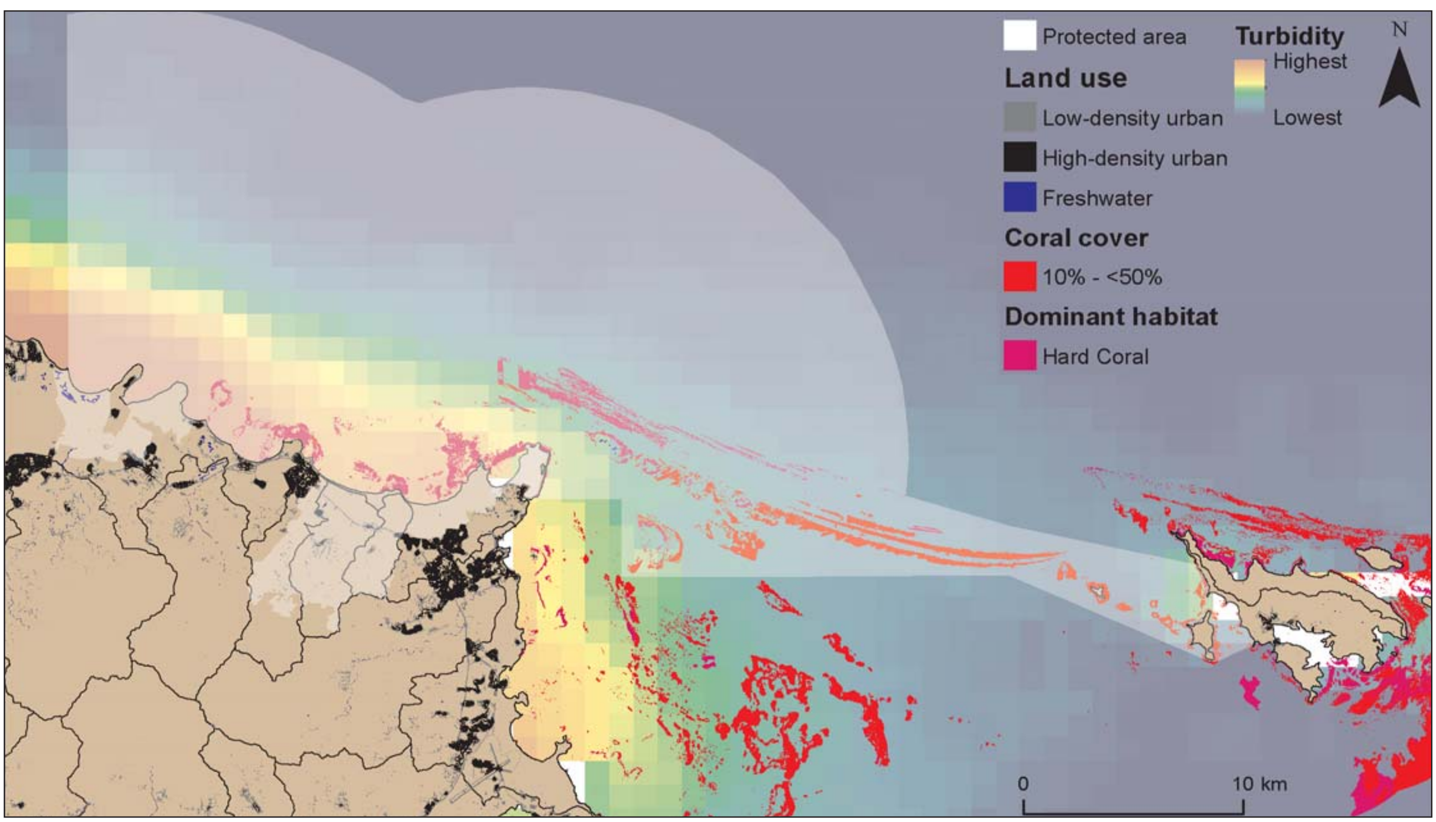


Figure 13. Ocean color satellite data (2003-2011) showing relative turbidity and the distribution of corals. The northern shore shows highest turbidity due to river outflow.

Background and Objectives

1.3.2 Climate change

Rise in global temperatures

Analyses conducted for Puerto Rico Climate Change Council (PRCCC, 2013) showed significant increase in annual and monthly average air temperatures. For instance, based on past trends, San Juan's average annual temperature is expected to increase to 27°C (80.6°F) in 2050, compared with 25.5°C (77.9°F) in 1950. In the oceans too, water temperature has increased. Analyses of sea surface temperatures (SST) recorded by a moored array and by satellite found an increase of 0.026°C and 0.027°C per year respectively between 1981 and 2011 (PRCCC, 2013). An increase in the duration and frequency of thermal stress events beyond the threshold for coral bleaching is expected, resulting in increased coral mortality. After the 2005 thermal stress event, when widespread bleaching and disease occurred, almost all colonies of important reef-building coral suffered significant partial colony mortality in Culebra Island (García-Sais et al., 2008). In the northeast region, coral bleaching has been observed during and after thermal stress events in 1987 (Culebra), 1998 and 1999 (Pinnacles, Fajardo, Culebra), 2003 (Cayo Lobo, Punto Aguila, Cayo Diablo, Culebra), 2005 and 2006 (Cayo Largo, Isla Pinero and Palominitos Island; ReefBase.org; Figure 14). Bleaching was more severe and prolonged at protected (leeward) reefs than on reefs under moderate or strong water circulation (Hernández-Delgado et al., 2006). Figure 14 shows a 30-year time series of summer (July to December) mean SST in degrees centigrade and degree heating week (DHW) for 10 pixels across the northeast study region from 1985-2015. DHW is calculated by adding up the occurrence of pixels with temperatures that are above the bleaching threshold over the previous 12 weeks. When DHW reaches 4 degree-Celsius-weeks, corals will have high thermal stress. When DHW reaches 8 degree-Celsius-weeks or more, widespread bleaching and mortality will likely occur. Due to a change in satellites, the first 20 years is from the Coral Reef Temperature Anomaly Database (CoRTAD; http://www.nodc.noaa.gov/sog/cortad/) collected weekly by the Pathfinder satellites, and from 2005-2015 we show a compilation from daily data collections from satellite microwave and infrared (MW_IR) sensors, which combines the through-cloud capabilities of the microwave data (MW) with the high spatial resolution of the infrared (IR) SST data to produce a 9 km resolution product (http://www.remss.com/measurements/sea-surface-temperature/oisst-description).

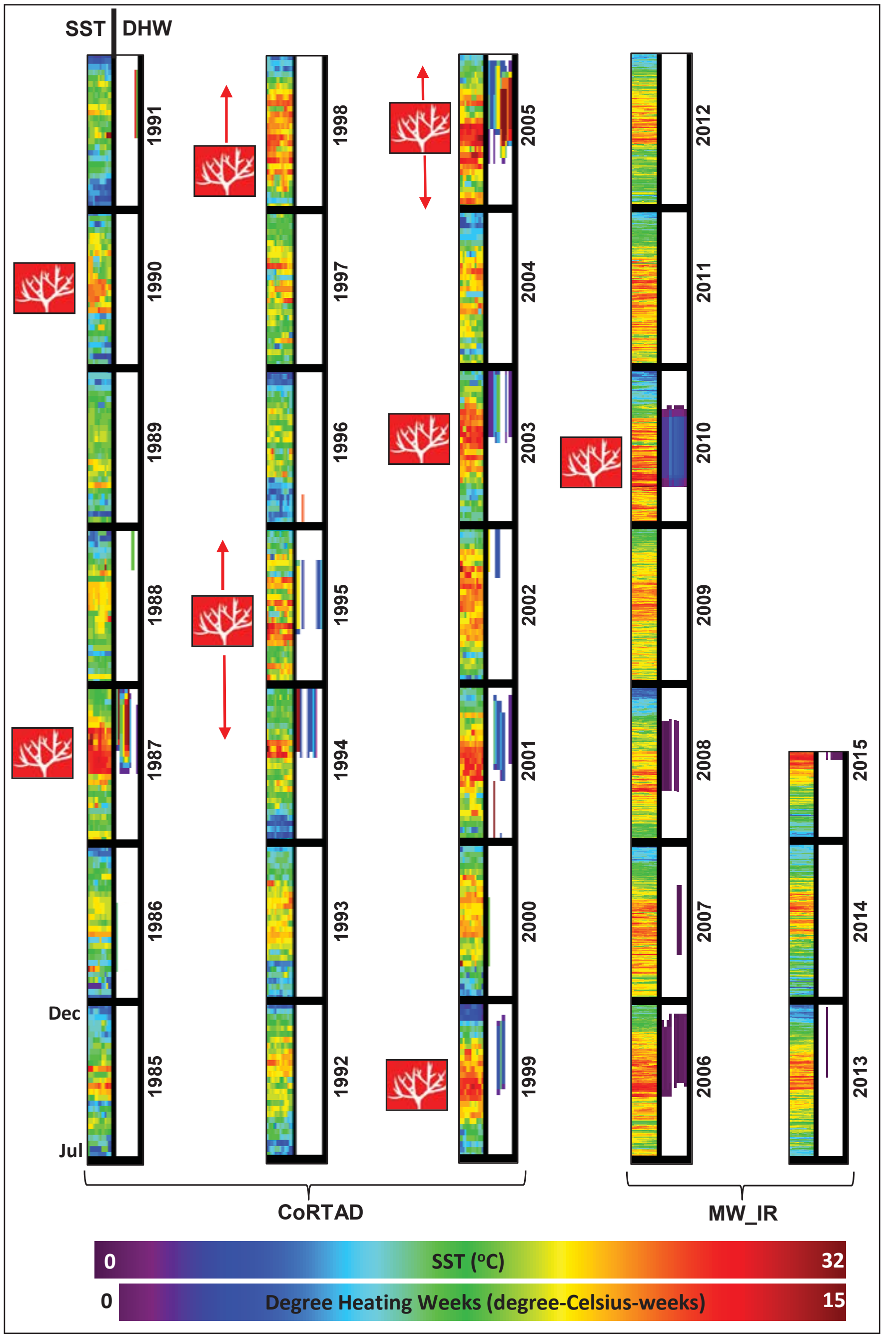
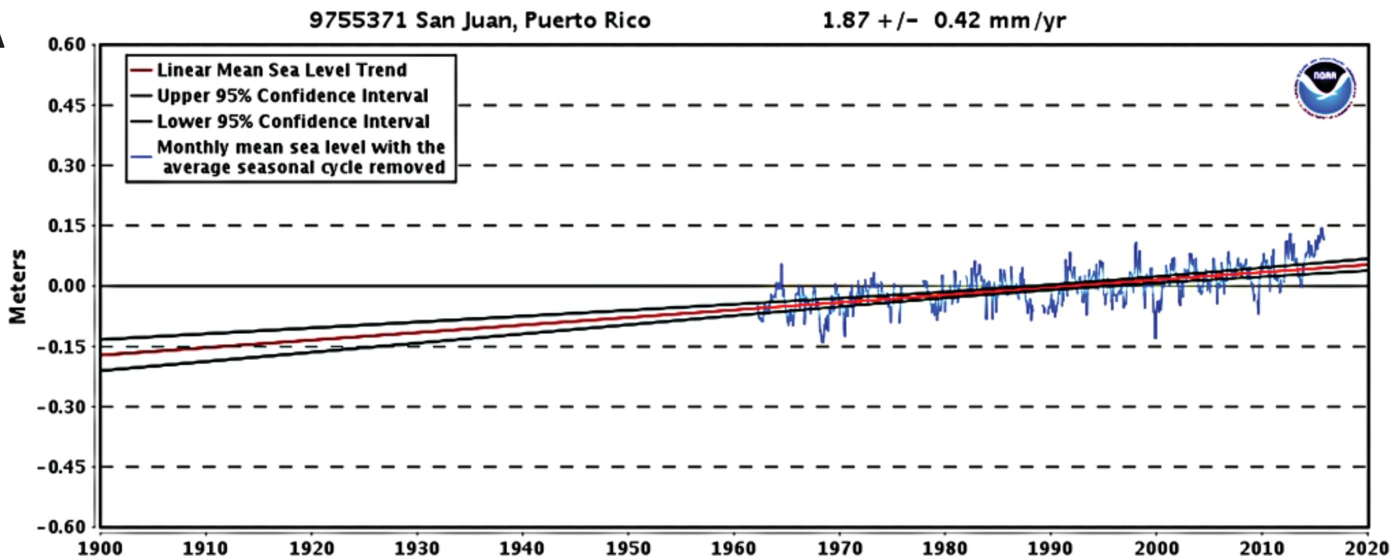


Figure 14. Thirty-year data set (1985-2015) of summer (July to December) sea surface temperature (SST) and degree heating weeks (DHW) from satellite data for a sub-region of the northeast Puerto Rico project area (offshore San Juan to Fajardo). Periods with high thermal stress which resulted in widespread coral bleaching are identified with a red square with bleached coral.

Sea-level rise

Sea-levels have been rising in San Juan, Puerto Rico at a rate of 1.87 mm (± 0.42) per year between 1962 and 2010, based on monthly mean sea level data from 1962 to 2014, which is equivalent to a change of 0.62 ft in 100 years (Figure 15a). U.S. Army Corp of Engineers (USACE) have estimated sea levels around San Juan to increase from 0.07 to 0.57 m (0.20 to 1.87 ft) above current mean sea level by the year 2060, and between 0.14 and 1.70 m (0.40 to 5.59 ft) above current mean sea level by the year 2110 (Figure 15b). Based on this information and future projections for sea level rise, the PRCCC recommends planning for a rise of 0.5-1.0 m by 2100.

A



B

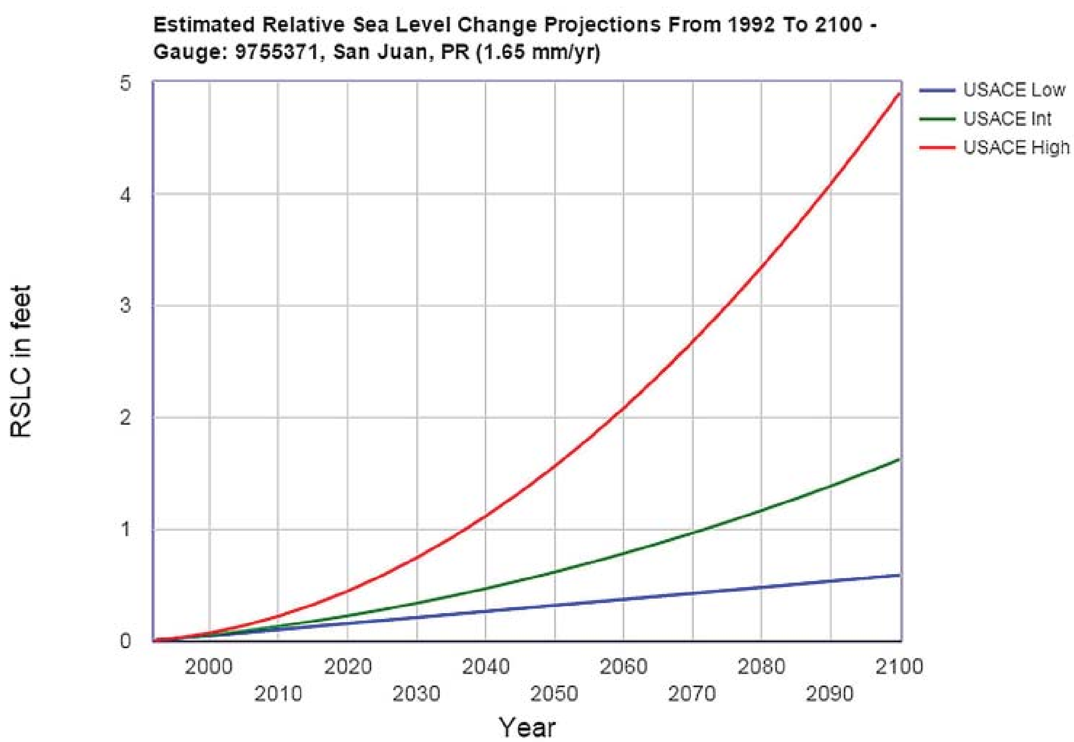


Figure 15. A) Historical sea level changes for San Juan (1957-2015); and B) Scenarios of future sea level rise for Puerto Rico from 1992 to 2100. Source: http://www.corpsclimate.us/ccaceslcurves.cfm

Background and Objectives

Based on USACE projections, a 1 ft rise in sea level could occur by 2036 (High projection curve – NRC Curve III) or by 2071 (Intermediate projection – NRC Curve I). This increase is expected to submerge many of the low-lying cays and islets in the RN Arrecifes de La Cordillera (Figure 16), as well as significant areas of the coastline. These data illustrate the scale of potential flooding, but not the exact location, nor do they account for erosion, subsidence, or future construction. Inundation is shown as it would appear during the highest high tides (excludes wind driven tides) with the sea level rise. These data should be used only as a screening-level tool for management decisions. A detailed methodology for producing these data can be found here: https://coast.noaa.gov/digitalcoast/tools/slr.

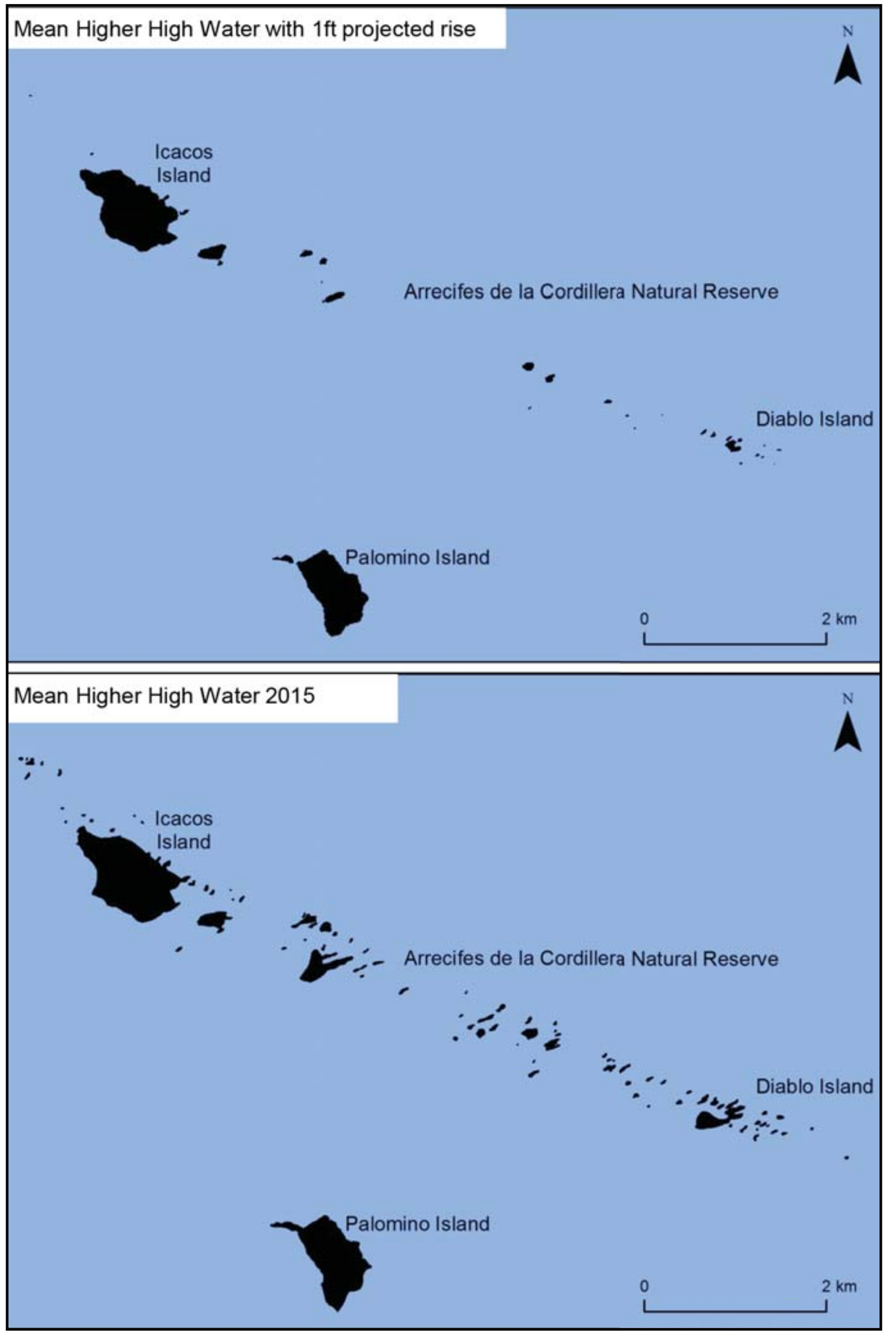


Figure 16. The inundation of the Cordillera Natural Reserve cays and islets resulting from a projected 1 foot rise in sea level (top) above current Mean Higher High Water (MHHW) conditions (bottom) using data downloaded from the NOAA Sea Level Rise and Coastal Flooding Impacts Viewer. https://coast.noaa.gov/slr/

Storms and hurricanes

Results from high-resolution models and global models predict a likely increase of peak wind intensities and increased near-storm precipitation in future tropical cyclones in the Caribbean region. Most recent studies investigating tropical storm frequency simulate a decrease in the overall number of storms and increase in the numbers of the most intense tropical cyclones (IPCC, 2007). Analyses of model simulations suggest that for each 1°C increase in tropical sea surface temperatures, hurricane surface wind speeds will increase by 1 to 8% and core rainfall rates by 6 to 18% (CCSP, 2008).

Past hurricanes (Figure 17) have damaged coral reefs and seagrasses in Puerto Rico through sedimentation and physical wave impact. Hurricane Hugo in September 1989 destroyed coral colonies around Culebra, including *Acropora palmata* (elkhorn coral) in eastern Culebra, as well as tens of square kilometers of seagrass meadows (Rodriguez et al., 1994). During the 1990s a number of other coral reef areas (i.e., Islote Palominitos, Los Corchos Reef, Cayo Dákity, Playa Larga, Culebra) showed severe physical destruction due to several hurricanes, including Luis (1995), Marilyn (1995), and Georges (1998; Goenaga, 1990; Hernández-Delgado, 2000).

1.3.3 Fishing

Marine animal populations of the northeast region support a diverse and locally important fishery, which includes commercial fishing using four major gear types (line, net, diving, trap), recreational fishing (including sportfishing) and the collection of live fish for the ornamental fish trade. The fisheries are characteristically small-scale, comprised of owner-operators who utilize small vessels landing a wide variety of species (Griffith and Valdés-Pizzini, 2002). In addition, considerable landings of commercial conch, lobster and shrimp have been recorded. Spatial information on the distribution of fishing effort is rare in the U.S. Caribbean. This study compiled existing data on sites for recreational fishing, and interviewed a senior fishery manager to record fishing grounds on a navigation chart of the area (Figure 18).

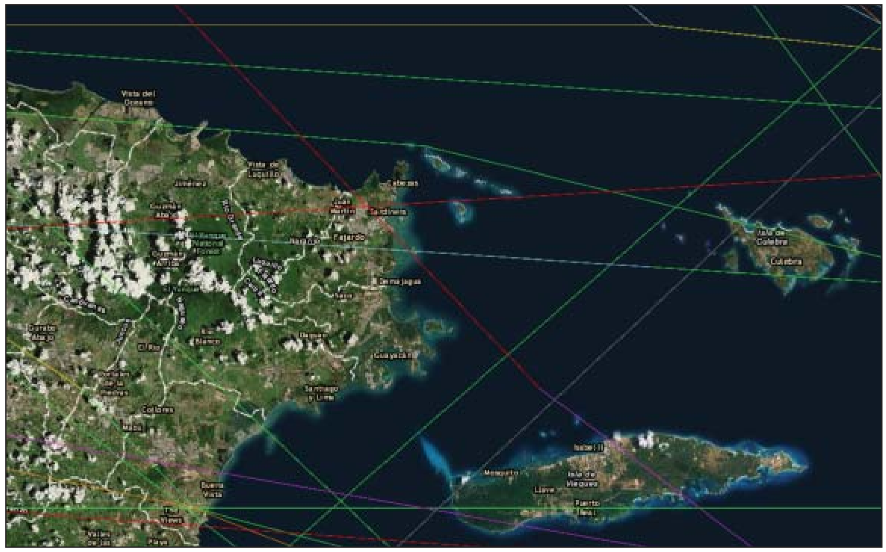


Figure 17. Historical hurricane tracks across the northeast region of Puerto Rico. Source: https://coast.noaa.gov/hurricanes/

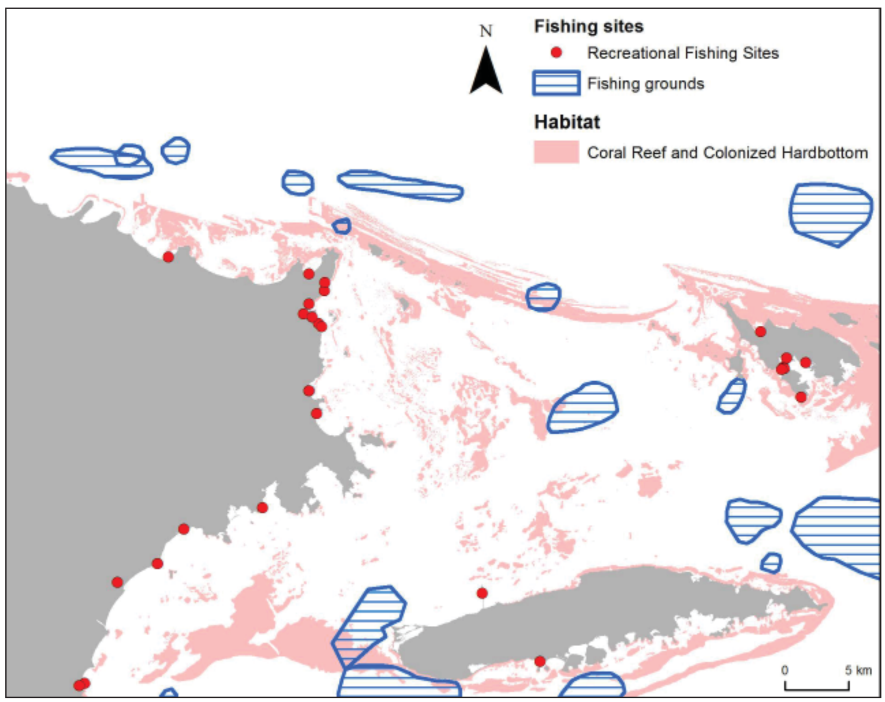
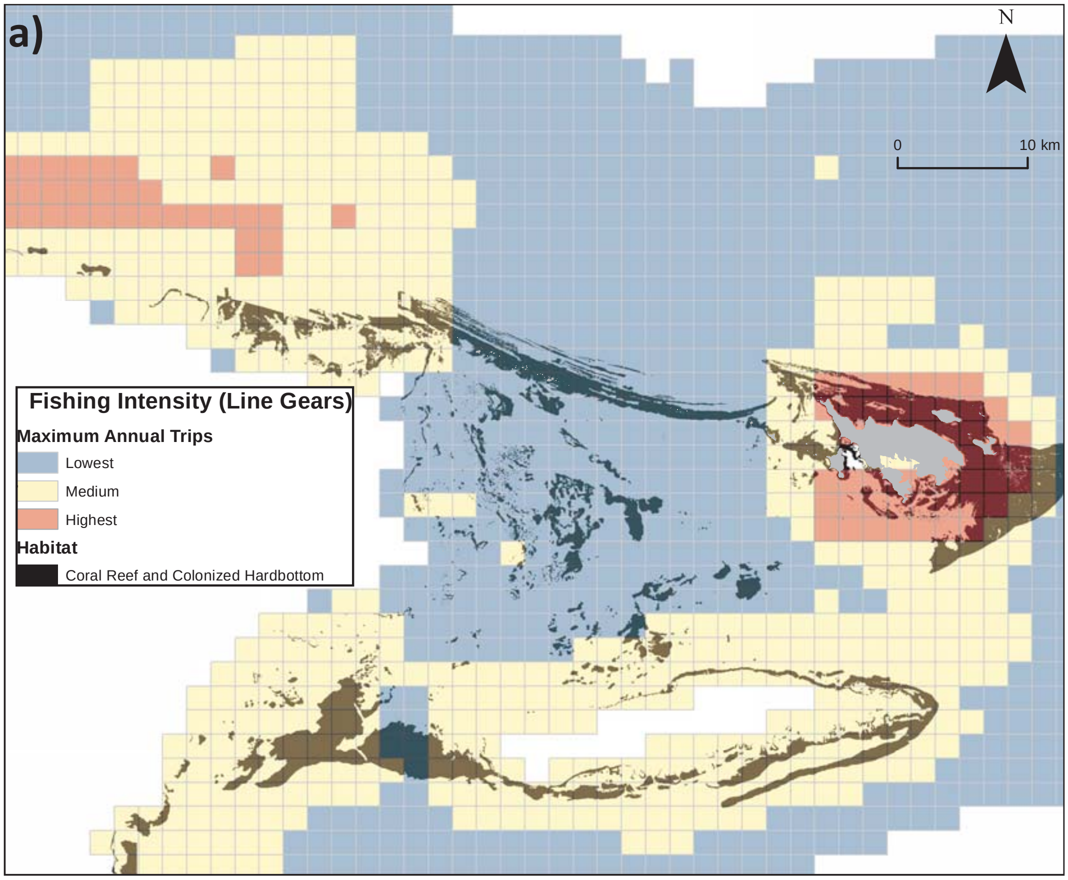


Figure 18. Fishing sites based on expert knowledge and point data received from Puerto Rico Department of Natural Environmental Resources.

In 2009, a NOAA funded study surveyed 350 commercial fishers to collect socio-economic information and to conduct a spatial characterization of the fishery by gear type and benthic habitat. The study surveyed a random sample of 66 from a total of 216 licensed commercial fishers from east coast municipalities and asked fishers to mark on a map the areas where they fish and the gear used. The list of fishers was based on the 2008 Puerto Rico commercial fishery census data. The density of fishers per cell was calculated from the maps and assigned to grid cells (1.5 square miles). After delineating the fishing grounds used for each individual gear type, the fishing intensity was calculated using the fishing grounds data and the annual trips taken by each fisher for each gear type. The resulting maps describe the pattern of use for each gear category (line and net [Figure 19]; diving and traps [Figure 20]), and the value of each cell reflects the maximum possible annual fishing intensity, not necessarily the actual annual fishing intensity in that cell for the given gear type. The study found that the east coast fishery focused extensively on shallow habitats located in proximity of the region's main ports where fishers targeted a variety of reef fish, conch and lobster (Koeneke, 2011) While fishing intensity with line gear varied within the study area, use of net gear was generally low.



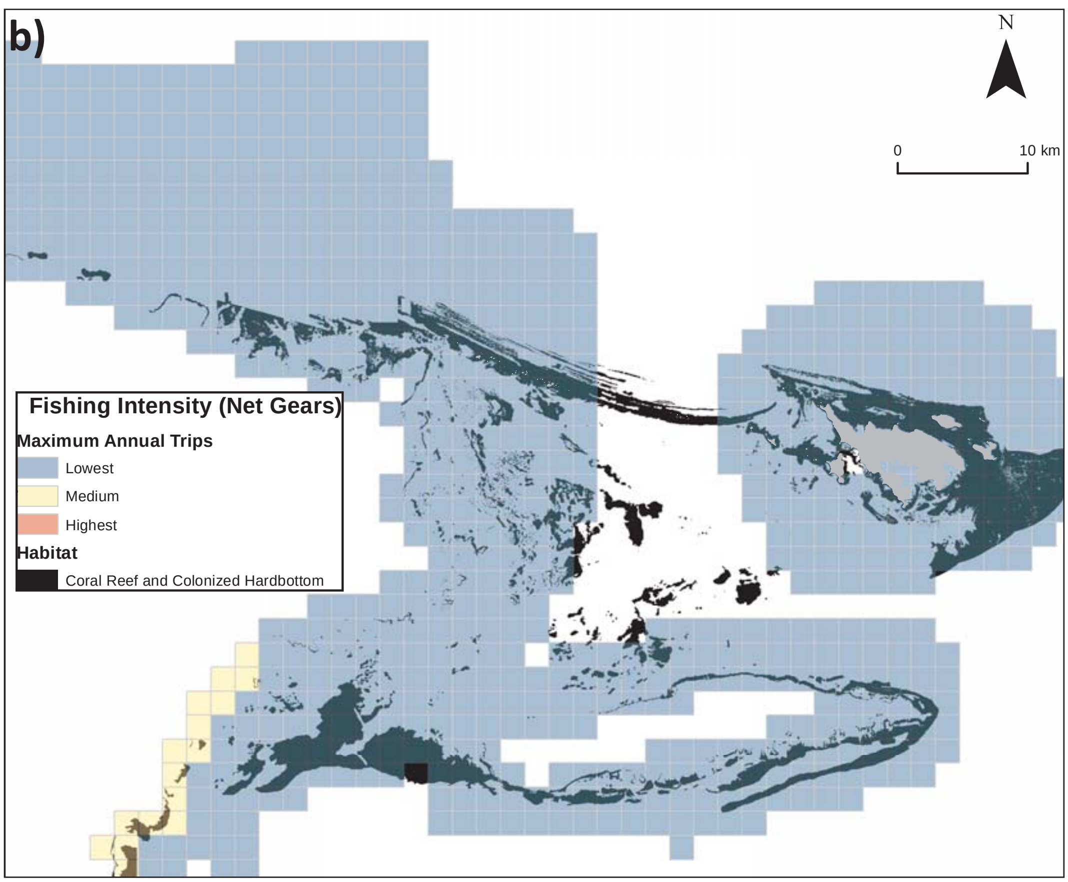
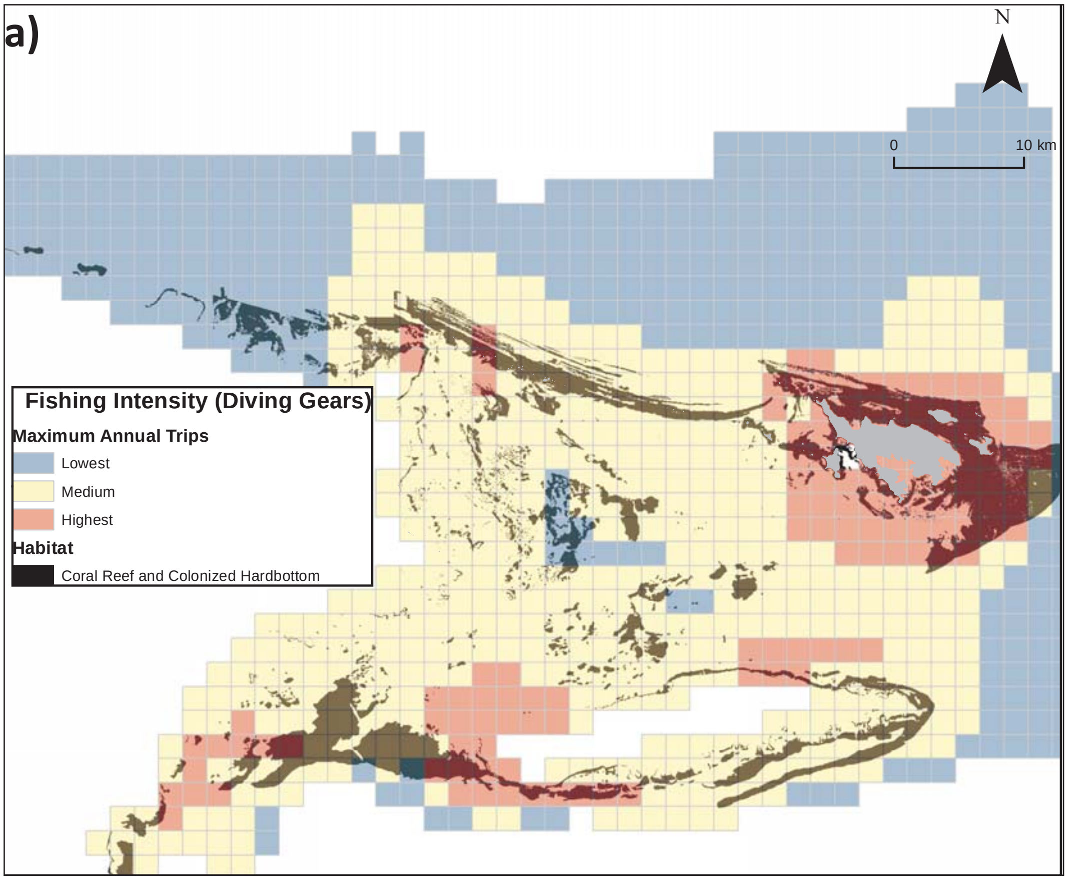


Figure 19. Relative index of fishing intensity per cell for: a) line fishing gears (handline, anchored vertical line, vertical line with buoy, horizontal line, longline, trolling line, trolling rods, rod and reel, other); and b) net gears (gillnet, lobster trammel, fish trammel, bait cast net, shrimp cast net, beach seine, wahoo seine, ornamental fishery nets, other) in 2008. Source: Adapted from Koeneke (2011).



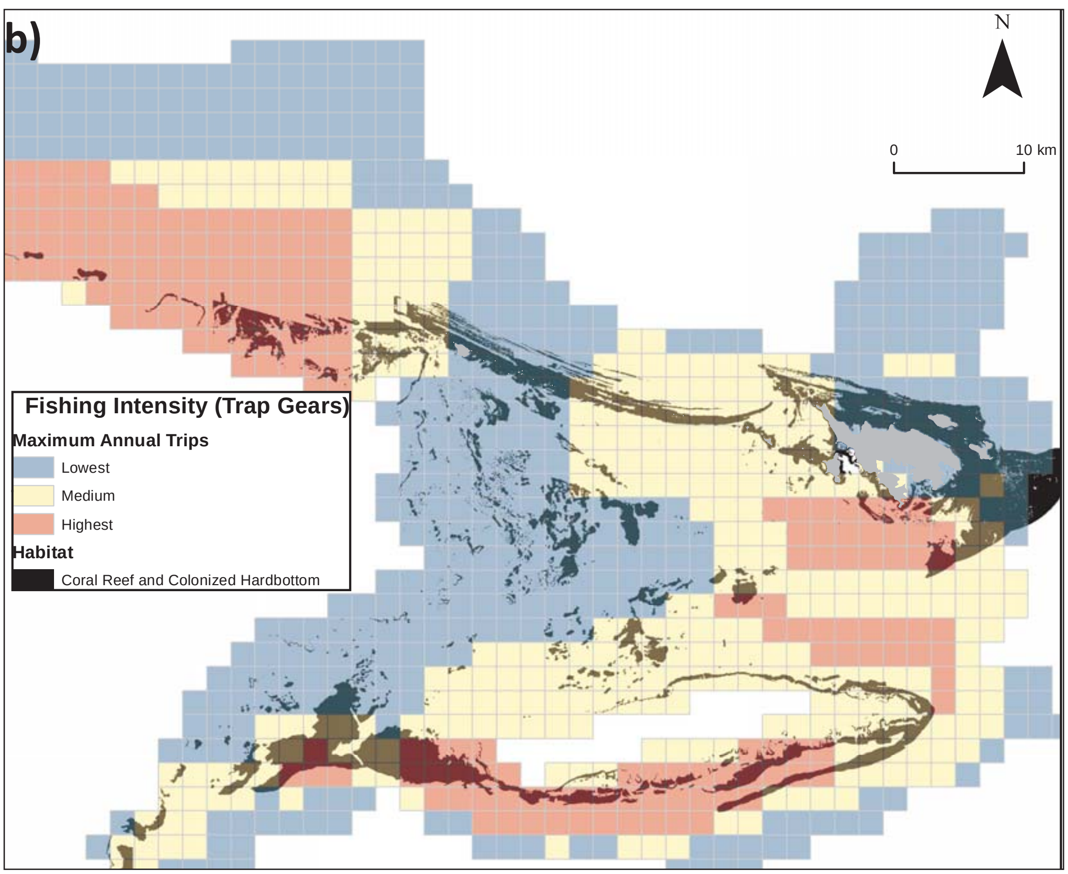


Figure 20. Relative index of fishing intensity per cell for: a) diving (SCUBA diving, skin diving, other diving); and b) trap gears (fish traps, deep water snapper traps, lobster traps) in 2008. Source: Adapted from Koeneke (2011).

1.3.4 Other threats and stressors

Other threats and stressors associated with human activity, including vessel traffic, coastal infrastructure (e.g., marinas, cables, anchorage), light pollution, coral bleaching, agricultural and urban coastal pollution were modeled for this project. In addition, population size was mapped as a spatial surrogate to represent multiple unmeasured human impacts. These variables are described in Section 2.2 and Appendix B. The spatial location of fishing effort was not considered sufficiently accurate to map as a stressor, but can be considered separately through fisheries management planning in consultation with the newly protected areas. The fisheries effort data presented here requires further evaluation for accuracy. Note: Expert opinion at DNER indicates that the map representing net gear use may underestimate the importance of nets to the fishery, particularly the non-licensed commercial fishers. Fishing intensity at fish spawning aggregations is also likely to be underestimated in these data. Very little is known about the spatial distribution and intensity of fishing by the non-licensed sector of the fishing industry. This should form a priority data need for the effective management of the northeast region.

Chapter 2: Mapping ecological priority areas and threats

Information on priority ecological resources, threats, and cumulative impacts to priority resources were gathered from: 1) local expert knowledge, and 2) existing spatial data sources. The following sections describe the process of gathering and mapping these data. We recognized the importance of collecting both quantitative field data and spatial models, as well as local expert knowledge to gain a comprehensive set of data to identify ecologically important areas and potential threats to those areas. Both sources of data have different strengths and weaknesses and are therefore likely to be complementary when combined. For example, local expert knowledge has the benefit of being gathered over a longer duration than most field survey data, but is usually concentrated to specific focal areas of interest. In contrast, modeled data derived from remote sensing data will typically have a broader and more continuous spatial coverage, but often captures a discrete snapshot in time or series of snapshots. Both data types have inherent bias and error, but together can be used to assess the weight of evidence for identifying places of special interest. These data combined form our best available information for the Northeast Marine Corridor.

2.1 MAPPING ECOLOGICAL PRIORITY AREAS AND THREATS FROM LOCAL EXPERT KNOWLEDGE

2.1.1 Introduction

This part of the project documented qualitative knowledge on priority sites and threats from recognized scientific experts in the region using a participatory mapping exercise. Information gathered from experts was integrated into a geodatabase with biophysical data collected through in-water surveys from the same region, in order to identify and characterize priority areas for conservation and management. The collection of local expert knowledge allowed us to provide a voice to the local scientists, many of which have decades of experience observing and collecting data on the marine environment of the northeast region. The data also allows us to address data gaps and to compare with existing field data and modeled data to assess concurrence of evidence for geographical priority areas and threats.

2.1.2 Methods

Large format (26 x 42 in) paper maps of the project area were produced showing bathymetric imagery, contour lines, nautical charts, land cover imagery, and management boundaries of the existing reserves (map scale: 1:256,683; Figure 21). Eight local scientific experts were identified for the exercise based on their widely-known experience conducting research or working in the coastal and marine environment of the area of interest. Experts were led through a semi-structured interview process in small groups (or one-on-one) in order to identify priority ecological sites by marking sites and descriptive attributes on paper maps. Each expert received his/her own map to mark on for the exercise, with the exception of two people, who shared one map, but distinguished their contributions by marking their initials on each mark or descriptive attribute (Figure 22).

Experts were asked about their professional area of expertise (i.e., habitat, species of interest or other research focal area) and estimated the number of years they had been conducting research and amount of time they had spent in the field in the area of interest. They then circled their focal areas of research on the map with a marker and wrote down the names of these focal areas on the maps as they are locally known. Next, experts were asked to write down on a worksheet their definition of a priority ecological site. They identified the locations of priority ecological sites on the paper map using stickers. A second paper map with finer-scale nautical charts for the study region was provided to the participants for reference. The experts were instructed to add color-coded stickers to describe selected ecological criteria (Table 1).

These ecological criteria and threats were selected by the principal investigators before the start of the study based on the goal of defining priority ecological areas for conservation in the management planning process. Participants were encouraged to define additional ecological criteria and threats, and add them to their map.

Mapping

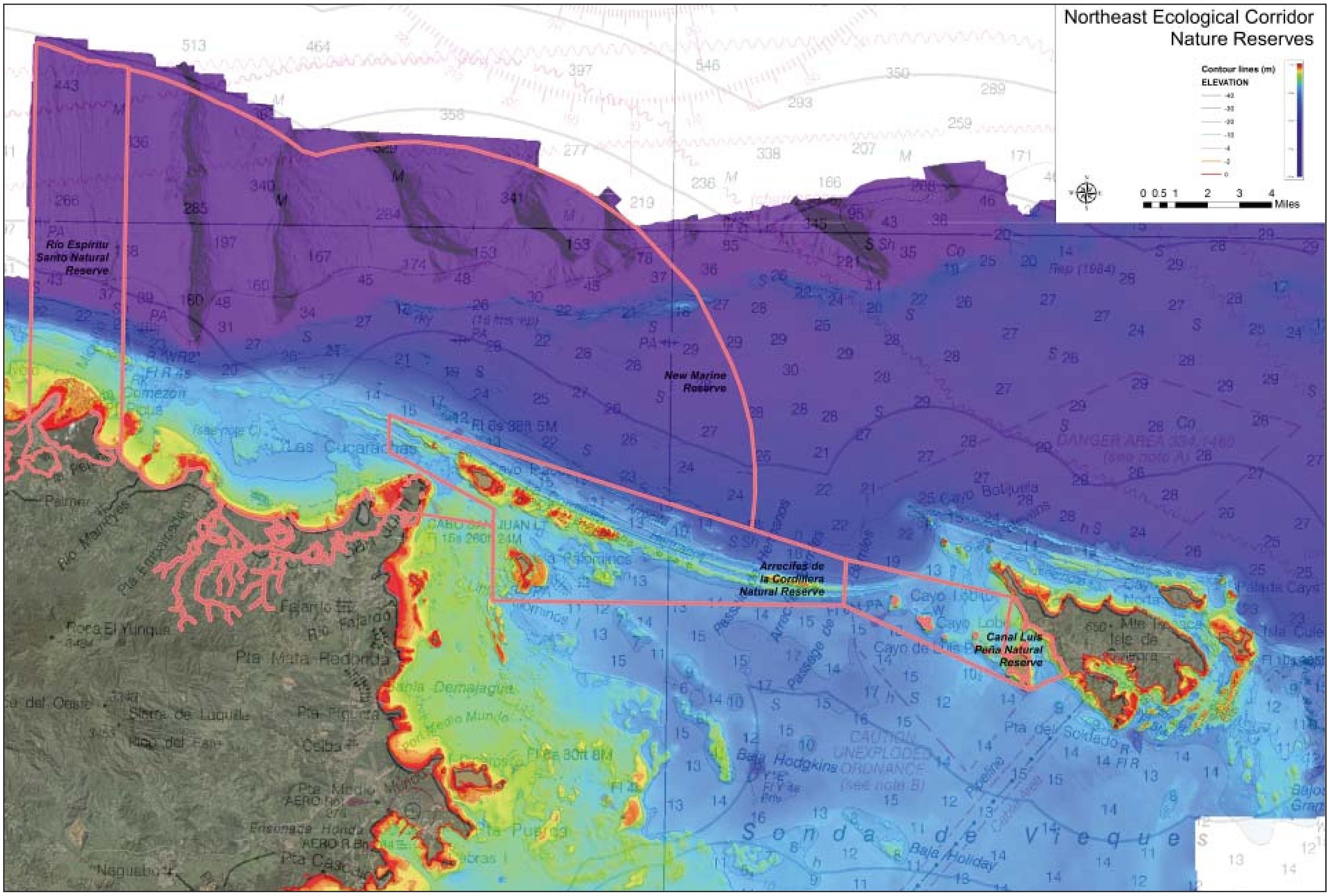


Figure 21. The paper map provided to the volunteer marine experts showing seafloor features and navigation charts for northeast Puerto Rico.

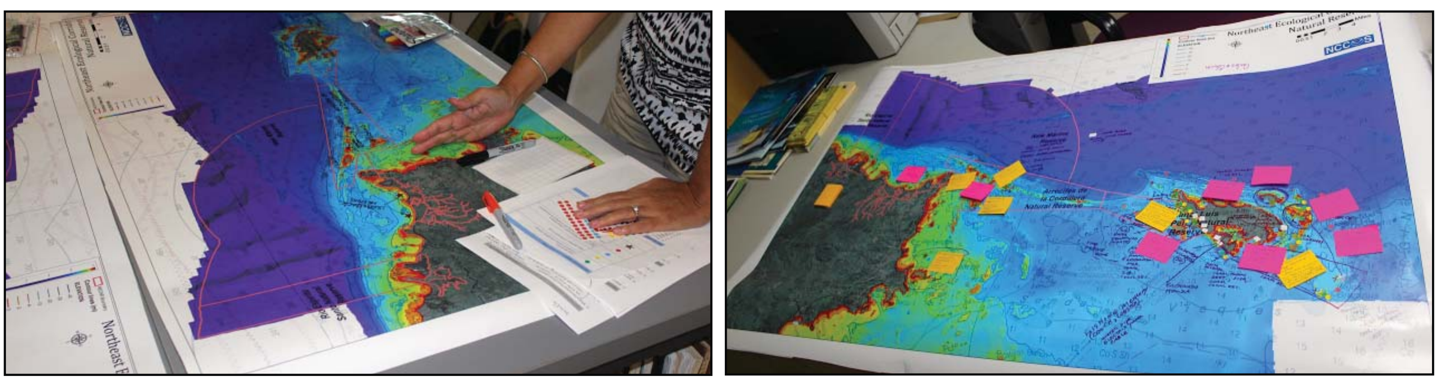


Figure 22. Marine experts worked through the participatory process by identifying priority ecological features and threats to ecosystem health on the regional map.

Table 1. Suggested ecological criteria and threat types defined for the prioritization exercise.

Ecological criteria	Threats and conflicts
High biodiversity (*fish species richness, coral species richness*)	Poor water quality (*runoff, rivers*)
High abundance of fish and/or coral	Invasive species
Rare/Vulnerable species/critical habitats (*ESA species, nesting sites*)	Thermal stress (*bleaching, disease*)
Abundance of large-bodied fish	High human use (*boating, diving*)
Spawning and nursery areas	Fishing (*commercial or recreational*)
Other (define)	Anchoring
	Others (specify)

Of the areas identified as priority ecological sites, the participant identified the greatest threats to that area. Finally, each participant ranked the ecological importance of sites he/she identified on a worksheet, and give a brief justification for each ranking.

All priority sites, ecological criteria and threats that were mapped by the experts on paper maps were digitized and compiled into a geodatabase in ArcMap. Focal areas of research were defined by polygons, while places identified as priority sites, and described by ecological attributes (criteria) or threats were digitized as point shapefiles in the GIS. Attributes that describe the priority sites include the name of the place, a list of ecological attributes, a list of threats, respondent code, and any notes or additional comments made by the respondent about the site. Each ecological criterion and threat also exists as an independent feature layer. A geo-PDF version of the digitized map with a summary of the combined information of priority ecological sites and threats was sent back to the participants for review and comment. After the comment period, ecological criteria and threats were summarized by a 1-km grid framework for the project area (Figure 23).

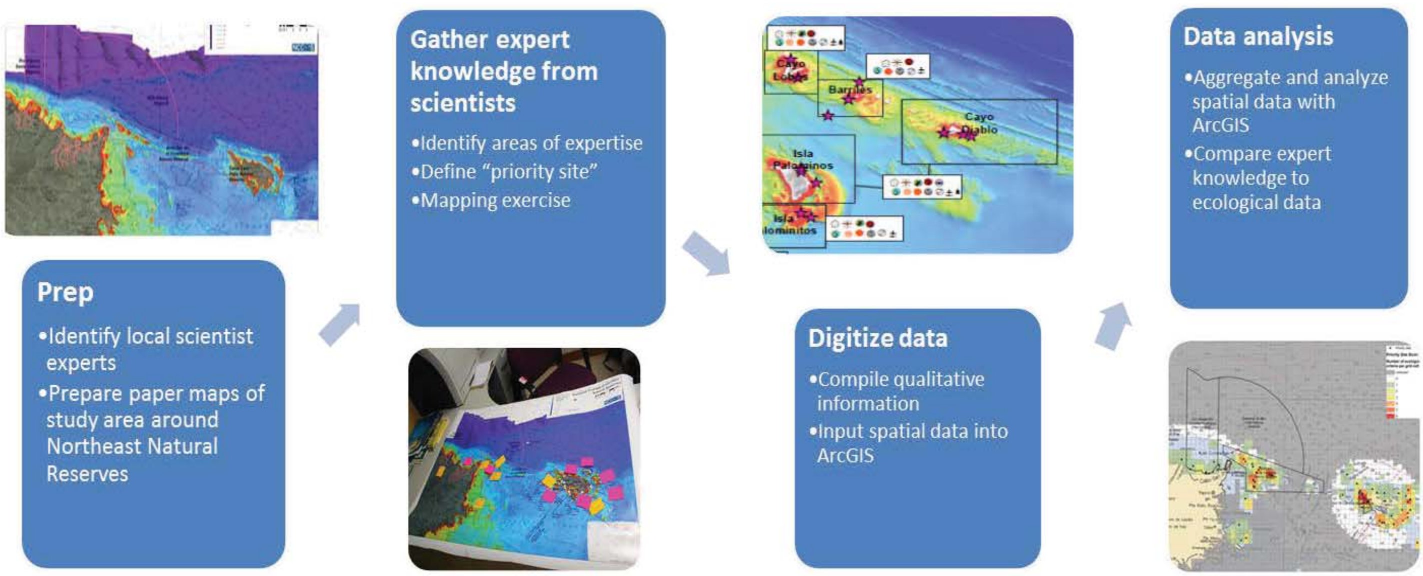


Figure 23. The participatory GIS process from map production to digital synthesis of data and interpretation.

2.1.3 Results and discussion

Participants' background information

Qualitative information was collected through local expert review of paper maps that visualized data along with ecological criteria and threats for selected focal areas. Additional background information was also recorded separately on worksheets. Topical areas of work and research among the seven participants varied, but focused mainly on coral reef and sea turtle ecology and management (Table 2). At the time of the interviews, participants had between seven and 42 years of professional experience in their respective fields, an average of 21.25 years of experience and 170 years of cumulative experience (Figure 24).

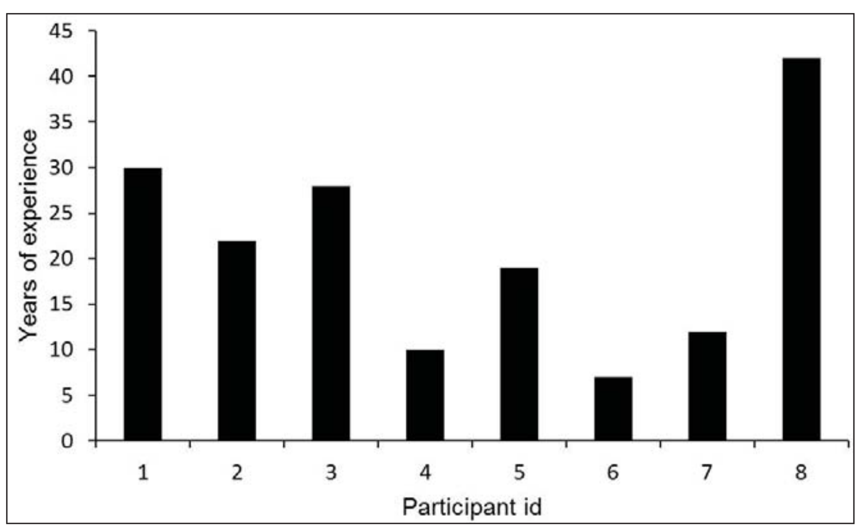


Figure 24. Years of professional experience in marine science and management per participant.

Mapping

During 2014, participants reported that they spent between 10 and 365 days in the field, for an average of 73 field days. Where a routine daily beach survey was conducted one participant reported 365 days. Of these field days, 36.5% were spent conducting research or underwater surveys. All participants had experience conducting research or working in a portion of the defined area of interest within the project area.

Five of the seven participants circled their focal research areas on their paper maps (Figure 25). It was presumed, based on conversation with the participants, that all the local scientist experts had some knowledge of areas outside their focal research areas, but possessed most knowledge about the areas that they circled.

Seven of the eight experts wrote down their definitions of a “priority ecological site”. Several characteristics of a priority ecological site emerged from the participants’ definitions: a) areas with species or habitats in need of protection, restoration, or that are rare/vulnerable/unique or endangered; b) healthy, high-functioning areas of great value (i.e., high biodiversity, abundance, or coral cover); and c) spawning and nursery habitats. Not all participants mentioned all three characteristics in their written definitions, and one participant did not want to

Table 2. Primary area of expertise for survey participants.

Participant	Areas of professional expertise					
	Underwater surveys of fish and/or coral	Coral restoration and monitoring	Sea turtle research and monitoring	Anthropogenic impacts to coral reefs	Spawning aggregations	Other
1	X	X				X
2	X		X			
3	X	X		X		
4	X	X	X		X	
5			X			
6	X		X			X
7	X			X		X
8	X				X	X

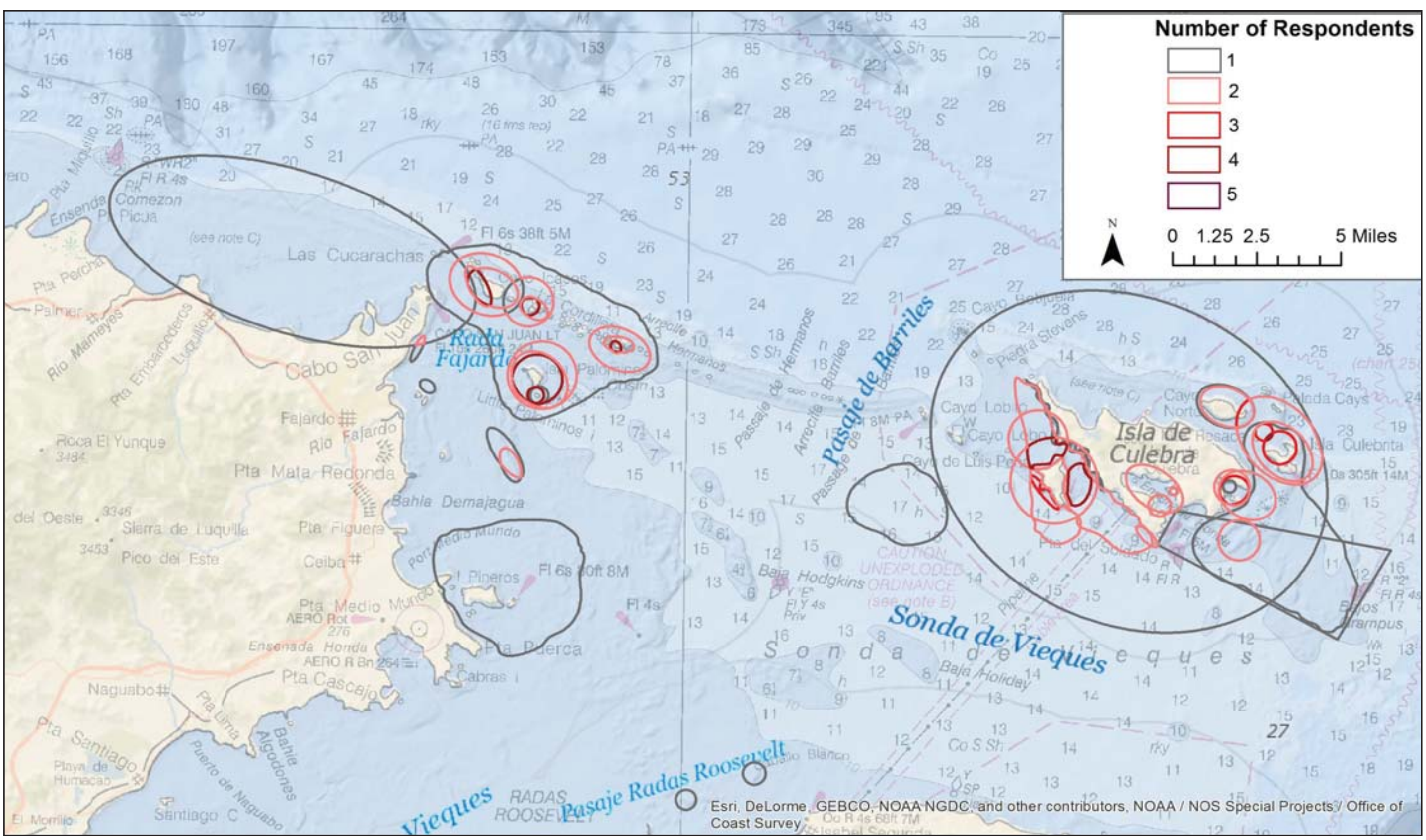


Figure 25. Number of respondents per research area (n=5).

include areas with rare/vulnerable species in his/her priority sites because they were considered in very poor condition. The priority ecological sites mapped by participants met at least one, if not all, of the three criteria specified above.

Mapping Exercise

Participants completed the mapping exercise, placing a total of 73 priority ecological sites in the project area. Participants each mapped between 3 to 22 priority sites (average of 11 sites mapped per participant). Some places were selected by multiple participants as being priority sites. Thirty-seven independent places were identified by at least one participant as a priority ecological site. Places selected by four participants as being priority ecological sites include: Isla Palominos, Cayo Diablo, Barriles and Bahia Culebrita (see place name map Figure 2). Nine places were selected by three participants as being priority sites, and six locations were classified as priority sites by two participants. Participants then characterized each of the priority sites with ecological criteria and threats (Table 3).

Thirty-two locations were chosen by respondents as having high biodiversity (fish species richness and/or coral species richness). Of these 32 locations, 11 were located along the northwest coast of Isla Culebra, nine were on the southeast side of Isla Culebra, and 12 were in the region of the Cordillera (Figure 26a). For the criteria "high abundance of fish and/or coral", 42 locations were marked, the majority being in the southeast part of the Cordillera and the area near Cayo de Luis Peña (Figure 26b).

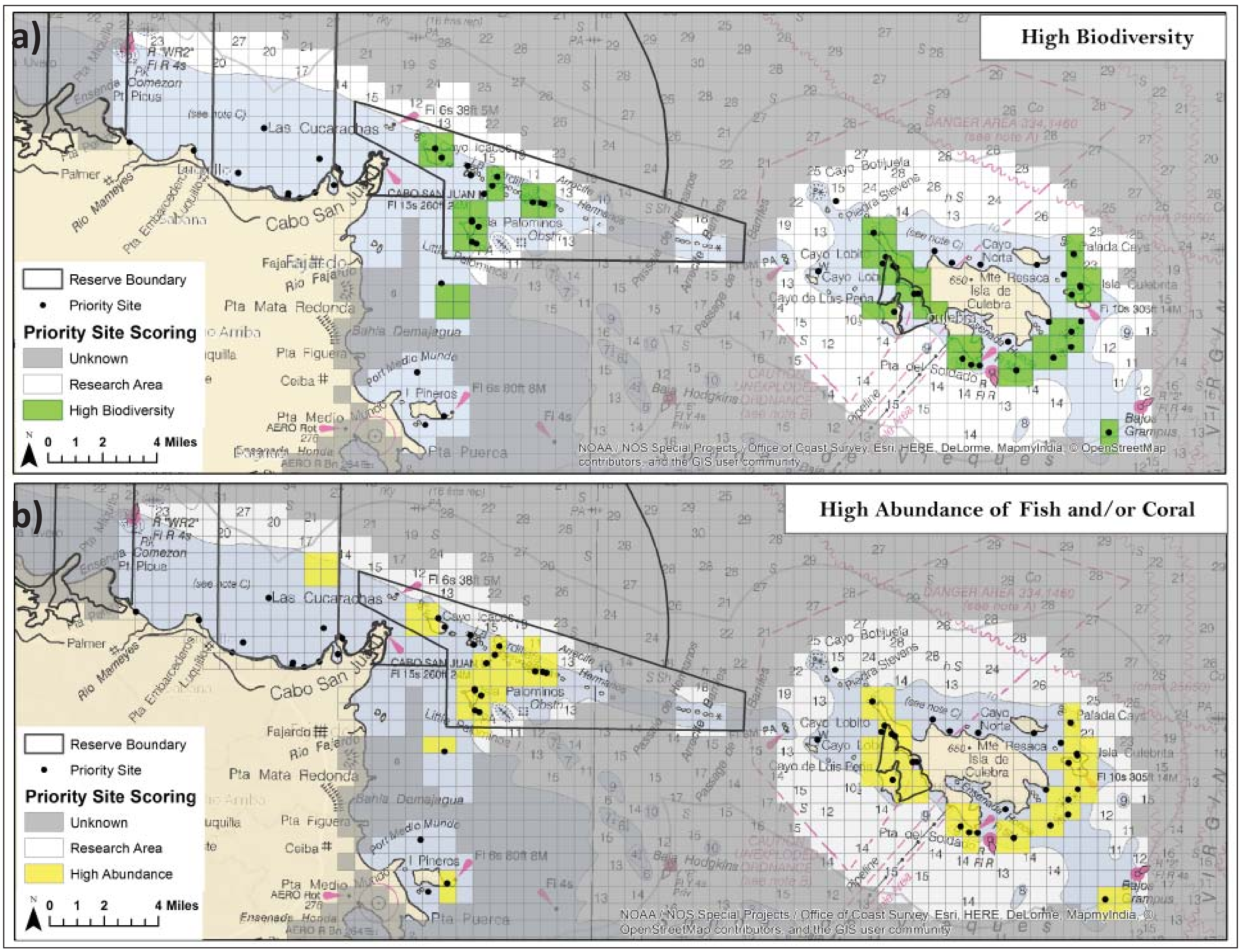


Figure 26. Maps of 1km-squared grid cells intersecting with a 400 m buffer radius of places marked as: a) high biodiversity, and b) high abundance of fish and/or coral according to expert knowledge.

Mapping

Table 3. Priority ecological site names with their associated ecological criteria, threats, and the number of respondents that marked a given place as a priority site.

	Priority Site Name	Ecological Criteria	Threats	# of Experts
1	Alcarraza		-	1
2	Arrecife Culebrita			2
3	Bahia Culebrita			4
4	Bahia Mosquito			1
5	Bahia Tamarindo			3
6	Bajos Grampus			1
7	Barriles			4
8	Cabezas Crespas			1
9	Cayo Botella		-	1
10	Cayo de Luis Peña			1
11	Cayo Diablo			4
12	Cayo Largo			1
13	Cayo Lobo		-	1
14	Cayo Lobos			2
15	Cayo Norte			1
16	Cayos Geniqui		-	1
17	Costa Azul		-	1
18	Culebrita			1
19	Icacos			3
20	Isla Palominitos			2
21	Isla Palominos			4
22	Isla Piñeros			3
23	Laguna de Aguas Prietas	*Bioluminescent bay*		1
24	Las Cucarachas			1
25	Los Corchos			2
26	Peninsula Flamenco		-	2
27	Playa Brava			3
28	Playa Carlos Rosario			3
29	Playa Colona			2
30	Playa Convento		-	1
31	Playa Paulinas			3
32	Playa Picua			1
33	Playa Resaca			3
34	Playa San Miguel			3
35	Puerto de Manglar			1
36	Punta del Soldado			3
37	Punta Flamenco		-	1

Ecological Criteria

- High biodiversity
- High abundance of fish and/or coral
- Rare/vulnerable species and/or critical habitats (coral)
- Rare/vulnerable species and/or critical habitats (sea turtles)
- Abundance of large-bodied fish
- Coral nursery/ restoration

Threats

- Poor water quality (runoff, rivers)
- Invasive species
- Thermal stress (bleaching, disease)
- Human use (i.e., boating, recreational diving)
- Fishing (commercial and recreational)
- Anchoring
- Coastal development
- Vessel groundings

The attribute for rare/vulnerable species and/or critical habitats was divided into sea turtle nesting sites or feeding grounds, and acroporid corals (*Acropora cervicornis*, *Acropora palmata*). Fifty sites were marked as having acroporids, and 37 sites had sea turtle nesting sites or feeding grounds, totaling 87 locations characterized by the presence of rare and vulnerable species and/or critical habitats (Figure 27). Nineteen sites were identified as having a high abundance of large-bodied fish, although many of these sites did not correspond with the priority ecological sites selected by participants, but instead were located in deeper water (Figure 28a). Cayo Diablo and the northwest corner of Isla Culebra had the highest abundance of large-bodied fish, according to the participants. Fourteen spawning and nursery sites were located in the project area (Figure 28b). The total number of ecological attributes mapped was 194, with the highest concentration of all types of ecological criteria being around Cayo Diablo, Isla Palominos and Punta Soldado (Figure 29).

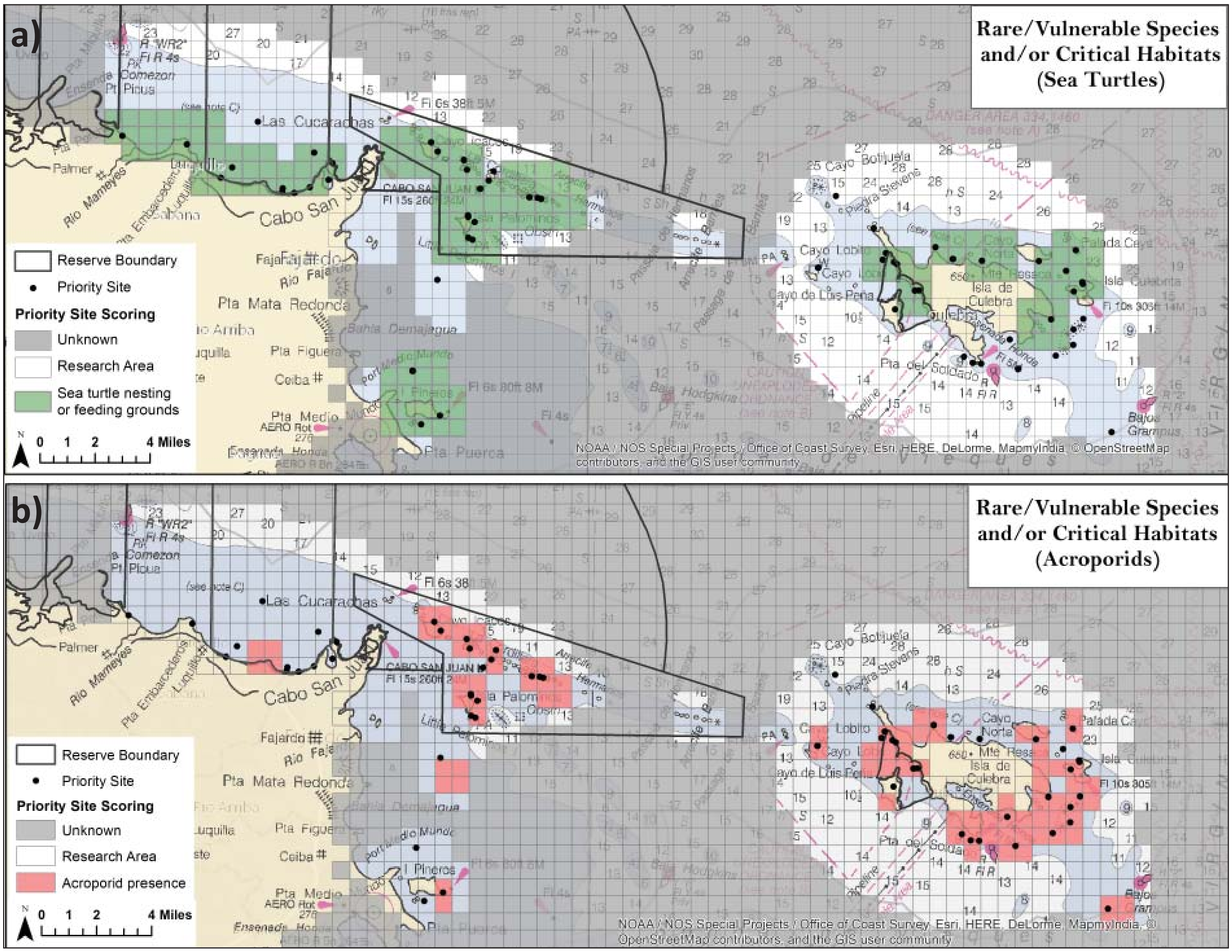


Figure 27. Maps of 1km-squared grid cells intersecting with a 400 m buffer radius of places marked with presence of rare/vulnerable species and/or critical habitats for: a) sea turtles and b) Acroporids species according to expert knowledge.

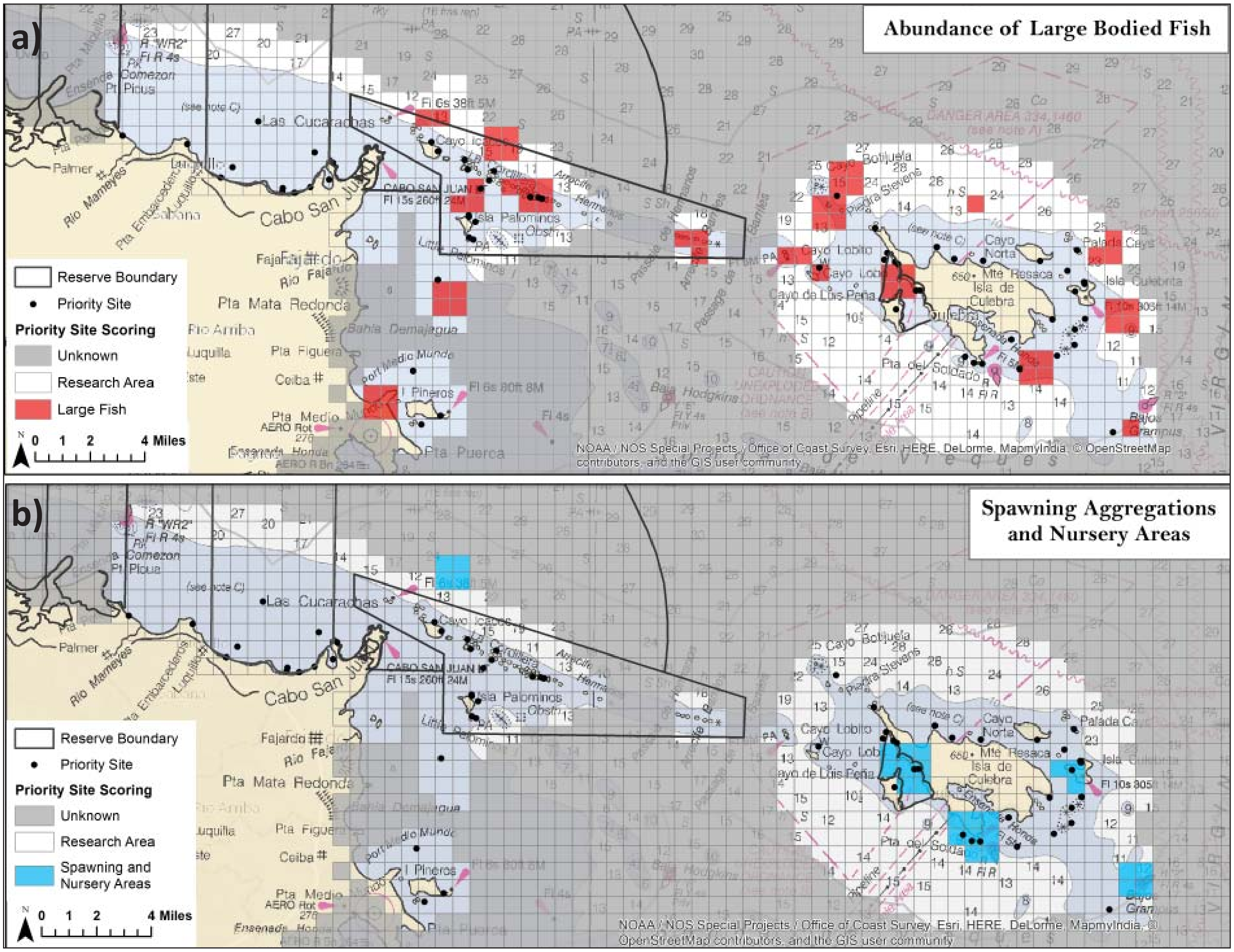


Figure 28. Maps of 1km-squared grid cells intersecting with a 400 m buffer radius of places marked with presence of: a) abundance of large-bodied fish, and b) spawning aggregations and nursery areas according to expert knowledge.

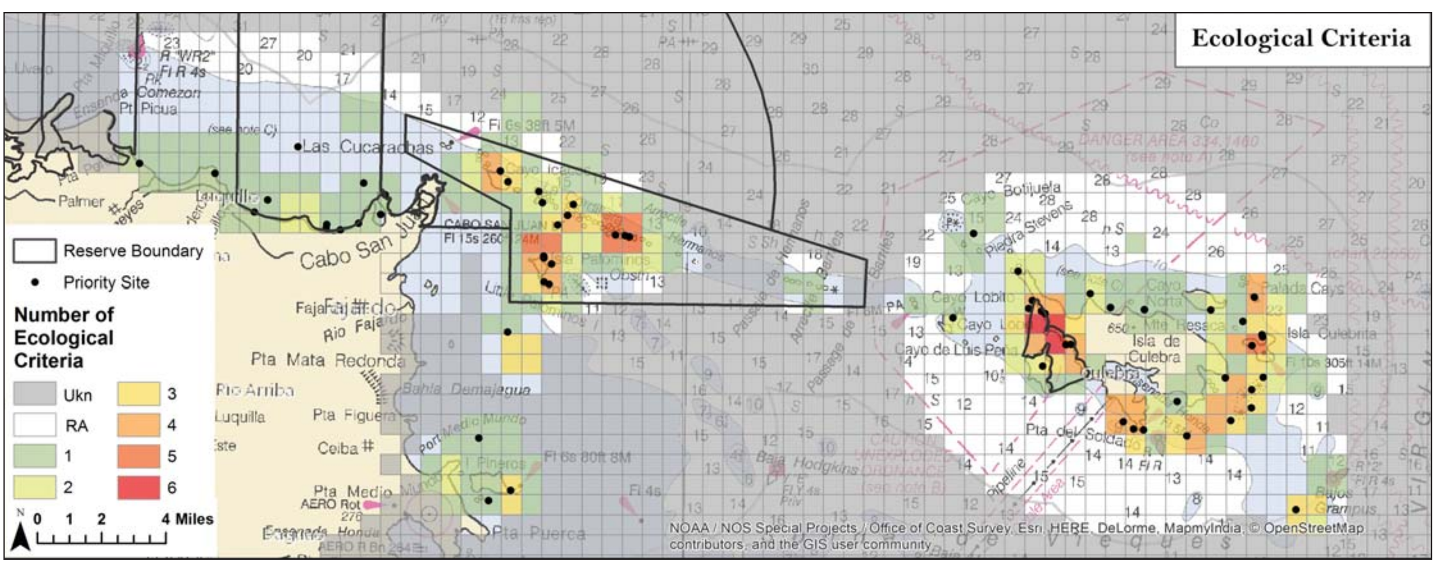


Figure 29. Number of different ecological criteria mapped per 1 km-squared grid cell (and 400 m buffer).

The second part of the mapping exercise was to describe the threats to each of the priority ecological sites. To the six threats suggested by researchers (Table 1), participants added coastal development and vessel groundings. Other specific threats mentioned by participants included boating, recreational activities and navigation, and were grouped into single category named "high human use". Light pollution was merged with the “coastal development” category. Of the eight threats considered, the maximum number of threats attributed to a given priority ecological site was six. Thirty-three sites did not have any specific threats associated with them, but were likely impacted by global stressors, such as thermal stress. Many of the threats were assumed to affect a broad spatial scale, and thus, in some cases, it was more difficult for participants to determine which threats directly affected a specific priority ecological site. Thirty-five areas were identified by participants as having poor water quality. Thirteen locations were associated with invasive species, such as lionfish. Most participants acknowledged that thermal stress was ubiquitous, but they identified 24 specific locations showing signs of thermal stress, such as coral bleaching. Thirty-seven sites were mapped as having ‘high human use intensity’ from activities such as boating and recreational diving. Thirty-five sites were observed to be affected by fishing pressure, and thirty sites were thought to be impacted by anchoring. Finally, coastal development was a threat in four sites (sea turtle nesting beaches), and eight locations were selected under the ‘vessel groundings’ class of threats. A total of 186 threat sites were mapped (Figure 30).

In the participatory mapping exercise, local scientific experts in Puerto Rico provided insights on the locations of ecologically important sites, specific ecological attributes that describe these sites as special, and the threats to these areas that may affect the long-term health of coral reef ecosystems in the region. By interacting face-to-face with local experts, additional qualitative data was obtained that added a great amount of added value, including the local names of places, additional observations made at the site, and management recommendations to improve the prioritized areas. Information collected from local experts was used to inform management in the area of the Northeast Marine Corridor through integration of spatial data on human use, environmental stressors, and areas of high ecological value compiled from various sources (Chapter 3).

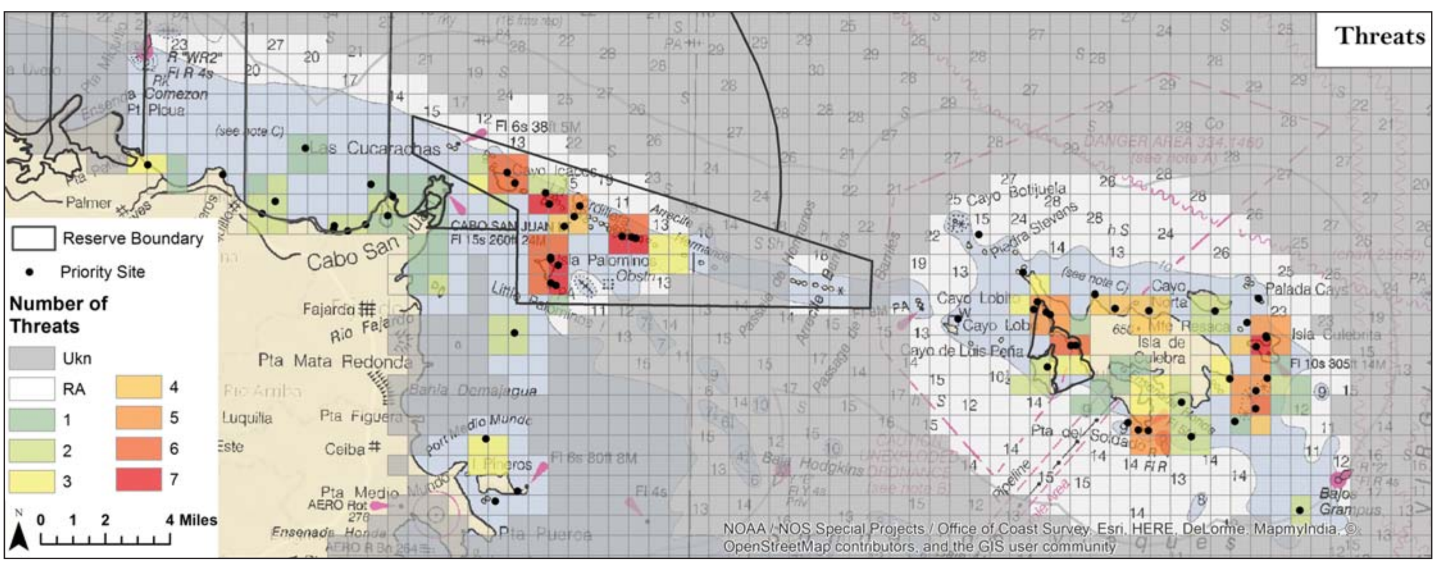


Figure 30. Number of different threats to priority sites mapped per 1 km-squared grid cell (and 400 m buffer).

Mapping

2.2 MAPPING ECOLOGICAL PRIORITY AREAS AND THREATS FROM DIRECT MEASUREMENTS AND SPATIAL MODELS

2.2.1 Introduction

This section describes an assessment of empirical field observations and modeled spatial data with the purpose of identifying ecologically important areas. The assessment comprises selection and application of ecological criteria to identify ecologically important elements, and an evaluation of cumulative human impacts. The assessment addresses the following questions:

- What and where are the ecological priority areas?
- Where do multiple ecological priorities co-occur in space?
- Which human impacts threaten priority areas?
- At which locations are ecological priorities most threatened?

Identifying ecologically important areas and evaluating the stressors and threats to those places enables the identification of areas of concern and can guide strategic management actions. Management actions might consist of creating new protections, mitigating ecosystem degradation, or restoring damaged habitats.

2.2.2 Methods

Defining and mapping ecological elements

Ecological importance was quantified using existing data describing the distribution of important animals, plants, habitats and oceanographic processes in the project area. We used criteria defining ecological importance with a conservation planning perspective and a goal of maintaining and protecting the health, biodiversity, resilience, and functioning of the marine ecosystem. In order to achieve this goal, we analyzed the distribution of ecological elements including: rare or endangered species; habitats essential to the survival of fish and wildlife populations (i.e., areas for feeding, calving, breeding, and nursing); or unique communities and oceanographic processes.

A comprehensive analysis of existing ecological data and corresponding data gaps was undertaken prior to criteria selection. Using readily-available data, we identified 18 different biological and ecological elements (Table 4) which met our ecological criteria.

All biological and ecological elements, data sets, and selection criteria were reviewed by staff from DNER, The Nature Conservancy, and in-house peers for completeness, accuracy and relevance. It was understood that the selected biological and ecological elements did not identify all species and habitats that are ecologically significant in the study area; rather the strategy called attention to areas of particularly high ecological significance, where conservation actions could be preferentially targeted. The best available data was used with the understanding that the conservation decisions will be restricted by the spatial and temporal extents of datasets, and heterogeneously distributed effort will bias results.

Defining and mapping human threats to ecological elements

Humans impact ecological elements by extracting biomass, adding pollution, destroying habitat and altering species behavior. These activities vary in intensity with some areas appearing unaffected, while other areas appear to be stressed with communities fundamentally altered. Maps and analysis of all human uses and their cumulative impacts are needed to implement coastal zone management and organize ocean zoning. These maps identify areas where conservation actions and threat mitigation are most needed in the study area. We used a standardized, quantitative method, which builds on work by Halpern et al. (2008), Selkoe et al. (2009) and Burke et al. (2011), to map human impacts. Eight distinct human impacts to ecologically important elements were identified (Table 5), mapped and combined into a single comparable estimate of cumulative human impact. The list reflects an assortment of anthropogenic threats to ecological elements from activities such as shipping, recreation, land development, and global climate change.

Table 4. List of elements used to define ecologically important areas. ESI= Environmental Sensitivity Index, NCCOS= National Centers for Coastal Ocean Science, NCRMP= NOAA's National Coral Reef Monitoring Program, NMFS= NOAA's National Marine Fisheries Service.

Ecological Element	Brief description	Data sources
Threatened corals	Locations of seven threatened coral species listed in the Endangered Species Act	NOAA NCCOS 2015 benthic habitat map (Kågesten et al., 2015); interviews with dive shops; 2014 NCRMP diver surveys (, 2016)
Rare coral reefs	Areas with greater than 10% live coral cover	NOAA NCCOS 2015 benthic habitat map (Kågesten et al., 2015)
Extremely rare coral reefs	Areas with greater than 50% live coral cover	NOAA NCCOS 2015 benthic habitat map (Kågesten et al., 2015)
Conch	Conch concentrations areas	NOAA NMFS diver surveys (NOAA OST, 2015)
Bird nesting areas	Land where birds are known to nest	Puerto Rico ESI maps (NOAA ORR, 2014)
Bird hotspots	Land and coastal areas with high bird concentrations	Puerto Rico ESI maps (NOAA ORR, 2014)
Turtle feeding areas	Turtle feeding areas	Expert knowledge; Puerto Rico ESI maps (NOAA ORR, 2014)
Turtle nesting beaches	Turtle nesting beaches	Puerto Rico ESI maps (NOAA ORR, 2014)
Manatees	Areas with high manatee concentration	Puerto Rico ESI maps (NOAA ORR, 2014)
Fish spawning aggregation sites	Spawning aggregation sites for grouper, snapper, parrotfish and hogfish	Interviews with fishermen (Ojeda-Serrano et al., 2007)
Bioluminescent bay	The bioluminescent bay near Fajardo	NOAA coastal relief model (NOAA NCEI, 2014) and nautical charts 25650 and 25663 (NOAA OCS, 2014)
Hardbottom	Areas with hardbottom habitats (i.e., not sand or mud)	NOAA NCCOS 2015 (Kågesten et al., 2015) and 2001 (Kendall et al., 2001) benthic habitat maps
Mangroves	Areas with mangroves	NOAA NCCOS 2015 (Kågesten et al., 2015) and 2001 (Kendall et al. 2001) benthic habitat maps
Seagrasses	Areas with seagrasses	NOAA NCCOS 2015 (Kågesten et al., 2015) and 2001 (Kendall et al., 2001) benthic habitat maps
Shelf edge mixing zone	The shelf edge	NOAA coastal relief model (NOAA NCEI, 2014) and nautical charts 25650 and 25663 (NOAA NCEI, 2014)
Shelf edge reef	Estimated area of shelf edge reef	NOAA coastal relief model (NOAA NCEI, 2014) and nautical charts 25650 and 25663 (NOAA OCS, 2014)
High topographic complexity	Areas with high rugosity	NOAA NCCOS 2015 benthic habitat map (Kågesten et al., 2015)
Submarine canyons	Areas with submarine canyons	NOAA coastal relief model (NOAA NCEI, 2014) and nautical charts 25650 and 25663 (NOAA OCS, 2014)

Table 5. List of known stressors to important ecological elements. ERMA= Environmental Response Management Application, WRI= World Resources Institute

Threat	Brief description	Data sources
Vessel activity	Intensity of vessel traffic and location of vessel groundings	U.S. Coast Guard Automatic Identification System (AIS) and grounding records (http://www.navcen.uscg.gov/?pageName=NAISmain)
Coastal infrastructure	Extent of man-made structures (i.e., marinas, cables, and anchorage areas)	2015 NCCOS benthic habitat map; ERMA; Puerto Rico Planning Board; DNER data, NOS charts, WRI data (see Appendix B)
Light pollution	Ambient light levels	Visible Infrared Imaging Radiometer Suite (VIIRS) monthly nightlight composites (http://ngdc.noaa.gov/eog/viirs/download_monthly.html)
Coral bleaching	Number of coral bleaching watches, warnings and alerts	NOAA Coral Reef Watch (http://coralreefwatch.noaa.gov/satellite/index.php)
Marine-based pollution	Pollution derived from coastal infrastructure and vessel traffic	2015 NCCOS benthic habitat map; ERMA; Puerto Rico Planning Board; DNER data, NOS charts, WRI data; US Coast Guard Automatic Identification System (see Appendix B)
Agricultural pollution	Amount of upstream agricultural area reaching coastal discharge sites	Modified data from Gould et al. (2007)
Urban pollution	Amount of upstream urban area reaching coastal discharge sites	Modified data from Gould et al. (2007)
Coastal population	Nearby coastal population	2010 U.S. Census Bureau (http://www.census.gov/2010census/)

Mapping

We limited our analysis to human impacts with complete data coverage of the project area. Detailed descriptions of each impact and corresponding data sources are provided in Appendix B. Not all known threats could be analyzed because of data limitations. Notable data gaps include sedimentation, aquaculture, invasive species, tourism and fishing. Most of these impacts were addressed by Halpern et al. (2008), Selkoe et al. (2009) and Burke et al. (2011), but their data were mapped at spatial scales which are too coarse for analysis in the project area. The cumulative impact model follows a four step process outlined by Halpern et al. (2008). Data for each impact and ecological element were first compiled and reconfigured into 100 m² coastal and ocean cells. Second, impact data were log (x+1) transformed, and re-scaled between 0 and 1 to allow direct comparisons among all data. Third, for each 100 m² cell we multiplied each impact layer with each ecological element layer to create impact-by-element combinations, and then multiplied these combinations by a vulnerability weighting variable. Weights were classified as 0 or 1, where 1 denoted an ecological element that was vulnerable to a specific stressor. Fourth, we summed the weighted impact-by-element combinations to represent cumulative impact of human activities for each 100 m² cell (Table 6).

Predicted cumulative impact scores were calculated for each 100 m² cell as follows:

$$Cumulative\ Impact = \sum_{i=1}^{n} \sum_{j=1}^{m} D_i \times E_j \times \omega_{i,j}$$

Where D_i is the scaled and normalized value of a human driver at location *i*, E_j is the presence or absence of ecosystem attribute *j*, and $\omega_{i,j}$ are the impact weight defining vulnerability of driver *i* on attribute *j*. Impact weights (Table 6) were estimated using our expert knowledge, and then vetted by coastal managers and scientists working in the project area.

Table 6. Impact weights used in the estimation of cumulative impact. Weights are boolean variables where 1 indicates vulnerability and 0 indicates the absence of vulnerability.

Ecological Element	Human Impacts							
	Vessel activity	Coastal infra-structure	Light pollution	Coral bleaching	Marine pollution	Agricultural pollution	Urban pollution	Coastal pollution
Bioluminescent bay	1	1	1	0	1	1	1	1
Bird nesting areas	0	1	0	0	1	1	1	1
Bird hotspots	0	1	0	0	1	1	1	1
Submarine canyons	0	1	0	0	1	1	1	1
Rare coral reefs	1	1	0	1	1	1	1	1
Extremely rare coral reefs	1	1	0	1	1	1	1	1
Conch	0	1	0	0	1	1	1	1
Threatened corals	1	1	0	1	1	1	1	1
Hardbottom	1	1	0	0	1	1	1	1
Manatees	1	1	0	0	1	1	1	1
Mangroves	1	1	0	0	1	1	1	1
Seagrasses	1	1	0	0	1	1	1	1
Shelf edge mixing zone	0	1	0	0	1	1	1	1
Shelf edge reef	0	1	0	0	1	1	1	1
Fish spawning aggregation sites	0	1	0	0	1	1	1	1
High topographic complexity	1	1	0	0	1	1	1	1
Turtle feeding areas	1	1	0	0	1	1	1	1
Turtle nesting beaches	1	1	1	0	1	1	1	1

Impact distributions were analyzed with 100 m² cells, keeping ecological elements, impact scores and corresponding interactions close to native resolutions. Impact scores were later mapped using the hexagonal analysis units used in cumulative ecological element maps, where values correspond to the average of 100 m^2 score values. Averaging was performed to keep visualization of cumulative ecological elements and impact scores at the same spatial scale.

One of the main differences between the approach used by Halpern et al. (2008) and the approach adopted here is that here distributions of ecological elements are used, while Halpern et al. (2008) used maps of marine habitats (referred to as ecosystems, given the scale of their study). Our approach supports the issuance of importance and vulnerability to species, as well as habitats, and provides the opportunity to estimate human impacts to ecological elements spanning multiple habitats. For instance, impacts of human activities to bird breeding areas can be estimated even if breeding areas span multiple habitat types or ecosystems.

Impact scores are considered relative measures of human impact, where areas with higher scores indicate more ecological elements are threatened and/or elements are threatened by more human impacts compared to areas with lower scores. It is not possible to distinguish between these two options. Since empirical data was not used to groundtruth cumulative impact scores, a score should not be used as a threshold for management action, but as a signal to focus attention and gather additional information.

Each ecological element was chosen to provide accurate information at spatial scales relevant to conservation planning in the study area. Detailed descriptions of all ecological elements are provided in Appendix A. Data considered unreliable either because of age, spatial resolution or disagreement with other data or expert opinion were excluded. Excluded data were:

- <u>Estuaries</u>: Although reviewers noted estuaries were an important feature attribute to map, data defining estuaries was not readily available at the time of this assessment.
- <u>Cetaceans</u>: Data defining cetacean patterns in Environmental Sensitivity Index (ESI) maps were too coarse, and did not provide sufficient detail to distinguish important places from background values.
- <u>Fish</u>: Several fish data sets existed in the study area, such as CRCP's National Coral Reef Monitoring Program (NCRMP) and Reef Environmental Education Foundation (REEF), and neither provided sufficient information to reliably identify important areas for populations or biodiversity at spatial scales similar to other data. Consequently, we relied on benthic habitat types to serve as surrogates for fish distributions and diversity, an approach evidenced by Pittman et al. (2007), Harborne et al. (2008) and Dunn and Halpin (2009).

The influence of effort bias was mitigated by transforming ecological element distribution data into presence and absence, carefully selecting the most reliable data set when multiple data sets existed, and combining multiple data sets when feasible. The effect of combining data resulted in new synthesis layers, such as threatened corals and turtle nesting beaches.

We mapped where ecological elements co-occurred to quantify relative ecological importance and efficiently target areas with high conservation value. We used a network of hexagonal analysis units, each with an area of 20 hectares (0.2 km²), and which was also used to analyze configurations of management priority areas (Appendix C). A cumulative feature score was given to each unit in the study area and was defined as the number of ecological elements present within each unit. The study area extended onto land wherever hexagonal units intersected ocean or mangroves. Landward units were included to expose the connections of coastal resources with landward distributions (e.g., turtle nests, bird breeding sites and mangroves).

2.2.3 Results and discussion

Places where important ecological elements co-occur

Individually, each ecological element is capable of identifying important places, but examined together, maps that combine ecological elements identify places where multiple features can be conserved or managed together (Figure 31). Regionally, there are several noticeable patterns: 1) ecological elements co-occur most along coasts and around islands; 2) relatively high numbers of ecological elements are only found within the extent of benthic habitat maps; and 3) there are large data gaps in water deeper than 30 m. In addition, the northern coast of the main island has relatively fewer overlapping ecological elements than the eastern coast of the main island. Assessment of element distribution at spatial scales aligned with analysis units (0-1 km) indicate that elements are spatially partitioned along the northern coast, whereas they are more likely to occur together along the eastern coast. Eight or more ecological elements are in approximately 20% of the analysis units, and these units are distributed in four clear regions (Figure 32): 1) the area around Isla de Culebra; 2) nearshore areas along the eastern coast of the main island; 3) islands and reefs of La Cordillera; and 4) shoals around Bajo Chinchorro del Sur.

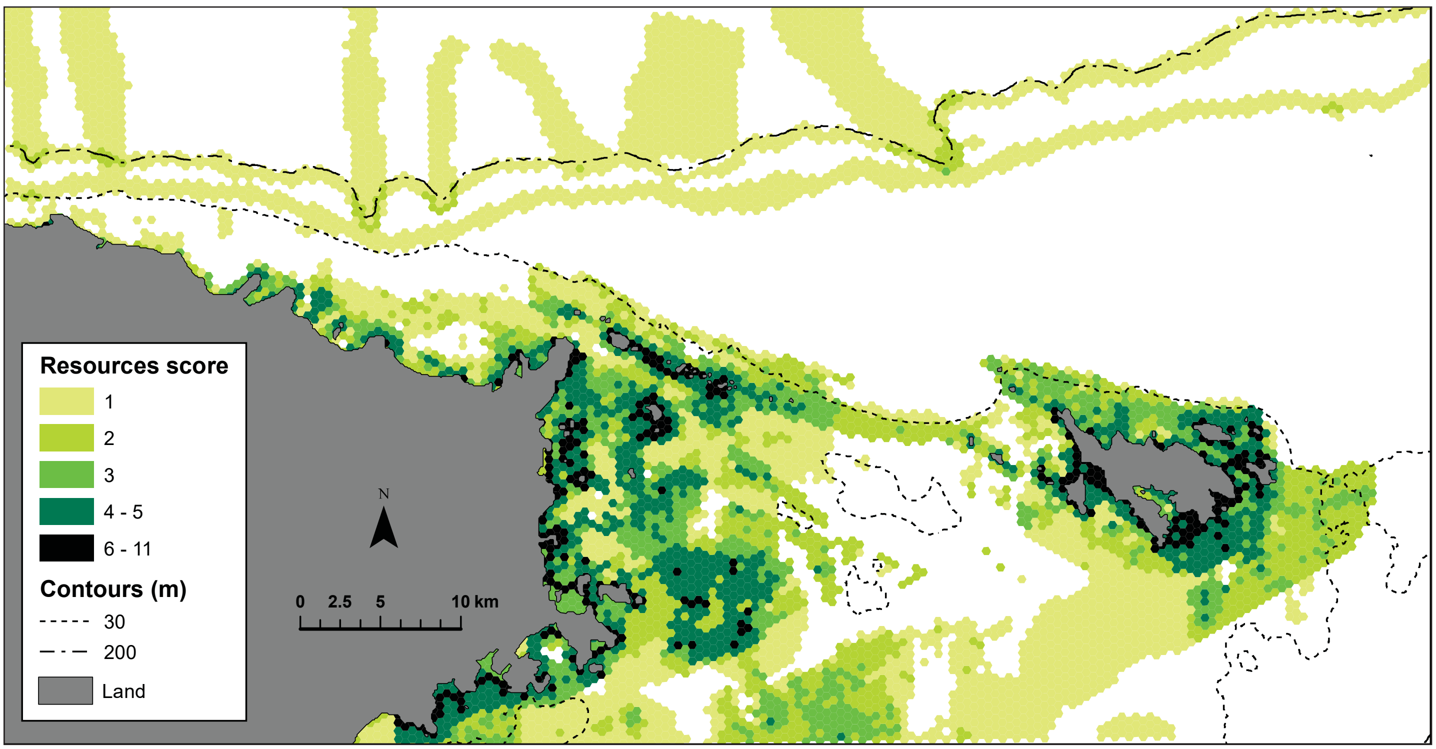


Figure 31. Map of overlapping ecological elements. Scores were defined by the number of overlapping ecological elements in a hexagonal analysis unit and are divided into quintiles. Darker areas have more overlapping elements.

The analysis and map provided in Figure 32,33 and 34 assume all ecological elements are equally important to managers. At the request of our DRNA partners, and to guide coral-focused conservati on decision-making, a second version of the map was produced to show the distributi on of a subset of ecological elements that were associated with corals (i.e. hardbott om, high topographic, 10% coral cover and 50% coral cover; Figure 32).The resulti ng map shows a high number of coral-centric ecological elements around Isla de Culebra, and islands and reefs of La Cordillera, and a relati vely fewer number of coral-centric elements in nearshore areas along the eastern coast of the main island and at the shoals around Bajo Chinchorro del Sur.

Overall, the maps showing ecological element distributions provide an integrated overview of ecologically important areas. However, the maps must be interpreted knowing that the maps do not identify how well an area achieves specific conservation goals, or what management actions are relevant to conserve ecologically important resources.

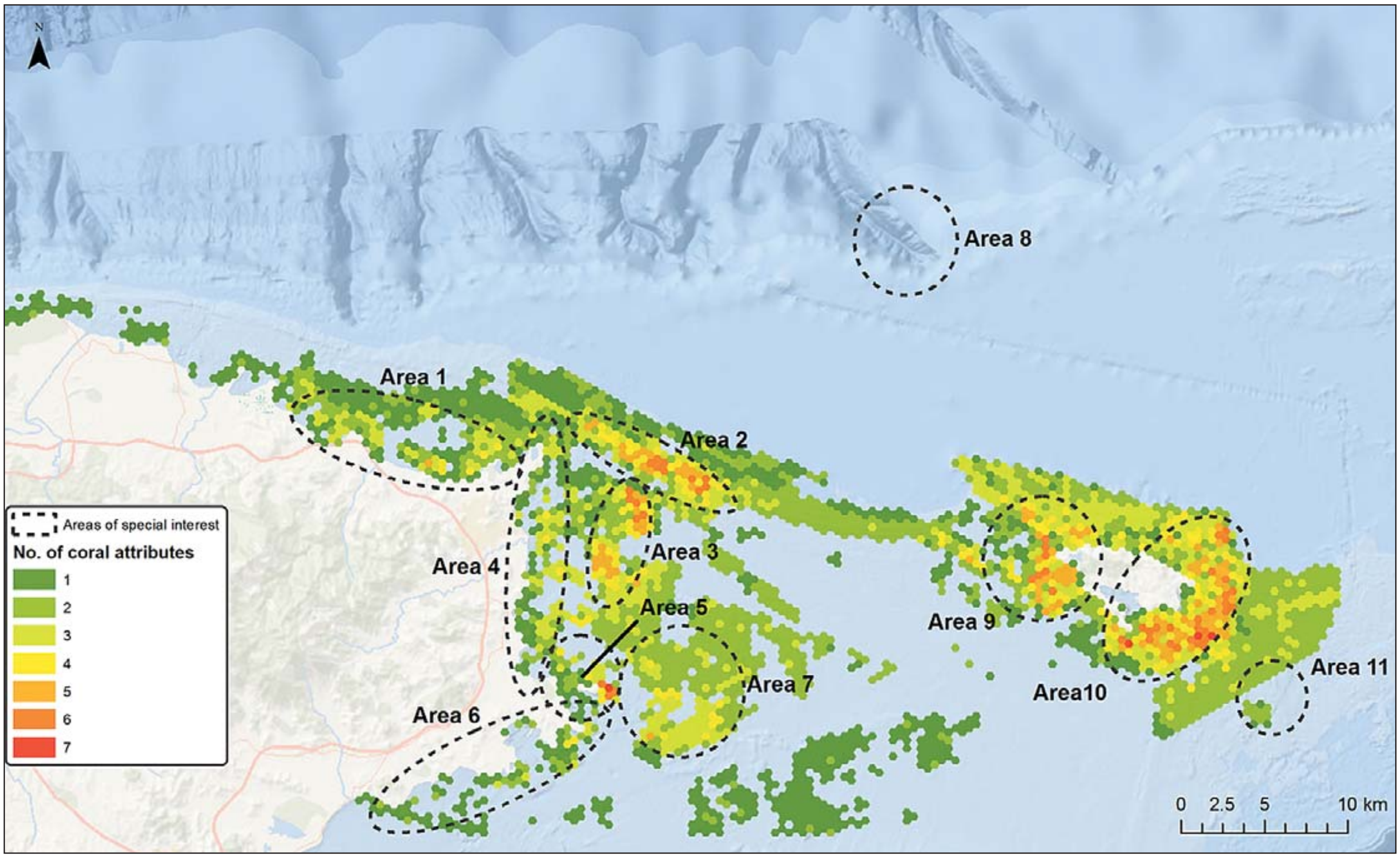


Figure 32. Map of cumulative coral related attributes. Scores are defined by the number of coral attributes in each cell (i.e., stacked rugosity, ESA corals, expert defined special places for coral, reefs with greater than 50% coral, etc.).

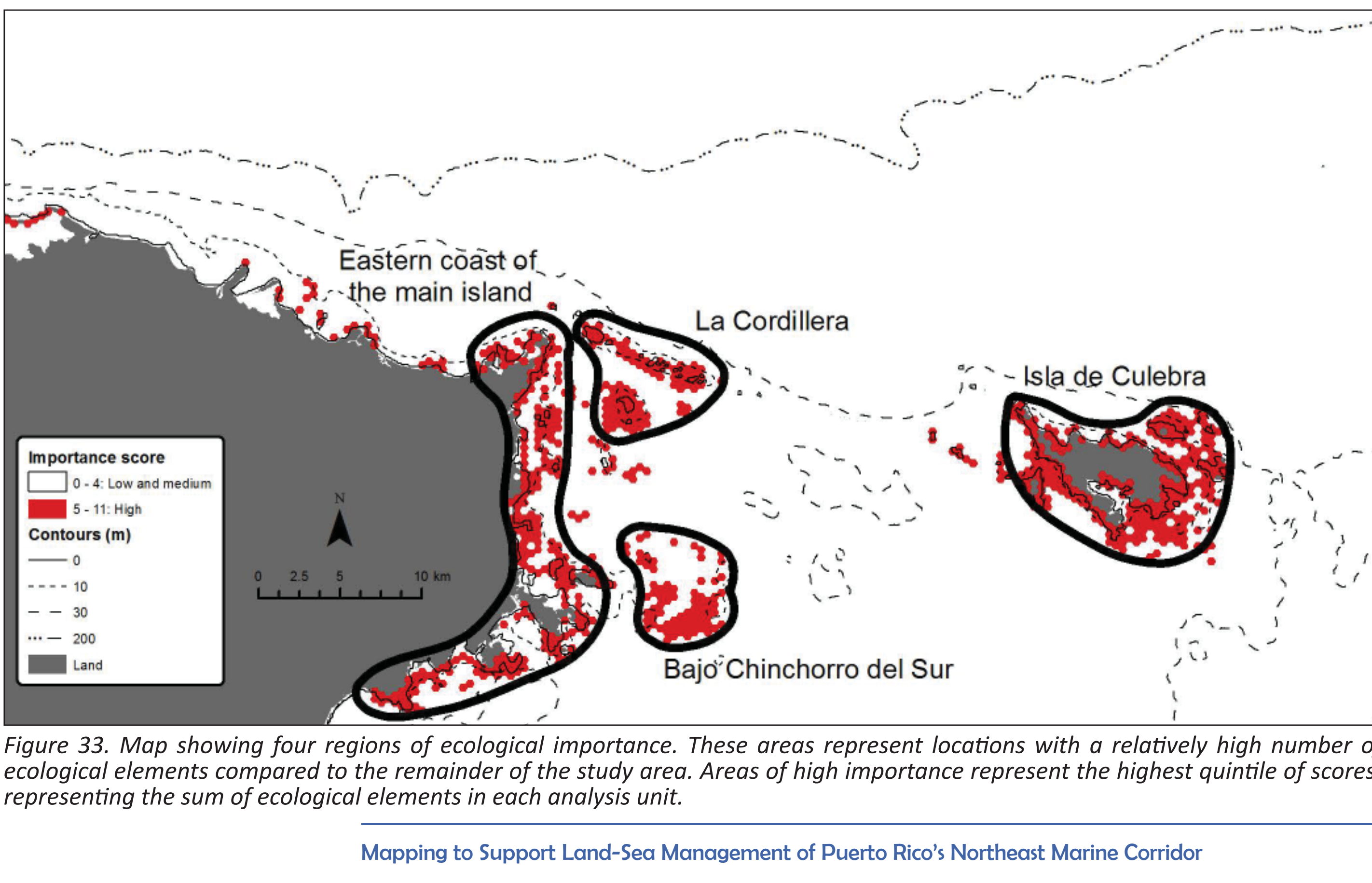


Figure 33. Map showing four regions of ecological importance. These areas represent locations with a relatively high number of ecological elements compared to the remainder of the study area. Areas of high importance represent the highest quintile of scores, representing the sum of ecological elements in each analysis unit.

Mapping

Places where important ecological elements are exposed to threats

Predicted human impacts in the study area are heterogeneously distributed (Figure 34). Every location in the study area with a mapped attribute showed some level of human impact. Most of the highest impact scores were in coastal areas and waters less than 30 m in depth, locations where impacts from land and sea-based activities overlap. In addition to analysis units with high impact scores scattered throughout the study areas, broad areas of relatively high human impacts occurred in four distinct geographical sub-regions:

1. Within the mangroves adjacent to the suburbs of San Juan and the town of Loiza.
2. Along the entire east and southeast coasts of the main island, with an especially large area of high impact east of Fajardo.
3. Among offshore shoals east of the main island, including Bajo Chichorro del Sur.
4. Nearshore and offshore waters south and southeast of Isla de Culebra.

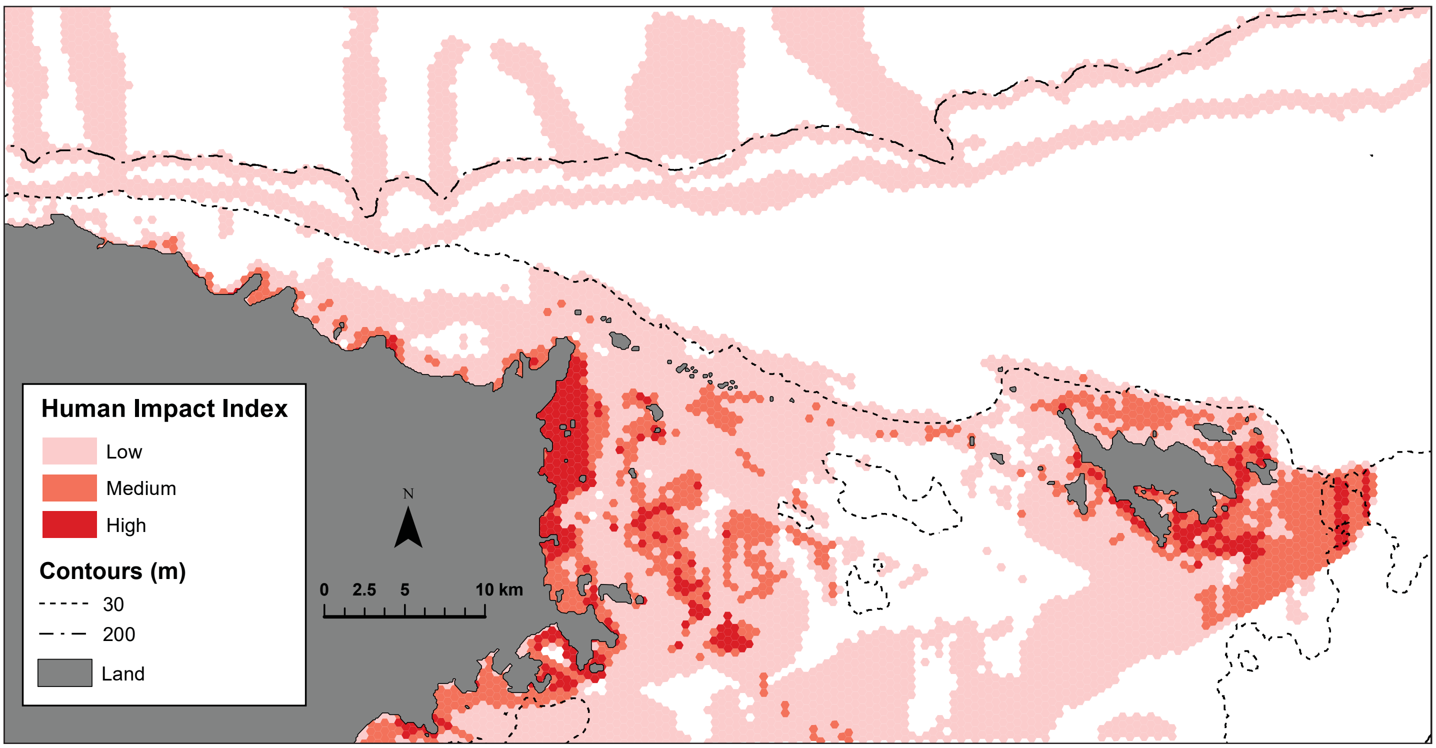


Figure 34. Map of cumulative human impact scores. Scores are the mean values registered in hexagonal analysis units. Darker reds indicate more impacts to ecological resources. Scores were divided into five quintile classes.

A large area with low human impact scores occurred offshore along the shelf edge, and in sand, seagrass and rhodolith habitats between the main island and Isla de Culebra. Similar sand, seagrass and rhodolith habitats close to shore (i.e., less than 5 km) typically have much higher impact scores. Our analyses did not take into account any type of fishing and we expect fishing could be high along the shelf edge. Greater distance from human populations could explain the broad inshore-offshore patterning. Halpern et al. (2008) wrote that human impact scores in their global study were generally inversely related to distance from human settlements, but distance did not ensure low scores, because threats from vessel activity, marine pollution and coral bleaching affected even remote areas. Attributes with the highest impact scores include coral reefs with greater than 10% and 50% coral cover, and threatened corals (Figure 35). These three attributes have impact scores at least twice as high as other resources. Offshore deeper habitats (i.e., shelf edge, shelf edge reefs, submarine canyons), spawning aggregation sites and conch had the lowest impacts. Conch and spawning aggregations are likely impacted by fishing pressure, which we did not include in this analysis. Bird nesting sites too had a relatively low impact score and are likely to be impacted by terrestrial activities.

There was wide variation in threat scores among human impacts (Figure 36). The impacts with the highest predicted threats were widely distributed, and affected the most resources. In contrast, human impacts which were typically either confined to discrete areas (i.e., infrastructure) or influenced a small subset of important resources (i.e., light) had the lowest predicted threat scores. Marine pollution was an exception to this common pattern. Although marine pollution was distributed widely and affected all investigated resources, it did not have a high threat score. This occurred because 90% of scaled and normalized values of marine pollution were very low (i.e., <0.06), suggesting marine pollution had a negligible effect across most areas.

Human impacts were grouped into three broad classes based on their origins: 1) marine-based, 2) terrestrial-based, and 3) climate change-based. Among these three classes, terrestrial-based impacts were the most influential, bearing the majority of the cumulative impact score, 53%. Marine-based impacts were the second largest contributor making up 37% of the score, with the remaining 10% made up by climate change impacts.

Our assessment of cumulative impacts identifies areas where anthropogenic drivers could be managed efficiently. Our data can also be used to target specific activities which impact high-value resources, arrange activities in space to reduce negative impacts, or focus effort to change anthropogenic drivers with the highest impact scores. For example, assessing elements and impact scores in unison provides managers information to: A) manage unthreatened resources and keep pristine areas pristine; B) manage the most threatened areas or attributes to efficiently mitigate impacts; or C) a combination of A and B.

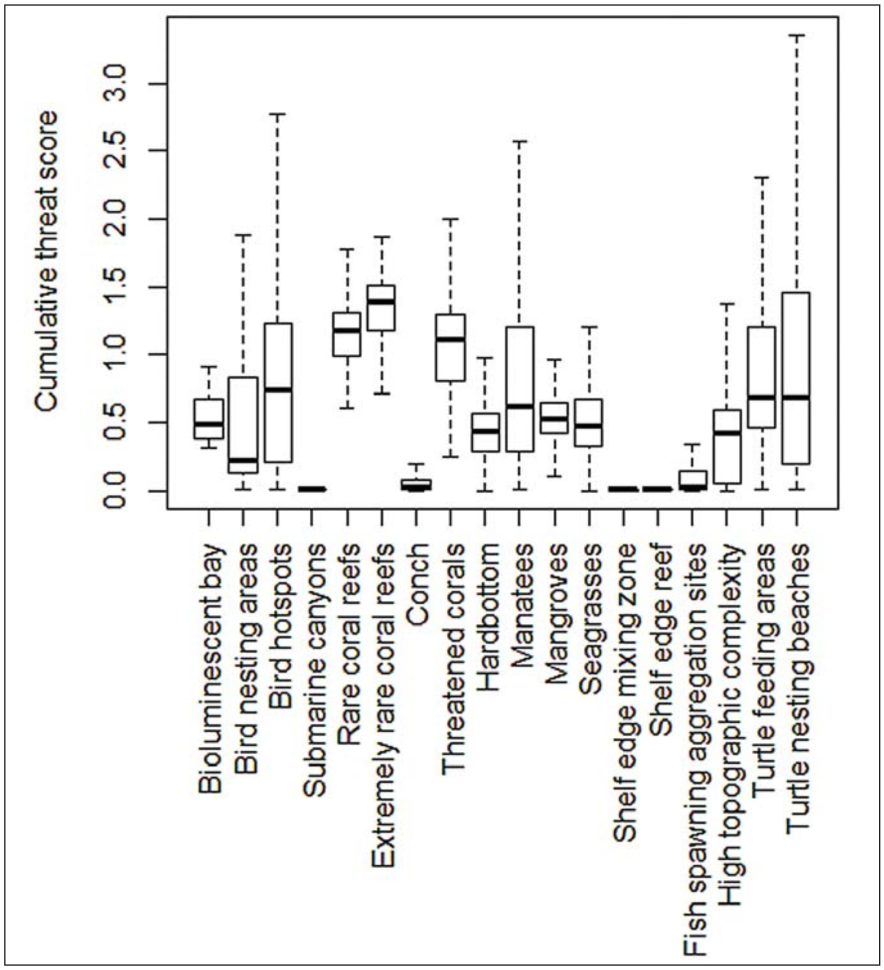


Figure 35. The distribution of cumulative impact scores for each ecological attribute in our analyses. Distributions are displayed as box-and-whisker plots.

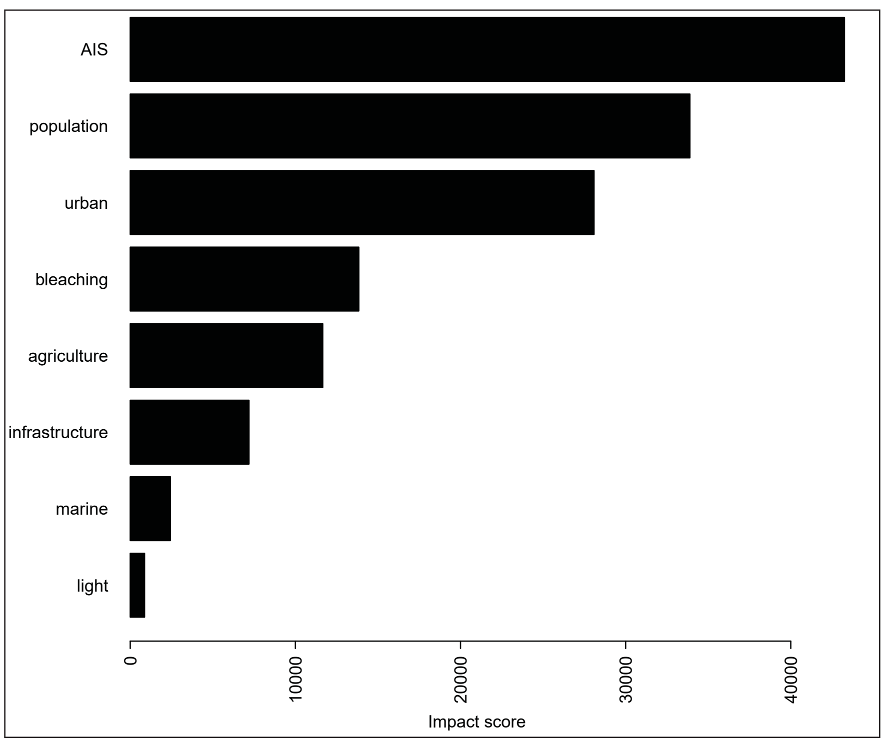


Figure 36. Total area affected (km^2) and summed threat scores for each human impact.

Chapter 3: Synthesis - Integration analyses to prioritize areas of special interest

In this chapter, eleven "areas of special interest" (ASI) were determined by spatially integrating important areas identified through empirical measurements and spatial models (Chapter 2). These ASI represent places with relatively high numbers of ecological elements.

Relatively large (>10 km^2) contiguous areas with the greatest relative number of ecologically important elements were encircled and highlighted as ASI (Figure 37). The total number of ecological elements within each analysis unit was counted separately for elements identified by empirical measurements and for those identified by local experts. Element totals in the top 10% of each distribution were used to determine units with the greatest relative number of ecologically important elements. Element totals greater than or equal to five represented the top 10% of distributions for empirical measurements. Element totals greater than one represented the top 10% of distribution for expert opinions. ASIs were purposefully chosen to represent generalized areas, and not from spatially explicit definitions of ecologically important areas. The generalization of spatial borders implicitly integrates uncertainties in data completeness and spatial accuracy. The generalization was also intended to compel managers to look more closely at the inherent caveats and data patterns within an ASI.

It is critical to understand that locations external to ASI should not be considered lacking in importance. Much of the project area possesses one or more mapped ecologically important element, and consequently could be considered ecologically important depending on local management objectives. This analysis identified areas with the greatest concentration of important ecological elements and highlighted places where information from empirical measurements coincides with priority sites defined by experts. Furthermore, it is important to consider that the spatial pattern of priority areas will likely change as new data becomes available, and these changes may adjust management decisions. To ensure decisions are relevant it is important to repeat conservation planning every several years or after a large contribution of new data. The analytical framework developed here could easily be repeated with new data.

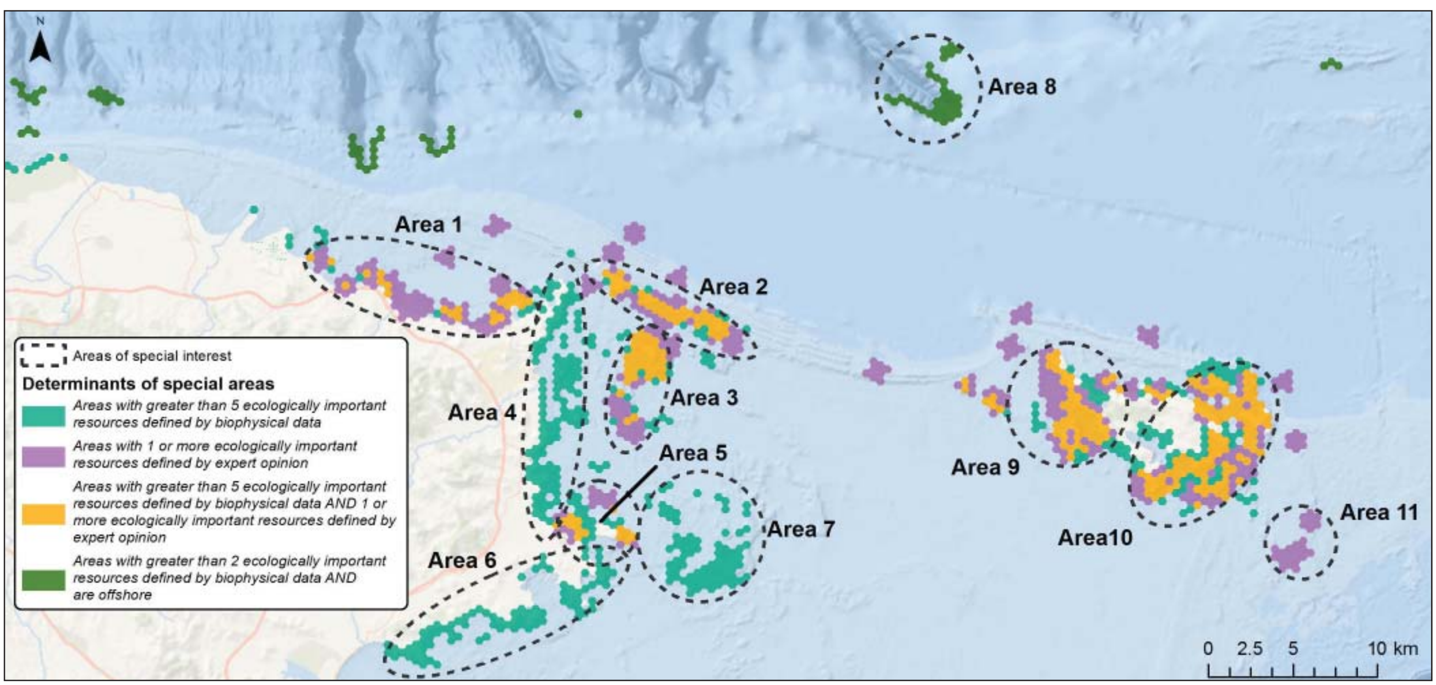
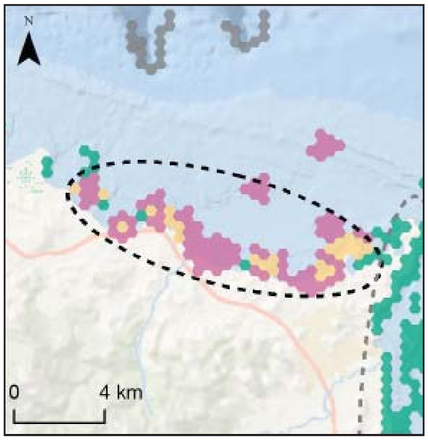
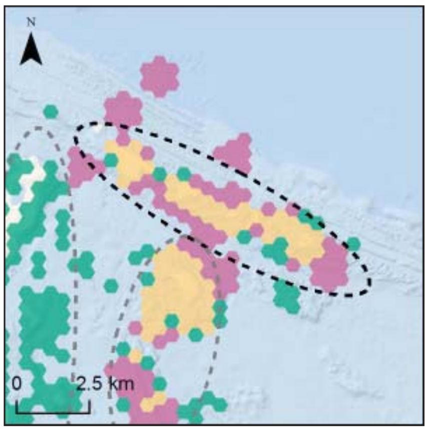


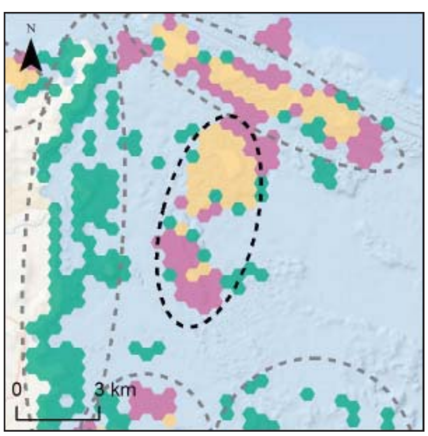
Figure 37. Eleven areas of special interest were identified based on expert knowledge and biophysical data, as well as combining both expert knowledge and biophysical data.



Area 1 - Nearshore northeastern coast near Luquillo:
This area was highlighted by experts as being especially important for sea turtles. The vast majority of beaches in this area are turtle nesting sites and there are large nearby turtle feeding areas. There are numerous nearshore patch reefs and broad swaths of hardbottom habitat offshore. The eastern edge of this special area has high topographic complexity. Additional important resources identified in this area include: endangered corals, bird concentration areas, bird breeding areas, seagrass beds and mangroves. This area is well understood by experts and the benthic habitats have been thoroughly mapped. There are few human impacts to most important resources; however, some turtle nesting beaches are likely impacted by relatively high light levels emanating from the city of Luquillo.

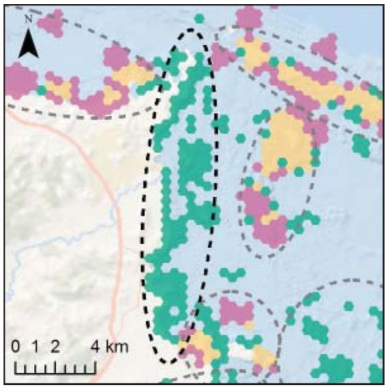


Area 2 - La Cordillera:
This area is characterized by a band of small islands, cays and breakers surrounded by large breadths of hardbottom habitat, much of which is pavement. Both experts and the empirical measurements define this area as having an abundance of ecologically important resources, especially an abundance of corals and fishes. The area has one the highest recorded densities of ESA coral sightings in the region. This density is likely attributable to the greater amount of survey effort in the area, but nevertheless this area includes the greatest known inventory of federally protected coral species in the region. The islands and cays serve as important nesting areas for many birds, the softbottom habitats are important for conch, and some of the coral reefs host spawning aggregation sites for at least one grouper species, snappers and parrotfishes. The area experiences a high degree of impacts from recreational activities due to its proximity to mainland Puerto Rico, but has few other impacts. Depending on which places are included in this spatial area, the western and southern edges could be affected by high shipping traffic and a higher probability of ship groundings.

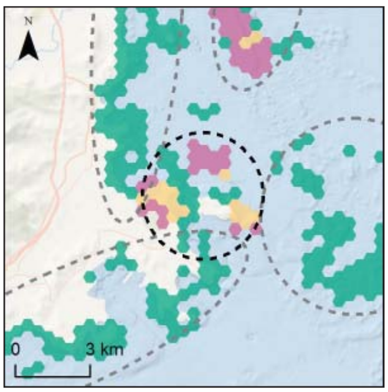


Area 3 - Isla Palominos:
This special area is located several kilometers off the coast of Fajardo. It includes Isla Palominos and Cayo Largo among many other offshore islands and cays. The area comprises many coral reefs, some sea turtle nesting beaches and a turtle feeding area. The northern area also includes habitat for conch, several spawning aggregation sites, and many observations of ESA corals. Many of the important resources coming from the empirical measurements are distributed in the northern half of this area, but experts agreed the southern half was a priority area with many fishes and corals, and high biodiversity. Although this area is several kilometers from the mainland, it receives a relatively high degree of human impact from recreational activities. In addition, several major vessel thoroughfares cross the areas.

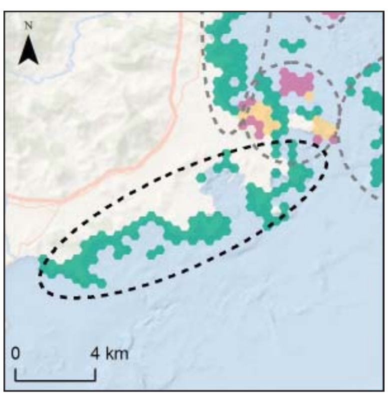
Synthesis



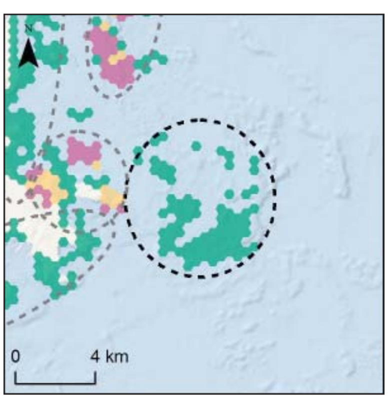
Area 4 - Eastern coast of Puerto Rico:
This area includes many important resources mapped by empirical biophysical data, but did not include priority sites defined by experts. There are relatively few hardbottom habitats or coral reefs in the area, and those which occur in the area are offshore. The important resources in this area are predominantly associated with a rare estuarine habitat, manatees, birds and turtles. This special area includes a rare bioluminescent bay which attracts many recreationists every year, and approximately one third of the region's mapped extents of turtle feeding and manatee concentration areas. In addition, more than half of the coast supports important bird habitats, turtle nesting beaches and mangroves. The area is affected most by threats associated with urban development around the city of Fajardo. This special area includes the largest expanse of very high cumulative human impact in the study area; however, given the lack of corals, impacts to corals and associated biological communities are low. Urban and agricultural runoff, light, shipping traffic and coastal infrastructure are all relatively high where the Rio de Fajardo enters the ocean.



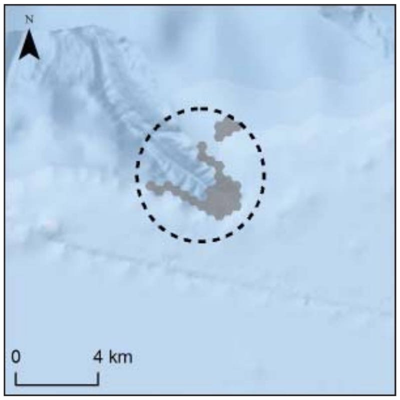
Area 5 - Isla Piñeros:
Both experts and empirical measurements agreed that many important ecological resources were located in this special area. The three surrounding special areas were determined exclusively from empirical measurements. Fish, coral, manatees and turtles are abundant surrounding the offshore islands and the adjacent mainland supports important habitat for many shorebirds. This special area is close to the mainland, but is adjacent to an unpopulated shore and is distant from highly populated urban centers.



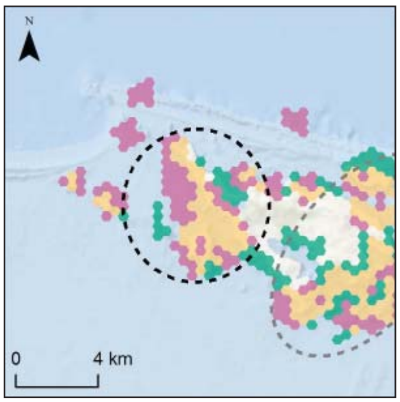
Area 6 - Southeast coast of Puerto Rico:
This area includes Ensenada Honda, Bahia Algodones and the waters off of the former Roosevelt Roads Naval Station. There are few coral reefs or other hardbottom habitats, but many other important resources exist. The vast majority of benthic habitat is classified as seagrass, and much of the coast is covered in dense mangroves. These serve as important habitats for manatees, conch, birds and turtles. Currently, there appear to be few human impacts in this area. Population density is low in nearby towns.



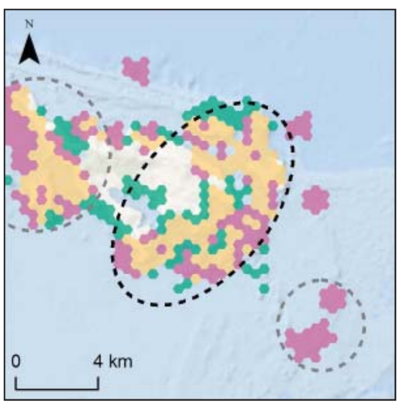
Area 7 - Bajo Chinchorro del Sur:
This special area comprises many offshore reefs and shoals between the mainland and the island of Vieques. This area was not identified as a priority area by experts, but empirical measurements suggest that the area possesses many special coral reefs. A relatively high number of reefs in this area comprise coral cover greater than 50%, a very rare occurrence in the Caribbean. In addition, the area supports conch, ESA corals, and a rich matrix of rugose reefs and seagrass beds. The offshore area has few human impacts. There are no nearby settlements, no polluting rivers and no coastal infrastructure. The greatest risk to important resources comes from shipping activity.



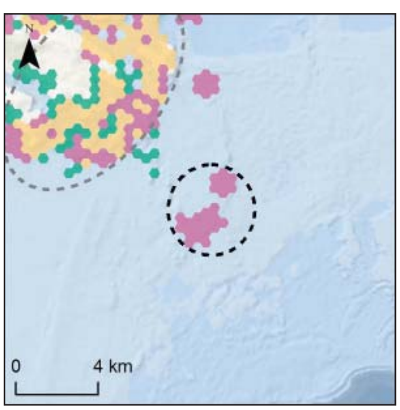
Area 8 - Offshore canyon:
The offshore environment was analyzed separately from nearshore sites, because there are fewer data and the ecosystem is different. This special area comprises the head of an unnamed submarine canyon, a shelf edge reef and multiple spawning aggregation sites for a fished grouper and snapper. Other offshore areas include the same important ecological elements, but this site has the greatest density of overlapping offshore elements. The cumulative human impact in this area is very low. Threats to ecological elements come from vessel traffic and marine pollution, as this site intersects a well-used traffic lane for vessels traveling north of Puerto Rico.



Area 9 - Western Culebra:
This area contains an existing no-take zone, and is extremely abundant in fish, corals, birds and invertebrates. Both experts and the empirical measurements defined this area as possessing abundant ecological elements. The beaches are important areas for sea turtle nesting, and offshore spawning aggregations and large fish are abundant. Cumulative human impact is low to moderate, with most threats attributed to marine pollution and small vessel trips. Much of this area has been a no-take protected area since 1999, as the Canal de Luis Peña Natural Reserve although enforcement has been very inconsistent.



Area 10 - Eastern Culebra:
This area was highlighted as a special area by both the empirical measurements and experts. It includes a barrier reef, bays, and possesses an abundance and variety of birds, fishes and corals, including endangered corals. Several bird sanctuaries are located on Culebra and on the small surrounding islands. Spawning aggregations and large fish are found in deeper waters nearby. Most human impacts are concentrated in Ensenada Honda, a busy recreational port where anchoring is unregulated. Cumulative human impact is low to moderate, with most threats associated with recreational use. Culebra and the offshore island of Culebrita are popular destinations.



Area 11 - Bajos Grampus:
This reef area was defined by experts as having a high abundance and diversity of fish and corals, including endangered species of corals. Empirical measurements were limited in the area, which represents a significant data gap. Several fish spawning aggregations for fished grouper and snapper are located among the shoals. Benthic habitat maps extend up to the edge of this study area, and outline a vast expanse of hardbottom habitat with coral coverage greater than 10%.

Spatial Planning

When combined, the 11 ASI represented approximately 10% of the horizontal ocean space in the project area. In terms of ecological representation, we found that some biological and ecological elements were very well represented by the 11 ASI and others were not. For instance, the bioluminescent bay, turtle feeding areas, areas with coral cover greater than 50%, and areas of high topographic complexity were very well represented. In contrast, shelf edge reef, canyons, and the shelf edge were poorly represented (Table 7).

We also evaluated the 11 areas of special interest based on the four determinants used in the delineation of ASIs:

5. Areas with greater than five biologically and ecologically important elements defined by biophysical data;
6. Areas with greater than one biologically and ecologically important elements defined by expert knowledge;
7. Areas having both of the former criteria; and
8. Off-shore areas with greater than two biologically and ecologically important elements.

The 11 ASIs captured 94% of the areas identified as having more than five biologically and ecologically important elements, 85% of the areas identified as having more than one biologically and ecologically important element by expert knowledge, 97% areas having both, and 42% of areas off-shore with greater than two biologically and ecologically important elements.

Table 7. Proportion and area of biological and ecological elements inside the eleven Areas of Special Interest (ASIs).

Element	Element inside ASI (%)	Hectares within ASI
Bioluminescent Bay	100.00	82
Turtle feeding areas	98.33	5899
Coral cover >50%	97.58	123
Endangered corals	85.73	769 (observations)
Manatee concentration areas	83.82	4677
Topographic complexity	79.39	209
Turtle nesting areas	71.43	1080
Spawning aggregations	57.08	1271
Hard bottom	55.06	7694
Mangroves	48.53	1247
Seagrasses	45.39	9761
Conch hotspots	44.27	16583
Bird nesting areas	37.20	1288
Coral cover >10%	34.07	2984
Bird concentration areas	21.08	1157
Canyons	5.82	1075
Shelf edge	5.82	178
Shelf edge reef	0.75	37

Chapter 4: Data gaps, next steps and future needs

Significant spatial data gaps exist for the northeast region of Puerto Rico. A comprehensive analysis of existing ecological data and corresponding data gaps occurred prior to the selection of data for the prioritization process. Available ecological data were not uniformly distributed in the study area and data gaps occurred where information was absent or biased (Figure 42). Observations of threatened corals are biased to areas where people typically dive, such as around Isla Culebra, Isla Palominos and La Cordillera, and therefore the distributions of threatened corals outside of these areas is an important data gap particularly with regard to conservation planning objectives to protect corals listed under the ESA. Recently funded (NOAA CRCP) projects to predictively map suitable habitat for ESA coral species are currently underway. Areas outside of the 2015 benthic habitat map that were mapped from 1999 aerial photographs had large areas of unknown habitat. These earlier maps also did not provide sufficient resolution data to identify classes of: rare coral reefs, extremely rare coral reefs and high topographic complexity reefs. Furthermore, many areas of seagrass were either unmapped or mapped with high classification error. Additional mapping efforts are required to address these gaps. Data gaps for coral and hardbottom habitats may extend to approximately 100 m given the depth limits reported for these resources (García-Sais et al., 2007), and the data gap for seagrasses is expected to extend to the 37 m isobath, the maximum reported depth of seagrass distribution in the Caribbean (Fonseca et al., 1992; Miller and Lugo, 2009). Observations over deep water reefs in the northeast region show existence of important high coral cover areas that provide essential fish habitat for commercially valuable species of fish. Data gaps associated with deeper coral habitats are significant because they likely encompass mesophotic reefs, which are regionally important (Lesser et al., 2009; García-Sais et al., 2007). Distributions for the remaining resources are not dependent on benthic habitat maps nor are they expected to occur outside of the boundaries of benthic maps. Very little spatial data was available to assess the distribution of exotic and invasive species, such as lionfish and the seagrass *Halophila stipulacea*. Very little is also known about the patterns of loss and gains in mangrove and seagrass distributions, as well as the drivers of change for these vulnerable shallow water habitats. Data on cetaceans, and for areas at sea that are important to rare and endangered seabirds, require additional survey and investigation.

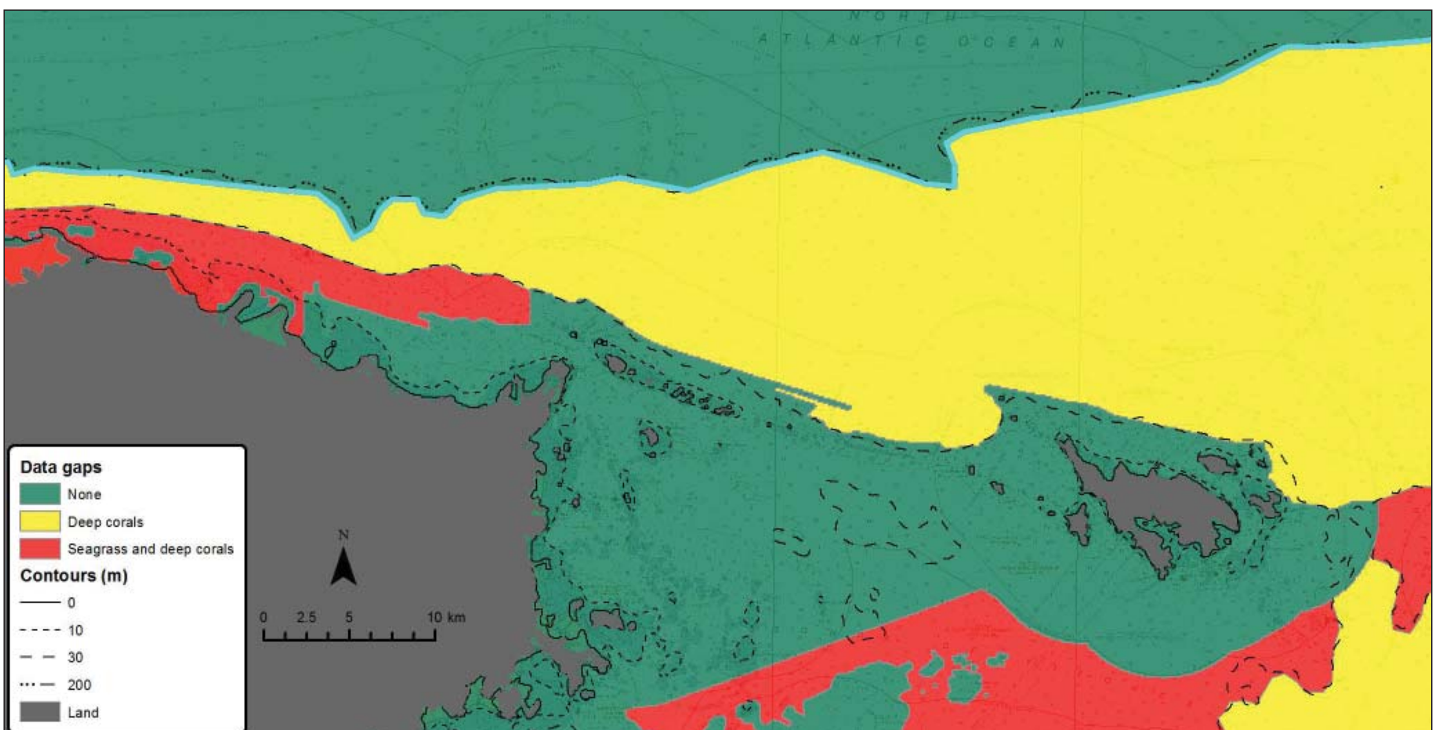


Figure 42. Map of data gaps in this study. Categories represent the extent of 1999 and 2015 benthic habitat maps in relation to the 37 m and 100 m depth limits for seagrass and deep coral reef habitats, respectively.

Data Gaps and Future Needs

In addition, major data gaps exist in our knowledge of ecological connectivity across the region. Addressing these knowledge gaps requires the development of three-dimensional hydrodynamic models of current circulation combined with particle tracking models which incorporate organism behavior. Managers need to identify the movement of organisms across the region, particularly coral larvae. There is considerable interest in understanding the connectivity between coral reefs of Culebra, the La Cordillera reefs and the mainland coastal reefs. For example, where are the strongest connections between sources and sinks for coral supply and settlement? This information is necessary to predict potential geographical patterns of recovery from disturbance and is critical for implementing an ecosystem-based approach to manage the interconnected corridor of protected areas in northeast Puerto Rico.

Data gaps also exist in our understanding of human uses and exposure to stressors across the region. Few direct field measurements of turbidity exist. Furthermore, surveys which include human use mapping are required in order to estimate carrying capacity across the spatially complex region, particularly with regard to the locations of the most sensitive marine habitats and species.

In summary, the information presented in this report provides a comprehensive review and analysis of available data for the Puerto Rico Northeast Marine Corridor. The data described herein also provides a useful baseline for assessing the current status of ecological priorities and threats within the boundaries and adjacent to the Marine Corridor. Furthermore, this report and the accompanying spatial data provide an information-based foundation upon which a comprehensive stakeholder supported management plan can be developed.

Ball, I.R. and H.P. Possingham. 2000. Marxan (V1.8.2): Marine reserve design using spatially explicit annealing: A manual prepared for the Great Barrier Reef Marine Park Authority. University of Queensland. 69 pp.

Burke, L., K. Reytar, M. Spalding, and A. Perry (eds.). 2011. Reefs at Risk Revisited. World Resources Institute. Washington, DC. 130 pp. Online: http://www.wri.org/sites/default/files/pdf/reefs_at_risk_revisited.pdf (Accessed 9 September 2016)

Caldow, C., Monaco, M.E., Pittman, S.J., Kendall, M.S., Goedeke, T.L., Menza, C., Kinlan, B.P. and Costa, B.M., 2015. Biogeographic assessments: a framework for information synthesis in marine spatial planning. Marine Policy, 51, pp.423-432.

CCSP. 2008. Weather and climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands: A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. NOAA National Climatic Data Center. Washington, DC.

CFMC. 1996. Fishery management plan, regulatory impact review, and final environmental impact statement for the queen conch resources of Puerto Rico and the United States Virgin Islands. Caribbean Fishery Management Council. San Juan, Puerto Rico.

CFMC. 1998. Essential fish habitat (EFH) generic amendment to the fishery management plans (FMPs) of the U.S. Caribbean including a draft environmental assessment. Caribbean Fishery Management Council, San Juan, Puerto Rico. 169 pp.

Clark, J.J. and P.R. Wilcock. 2000. Effects of land-use change on channel morphology in northeastern Puerto Rico. Geological Society of America Bulletin 112(12):1763-1777.

Domeier, M.L. and P.L. Colin. 1997. Tropical reef fish spawning aggregations: defined and reviewed. Bulletin Marine Science 60: 698-726.

Drew, C.A., L.B. Alexander-Vaughn, J.A. Collazo, J.P. Reid, and D.H. Slone. 2012. Science summary in support of manatee protection area (MPA) design in Puerto Rico. North Carolina Agricultural Research Service, College of Agriculture and Life Sciences, College of Agriculture and Life Sciences, North Carolina State University. Raleigh, NC. Technical Bulletin 330.

Dunn, D.C. and P.N. Halpin. 2009. Rugosity-based regional modeling of hard-bottom habitat. Marine Ecology Progress Series 377:1-11.

EPA 2016. Puerto Rico 305(b)/303(d) Integrated Report. Plans and Special Projects Division, Puerto Rico Water Quality Area Environmental Quality Board and U.S. Environmental Protection Agency. 243 pp.

Fonseca, M.S., W.J. Kenworthy, and G.W. Thayer. 1992. Seagrass beds: nursery for coastal species. pp. 141-147. In: R.H. Stroud (ed.), Stemming the tide of coastal fish habitat loss - A Symposium on Conservation of Coastal Fish Habitat. Marine Recreational Fisheries 14. National Coalition for Marine Conservation. 258 pp.

García-Sais, J.R., R. Castro, J. Sabater, M. Carlo, and R. Eteves. 2007. Characterization of benthic habitats and associated reef communities at Bajo de Sico Seamount, Mona Passage, Puerto Rico. Final report submitted to the Caribbean Fishery Management Council. San Juan, Puerto Rico. 91 pp.

Literature Cited

García-Sais, J., Appeldoorn, R., Battista, T., Bauer, L., Bruckner, A., Caldow, C., Carrubba, L., Corredor, J., Diaz, E., Lilyestrom, C. and García-Moliner, G., Hernández-Delgado, E., Menza, C., Morell, J., Pait, T., Sabater, J., Weil, E., Williams, E. and Williams S. 2008. The State of Coral Reef Ecosystems of Puerto Rico. In: J.E. Waddell and A.M. Clarke (eds.), The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

García-Sais, J.R., J. Sabater-Clavell, R. Esteves, J. Capella, and M. Carlo. 2011. Characterization of benthic habitats and associated mesophotic coral reef communities at El Seco, southeast Vieques, Puerto Rico. Final report submitted to Caribbean Fishery Management Council. San Juan, Puerto Rico.

Goenaga, C. 1990. Efecto de huracanes sobre los arrecifes de coral en Puerto Rico. Ponencia ante la Conferencia de Huracanes, junio 7 de 1990, Departamento de Recursos Naturales. San Juan, Puerto Rico. 16 pp.

Gould, W., C. Alarcón, B. Fevold, M.E. Jiménez, S. Martinuzzi, G. Potts, M. Solórzano, and E. Ventosa. 2007. Puerto Rico Gap Analysis Project – Final Report. USGS, Moscow ID and the USDA Forest Service International Institute of Tropical Forestry, Río Piedras, Puerto Rico. 157 pp.

Gould, W.A., S. Martinuzzi, I.K. Pares-Ramos, S.F. Murphy, and R.F. Stallard. 2012. Land use, population dynamics, and land-cover change in eastern Puerto Rico (Chapter B). pp. 25-42. In: S.F. Murphy and R.F. Stallard (eds.), Water quality and landscape processes of four watersheds in eastern Puerto Rico. U.S. Geological Survey Professional Paper 1789. 292 pp.

Griffith, D.G. and M. Valdés-Pizzini. 2002. Fishers at Work, Workers at Sea: A Puerto Rican Journey Through Labor and Refuge. Temple University Press, Philadelphia, Pennsylvania U.S.A.

Halpern, B.S., S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'Agrosa, J.F. Bruno, K.S. Casey, C. Ebert, H.E. Fox, and R. Fujita. 2008. A global map of human impact on marine ecosystems. Science 319(5865): 948-952.

Harborne, A.R., P.J. Mumby, C.V. Kappel, C.P. Dahlgren, F. Micheli, K.E. Holmes, K.E. and D.R. Brumbaugh. 2008. Tropical coastal habitats as surrogates of fish community structure, grazing, and fisheries value. Ecological Applications 18(7): 1689-1701.

Hernández-Delgado, E.A. 2000. Effects of anthropogenic stress gradients in the structure of coral reef fish and epibenthic communities. Ph.D. Dissertation, Dept. Biology, University of Puerto Rico, San Juan, Puerto Rico. 330 pp.

Hernández-Delgado, E.A. and A.M. Sabat. 2000. Ecological status of essential fish habitats through an anthropogenic environmental stress gradient in Puerto Rican coral reefs. In Proceedings of the Gulf and Caribbean Fisheries Institute 51:457-470.

Hernández-Delgado, E.A. 2003. Coral reef ecological change long-term monitoring program of the Luis Peña Channel No-Take Natural Reserve, Culebra Island, Puerto Rico: I. Status of the coral reef epibenthic communities (1997-2003). Tech. Rept. submitted to the US Coral Reef Institute, Department of Natural and Environmental Resources, San Juan, Puerto Rico. 163 pp.

Hernández-Delgado, E.A., C.G Toledo, H. Claudio, J. Lassus M.A. Lucking, J. Fonseca, K. Hall, J. Rafols, H. Horta and A.M. Sabat. 2006. Spatial and taxonomic patterns of coral bleaching and mortality in Puerto Rico during year 2005. Coral bleaching response workshop, NOAA, St. Croix, USVI, p 16

Hernández-Delgado, E.A., R. Hernández-Pacheco, and A.M. Sabat. 2009. Coral reef ecosystem collapse in Puerto Rico: Combined impacts of long-term local anthropogenic factors and climate change. Río Piedras Campus: External Scientific Advisory Committee (ESAC). Online: http://repositorio.upr.edu:8080/jspui/handle/10586/209 (Accessed 7 September 2016)

Hernández-Delgado, E.A. 2010. Puerto Rico coral reef long-term ecological monitoring program: CCRI-Phase III and Phase IV (2008-2010) Final Report. Caribbean Coral Reef Institute, University of Puerto Rico, Mayagüez, Puerto Rico.

Horner, R.R., J.J. Skupien, E.H. Livingston, and H.E. Shaver, 1994. Fundamentals of urban runoff management: Technical and institutional Issues. Terrene Institute: Washington, D.C.

IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, R.K. Pachauri and A. Reisinger [eds.]). IPCC, Geneva, Switzerland. 104 pp.

Kågesten, G., W. Sautter, K. Edwards, B. Costa, L. Kracker, and T. Battista. 2015. Shallow-water benthic habitats of northeast Puerto Rico and Culebra Island. NOAA Technical Memorandum NOS NCCOS 200. Silver Spring, MD. 112 pp.

Kendall, M.S., M.E. Monaco, K.R. Buja, J.D. Christensen, C.R. Kruer, M. Finkbeiner, and R.A. Warner. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA National Ocean Service, National Centers for Coastal Ocean Science, Biogeography Program. Silver Spring, MD. 46 pp.

Klein, C.J., Steinback, C., Watts, M., Scholz, A.J. and Possingham, H.P., 2010. Spatial marine zoning for fisheries and conservation. Frontiers in Ecology and the Environment 8(7):349-353.

Koeneke, R. 2011. Spatial characterization of Puerto Rican commercial fisheries: Gear usage across habitat classes and bathymetry ranges. Open Access Theses. Paper 251. 119 pp.

Larsen, M.C. and R.M.T. Webb. 2009. Potential effects of runoff, fluvial sediment, and nutrient discharges on the coral reefs of Puerto Rico. Journal of Coastal Research 25(1):189-208.

Lesser, M.P., M. Slattery, and J.J. Leichter. 2009. Ecology of mesophotic coral reefs. Journal of Experimental Marine Biology and Ecology 375:1-8.

Maddock, A. and M.J. Samways. 2000. Planning for biodiversity conservation based on the knowledge of biologists. Biodiversity and Conservation 9(8):1153-1169.

Mignucci-Giannoni, A.A. 2006. West Indian manatee (*Trichechus manatus*) mortality analysis for Puerto Rico: 1990-2005. Caribbean Stranding Network. Unpub. Report.

Miller, G.L. and A.E. Lugo. 2009. Guide to the ecological systems of Puerto Rico. United States Department of Agriculture, Forest Service. International Institute of Tropical Forestry. General Technical Report IITF-GTR-35.

Murphy, S.F. and R.F. Stallard (eds.). 2012. Water quality and landscape processes of four watersheds in eastern Puerto Rico: U.S. Geological Survey Professional Paper 1789. 292 pp.

Literature Cited

Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A.B. da Fonseca and J. Kent. 2000. Biodiversity hotspots for conservation priorities. Nature 403 (6772):853-858.

NOAA CRCP. 2010. Puerto Rico's Coral Reef Management Priorities. The Commonwealth of Puerto Rico and NOAA Coral Reef Conservation Program. Silver Spring, MD. Online: http://www.coris.noaa.gov/activities/management_priorities/prico_mngmnt_clr.pdf (Accessed 7 September 2016)

NOAA NCCOS. 2016. National Coral Reef Monitoring Program: Assessment of coral reef benthic communities in Puerto Rico from 2014-05-19 to 2014-12-03 (NCEI Accession 0151729). Version 2.2. NOAA National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. NOAA National Centers for Coastal Ocean Science Dataset. Data website: http://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0151729 (Accessed 9 September 2016)

NOAA NCEI. 2014. U.S. Coastal Relief Model. NOAA National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. Data downloaded May 2014. Data website: http://www.ngdc.noaa.gov/mgg/coastal/crm.html (Accessed 7 September 2016)

NOAA OCS. 2014. Rasterized Nautical Charts. NOAA Office of Coast Survey. Data downloaded May 2014. Data website: http://www.charts.noaa.gov/RNCs/RNCs.shtml (Accessed 7 September 2016)

NOAA ORR. 2014. Download ESI Maps and GIS Data: 2000 Puerto Rico ESI/RSI Maps. NOAA National Ocean Service, Office of Response and Restoration. Data downloaded May 2014. Data website: http://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html#PuertoRico (Accessed 7 September 2016)

NOAA OST. 2015. Interpolated conch hotspots off eastern Puerto Rico. Unpublished data. NOAA Office of Science and Technology. Provided by T. Marshak, October 2015.

Nytch, C.J., W.C. Hunter, F. Núñez-García, C. Fury, and M. Quiñones. 2015. Avian conservation planning priorities for Puerto Rico and the U.S. Virgin Islands. U.S. Fish and Wildlife Service. 410 pp.

Ojeda-Serrano, E., R.S. Appeldoorn, and I. Ruíz-Valentín. 2007. Reef fish spawning aggregations of the Puerto Rican shelf. Final report to the Caribbean Coral Reef Institute. 31 pp.

Pittman, S.J., J.D. Christensen, C. Caldow, C. Menza and M.E. Monaco. 2007. Predictive mapping of fish species richness across shallow-water seascapes in the Caribbean. Ecological Modelling 204(1):9-21.

Pittman, S.J., B.M. Costa and T.A. Battista. 2009. Using lidar bathymetry and boosted regression trees to predict the diversity and abundance of fish and corals. Journal of Coastal Research. Special Issue SI.53: 27-38.

PRCCC. 2013. State of Puerto Rico's Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate, Executive Summary. Puerto Rico Climate Change Council. Department of Natural and Environmental Resources, Puerto Rico Coastal Zone Management Program and NOAA National Ocean Service, Office of Ocean and Coastal Resource Management. San Juan, Puerto Rico. 27 pp.

Ramos-Scharrón, C.E., D. Torres-Pulliza, and E.A. Hernández-Delgado. 2015. Watershed-and island wide-scale land cover changes in Puerto Rico (1930s–2004) and their potential effects on coral reef ecosystems. Science of the Total Environment 506:241-251.

Rodriguez, R.W., R.M. Webb, and D.M. Bush. 1994. Another look at the impact of Hurricane Hugo on the shelf and coastal resources of Puerto Rico, USA. Journal of Coastal Research 1:278-96.

Sadovy de Mitcheson, Y. and B. Erisman. 2011. Fishery and biological implications of fishing spawning aggregations, and the social and economic importance of aggregating fishes. pp. 225-284. In: Y. Sadovy de Mitcheson and P.L. Colin (eds.) , Reef Fish Spawning Aggregations: Biology, Research and Management. Fish & Fisheries Series 35, Springer Netherlands. 622 pp.

Saliva, J.E. 2009. Puerto Rico and its adjacent islands. pp. 82-98. In: P.E. Bradley and R.L. Norton (eds.), An inventory of Breeding Seabirds of the Caribbean. University Press of Florida. 448 pp.

Selkoe, K.A., B.S. Halpern, C.M. Ebert, E.C. Franklin, E.R. Selig, K.S. Casey, J. Bruno, J., and R.J. Toonen. 2009. A map of human impacts to a “pristine” coral reef ecosystem, the Papahānaumokuākea Marine National Monument. Coral Reefs 28(3):635-650.

Sturm, P., R. Viqueira Ríos, and L. Meyer-Comas. 2014. Restoration and Implementation Efforts in Culebra. Ridge to reefs. Protectores de cuencas. Report. 27 pp.

UNEP. 2010. Regional Management Plan for the West Indian Manatee (*Trichechus manatus*) compiled by Ester Quintana-Rizzo and John Reynolds III. CEP Technical Report No. 48. UNEP Caribbean Environment Programme, Kingston, Jamaica.

U.S. Census Bureau. 2012. 2010 Census of Population and Housing, Summary Population and Housing Characteristics. CPH-1-53. Puerto Rico U.S. Government Printing Office. Washington, DC. 475 pp. Online (English): http://www.census.gov/prod/cen2010/cph-1-53.pdf (Accessed 7 September 2016) and Online (Spanish): http://www.census.gov/prod/cen2010/cph-1-53sp.pdf (Accessed 7 September 2016)

USFWS . 2014. Stock assessment report. West Indian Manatee (*Trichechus manatus*). Puerto Rico Stock. U.S. Fish and Wildlife Service, Caribbean Ecological Services Field Office. Boquerón, Puerto Rico. 12 pp.

Waddell, J.E. and A.M. Clarke (eds.). 2008. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. Silver Spring, MD. 569 pp.

Walker, L.A. 1997. Population dynamics of dinoflagellates in two bioluminescent bays: Bahía Fosforescente and Puerto Mosquito, Vieques. M.S. thesis, University of Puerto Rico, Mayagüez. 51p.

Warne, A.G., R.M.T. Webb, and M.C. . 2005. Water, sediment, and nutrient discharge characteristics of rivers in Puerto Rico, and their potential influence on coral reefs. US Geological Survey Scientific Investigations Report 2005–2006, U.S. Geological Survey, Information Services, Denver, CO.

Appendices

Appendix A: Important ecological elements

FISH SPAWNING AGGREGATION SITES

Spawning aggregation sites are essential to the survival of many fishes in the study area. They represent areas where one or more species aggregate to reproduce during specific times of the year, and may represent the only opportunity for a species to reproduce (Domeier and Colin, 1997). Not all fish species form spawning aggregations, but some of the most valuable fisheries in the region are supported by spawning aggregation sites (Sadovy de Mitcheson and Erisman, 2011).

We used an existing data set of spawning aggregation sites developed from interviews with fishermen to define the location of sites (Ojeda-Serrano et al., 2007; Figure A1). The analysis focused on records of groupers, snappers, parrotfish and hogfish. All other records were excluded. Since aggregation sites were defined in UPRs data as points and we expected aggregation sites to represent an area, we expanded the spatial dimensions of each site to an areas defined by a 250 meter radius around each point. These sites were compared to sites identified in other reports (CFMC, 1998; García-Sais et al., 2011), and reviewed by Graciela García-Moliner (CFMC) and Rick Nemeth (University of the Virgin Islands). Most of these sites have not been verified independently through field observations.

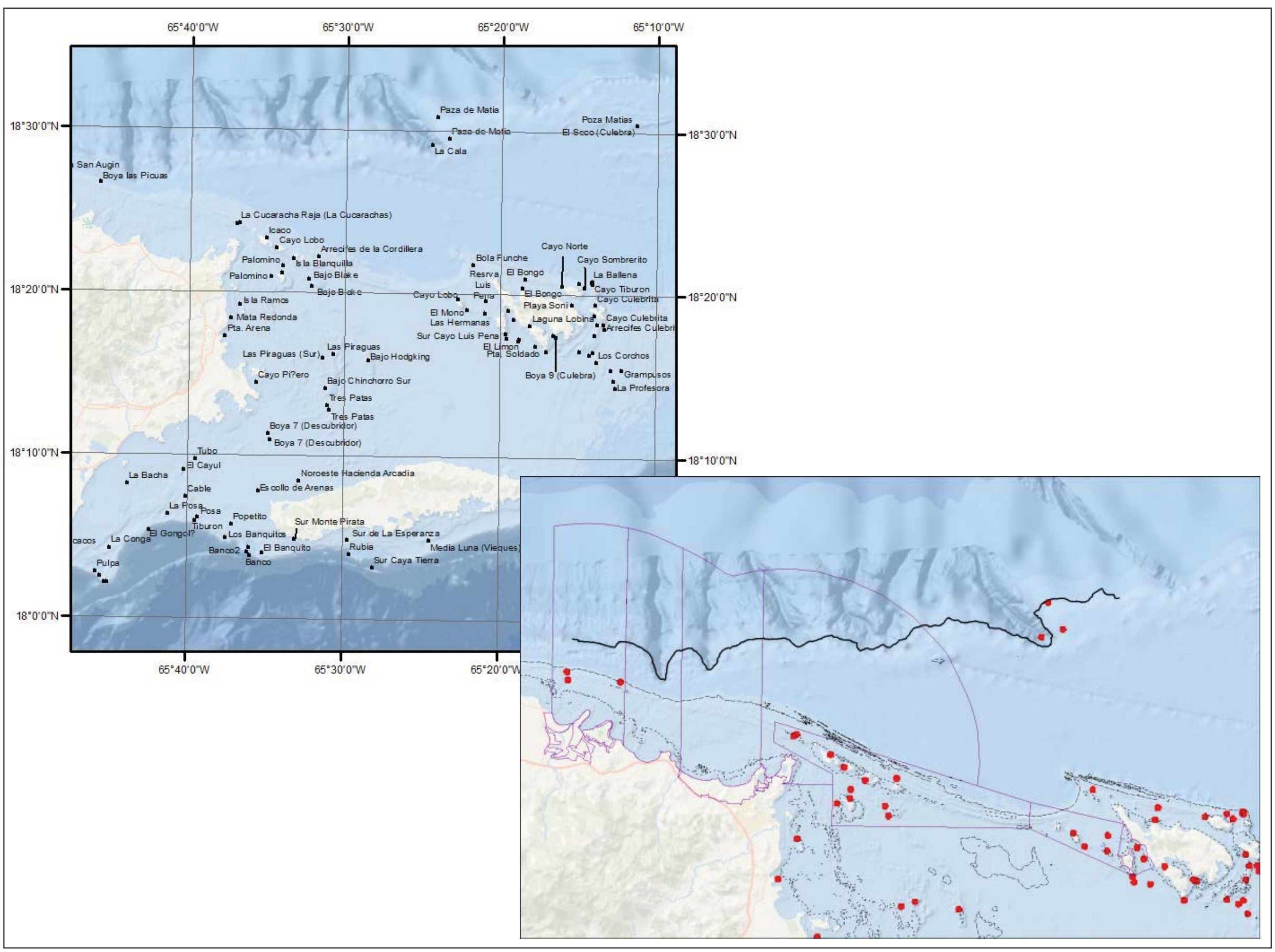


Figure A1. Locations of fish spawning sites reported through interviews with fishers in Puerto Rico conducted by Ojeda-Serrano et al. (2007).

Appendices

THREATENED CORALS

There are seven coral species listed as "threatened" under the Endangered Species Act and which occur in the Caribbean Sea (http://sero.nmfs.noaa.gov/protected_resources/coral/).

These species include: *Acropora palmata*, *Acropora cervicornis*, *Dendrogyra cylindrus*, *Mycetophyllia ferox*, *Orbicella annularis*, *Orbicella faveolata* and *Orbicella franksi*.

We synthesized a compilation of ESA-listed coral observations (Figure A2) from multiple data sources, because there is no single comprehensive survey of ESA-listed corals in the region. The sources included: photos and video surveys collected as part of developing the 2015 NCCOS benthic habitat map, interviews of Puerto Rico dive shops, and observations from 2014 NCRMP data.

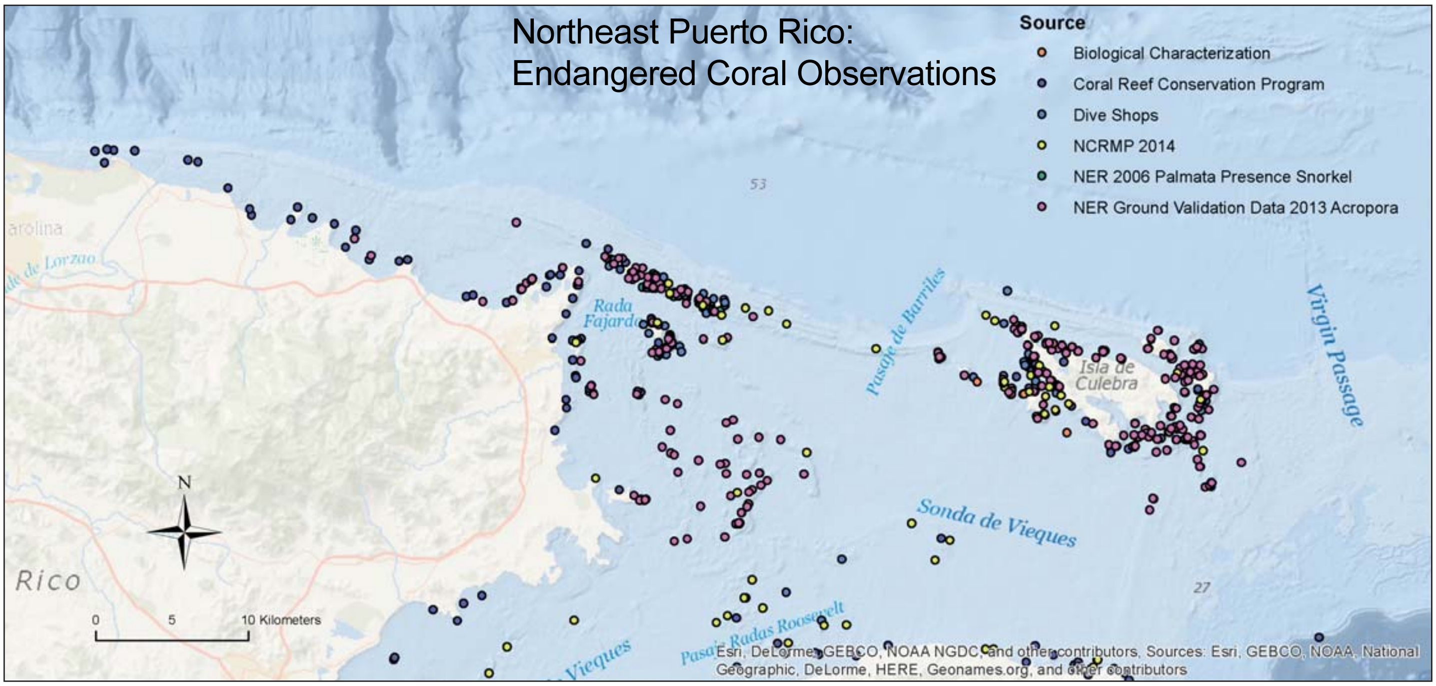


Figure A2. Locations of observed hard corals listed as threatened species by the U.S. Endangered Species Act in 1972.

BIOLUMINESCENT BAY

Bioluminescent bays are rare ecosystems, occurring as a result of a unique combination of topographic patterns, nutrient availability and species biogeography (Walker, 1997). The large bioluminescent bay located north of Fajardo, Puerto Rico, is both unique to the study area and significant for coastal eco-tourism and recreation. We delineated the Bioluminescent Bay by hand using the corresponding waterbody visible in the NOAA rasterized nautical chart.

COASTAL AND OFFSHORE HABITATS

Habitats serve as important integrators of animal and plant communities, and are useful proxies of species and ecological processes which we have limited data. Consequently, habitat protection is a common conservation objective in lieu of species, process and biodiversity data. We identified one coastal, two benthic and three offshore habitats as ecologically important (Figure A3).

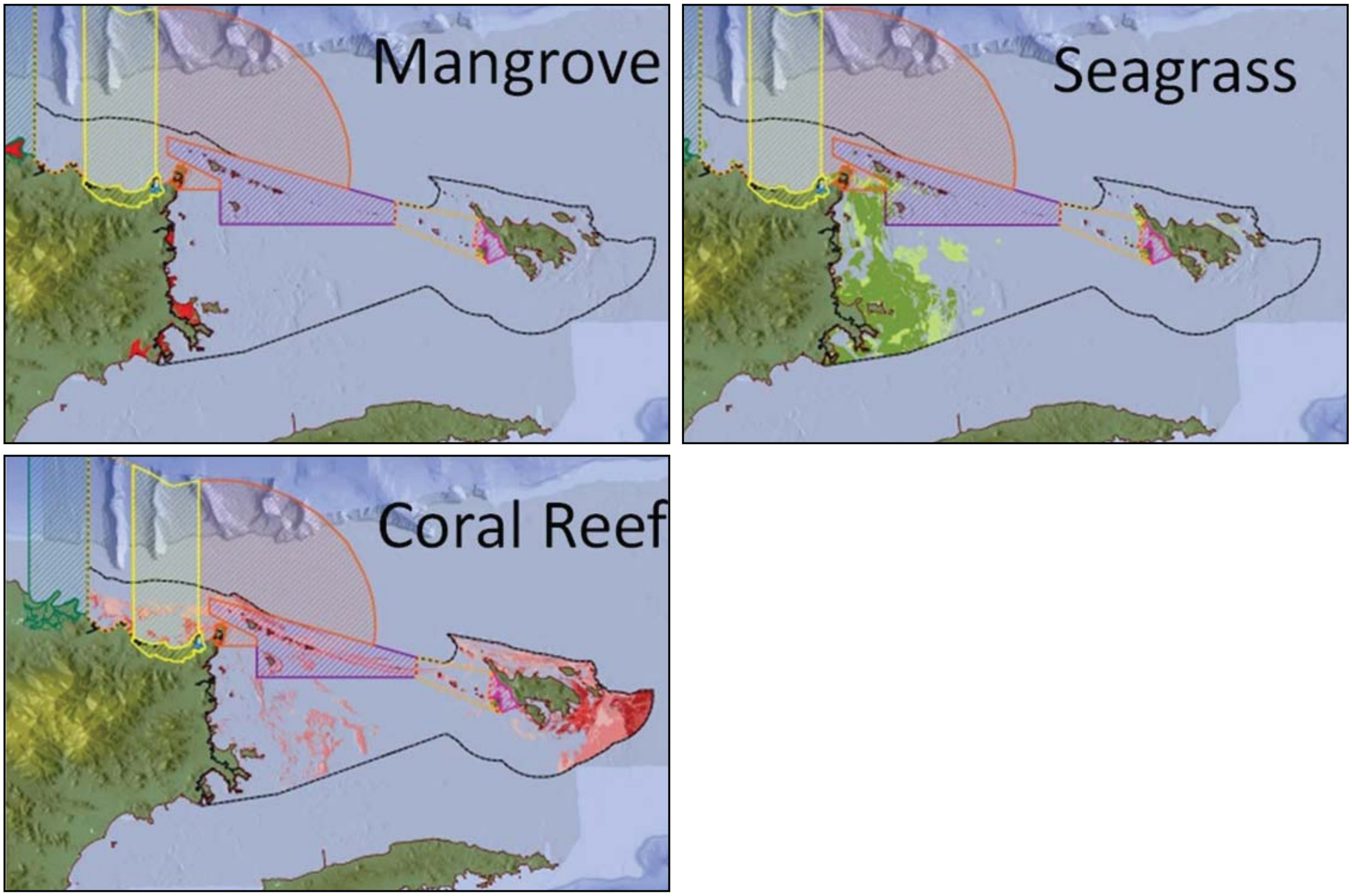


Figure A3. Distribution of priority benthic habitat types, including mangroves, seagrasses and coral reefs based on the benthic habitat map (Kågesten et al., 2015).

Coastal mangroves were derived from two benthic habitat maps (Kendall et al., 2001; Kågesten et al., 2015) using the most recent information where maps overlapped. This composite mangrove dataset represents the best available information on the spatial occurrence of mangroves in northeast Puerto Rico to date. However, a large amount of uncertainty and error (not quantified) remains in the location of mangroves because these features were delineated by different mappers using different classifications schemes and different source data. To qualitatively increase our confidence in the location of mangroves, imagery for the northeast Puerto Rico study area was also compiled in ESRI ArcGIS from three sources: 1) georeferenced imagery collected in 1999 by NOAA NOS National Geodetic Survey and U.S. Geological Survey (USGS); 2) 2007 digital orthophotos collected in 2007 by USACE; and 3) World View 2 Satellite Imagery collected by Digital Globe and obtained from USGS. World View 2 data were used to produce a Normalized Difference Vegetation Index (NDVI = [Red Band - NIR2] /[Red + NIR2]). These images were visually inspected and scanned by two experienced mappers (M. Kendall and T. Battista, NCCOS Biogeography Branch) to further identify mangroves that may not have been captured by previous mapping efforts. An overlay of the composite mangrove layer on top of the NDVI index indicated very high correlation between the polygons identified in existing habitat maps. Seagrass and hardbottom habitats were defined by the maps developed by et al. (2001) and Kågesten et al. (2015). Mapped habitat types of seagrass on unconsolidated sediment, and coral reef and hardbottom were used to select corresponding habitats. The most recent data were used where habitat maps overlapped.

Submarine canyons, the shelf-edge and shelf-edge reefs are offshore habitats expected to have high biodiversity, because they can concentrate nutrients and energy. These habitats were delineated by hand, digitizing their shapes using the NOAA coastal relief model and, wherever possible, the newly acquired bathymetry data collected from the R/V Nancy Foster. Submarine canyons were clearly visible by mapping bathymetric contours and delineating depressions between 200 m and 1000 m. The shelf edge was defined as the band between 100 m and 200 m, identifying only the upper portion of the insular shelf edge. Shelf edge reefs were defined by local bathymetric maxima adjacent to the shelf edge, where the seafloor was higher than the surrounding seascape. The shelf edge reefs commonly occurred between 50 m and 35 m, whereas the surrounding seascape was greater than 50 m deep.

AREAS OF HIGH CORAL COVER

Coral is a quintessential resource of Caribbean coral reefs. Coral abundance and diversity are drivers of ecosystem productivity and biodiversity. It is estimated that coral cover was commonly an order of magnitude greater than its current average in the Caribbean Sea. To represent areas with greater than average coral cover, reefs with greater than 10% and 50% live coral cover were identified (Figure A4). Each threshold was used to develop separate ecosystem resource maps. Coral cover estimates came from the 2015 NCCOS benthic habitat map (Kågesten et al., 2015).

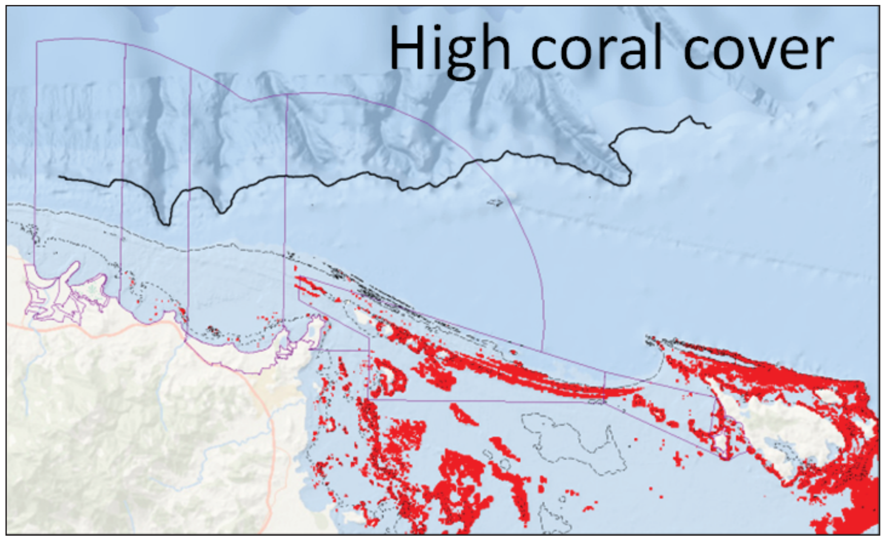


Figure A4. Locations of coral reefs with greater than average live coral cover using the benthic habitat map (Kågesten et al., 2015).

AREAS WITH HIGH RUGOSITY

Reef rugosity has been linked to greater coral and fish diversity (Pittman et al., 2007; Pittman et al., 2009). We mapped areas of high rugosity using the high terrain complexity resource in the NCCOS benthic habitat map (Kågesten et al., 2015). Areas of high rugosity are especially useful to identify areas with the potential for high coral cover, but which now support few corals.

IMPORTANT AREAS FOR BIRDS, TURTLES AND MANATEES

We describe important areas for birds, manatees and turtles together because similar synthesis processes and data were used to define corresponding special places. For all three taxonomic groups we relied heavily on ESI data for Puerto Rico, which defines areas essential to the survival of birds, manatees and turtles (http://response.restoration.noaa.gov/maps-and-spatial-data/environmental-sensitivity-index-esi-maps.html). Since all ESI data were produced in 2001, we verified accuracy of important places using more recent data from the 2007 Puerto Rico Gap Analysis Project, subject matter expert opinions, and peer-reviewed papers. Important places for birds were identified based on nesting sites and areas of high concentration recorded in ESI data. These areas corresponded to locations noted by Salva (2009). Important areas for sea turtles (Figure A5) were identified using ESI data and expert opinion to locate nesting beaches and feeding areas. Data from experts were originally received on paper maps. They were digitized and buffered with a 400 m range to account for potential mapping error due to the scale of the paper maps. The ESI and expert opinion data were then merged creating a new synthesis data set. Important areas were not distinguished according to species usage, as requested by experts. Important areas for manatees were identified by mating and calving areas in ESI data. Manatee distributions here showed similar spatial distribution patterns as found by Drew et al. (2012), who used animal tagging studies to determine special places.

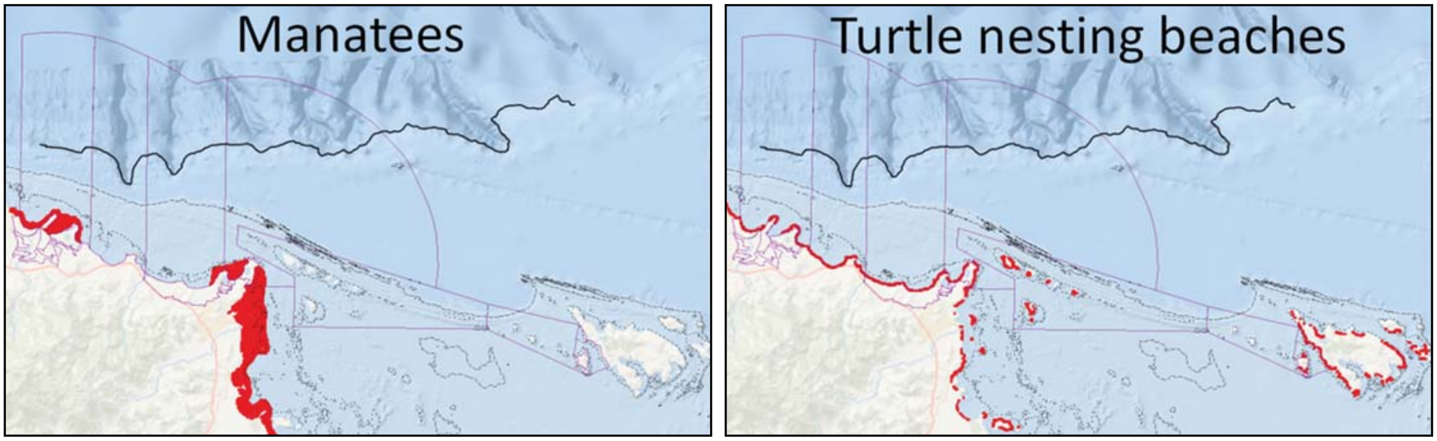


Figure A5. Manatee distributions and turtle nesting beaches based on local expert knowledge and sightings.

Table A1. Locations of nesting seabirds in the northeast Puerto Rico region. Compiled from records reported in Saliva (2009). Population status codes: PCL - Local Population Control needed to conserve other higher priority species; PR -Planning and Responsibility; MA – Management Attention; CR – Critical Recovery; IM – Immediate Management needed to reverse decline.

Common name	Status*	Approximate nesting period	Location	Region
Laughing gull	PCL		Cucaracha	Cordilla cays
Sooty tern	PR		La Blanquilla	Cordilla cays
Brown noddy	MA	April - August	La Blanquilla	Cordilla cays
Brown noddy	MA	April - August	Cayo del Agua	Culebra archipelago
Brown noddy	MA	April - August	Cayo Ratón	Culebra archipelago
Brown noddy	MA	April - August	Cayo Yerba	Culebra archipelago
Brown noddy	MA	April - August	Alcarraza	Culebra archipelago
Brown noddy	MA	April - August	Cayo Noroeste	Culebra archipelago
Brown noddy	MA	April - August	Cayo Molinos	Culebra archipelago
Brown noddy	MA	April - August	Cayos Geniquí	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo del Agua	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo Yerba	Culebra archipelago
Audubon’s shearwater	IM	February - July	Alcarraza	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo Lobito	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo Luis Peña	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo Matojo	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo Lobo	Culebra archipelago
Audubon’s shearwater	IM	February - July	Cayo Ratón	Culebra archipelago
Audubon’s shearwater	IM	February - July	Isla Culebrita	Culebra archipelago
White-tailed tropicbird	IM	February - Sept	Cayo Luis Peña	Culebra archipelago
White-tailed tropicbird	IM	February - Sept	Cayo Noroeste	Culebra archipelago
White-tailed tropicbird	IM	February - Sept	Cayo del Agua	Culebra archipelago
White-tailed tropicbird	IM	February - Sept	Cayo Molinos	Culebra archipelago

Table A1. Continued...

Common name	Status*	Approximate nesting period	Location	Region
Red-billed tropicbird	MA	May - Sept	Cayo Luis Peña	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Cayo Ratón	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Cayo Yerba	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Alcarraza	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Cayos Geniquí	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Cayo Molinos	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Cayo Lobito	Culebra archipelago
Red-billed tropicbird	MA	May - Sept	Cayo Matojo	Culebra archipelago
Masked booby	CR	Year round	Cayo Alcarraza	Culebra archipelago
Brown booby	IM	Year round	Alcarraza	Culebra archipelago
Brown booby	IM	Year round	Cayos Geniquí	Culebra archipelago
Red-footed booby	IM	February - June	Cayos Geniquí	Culebra archipelago
Laughing gull	PCL	April - August	Cayo Lobito	Culebra archipelago
Laughing gull	PCL	April - August	Cayo Matojo	Culebra archipelago
Laughing gull	PCL	April - August	Cayos Geniquí	Culebra archipelago
Royal tern	PR	May - July	Cayo Lobito	Culebra archipelago
Royal tern	PR	May - July	Cayo Matojo	Culebra archipelago
Sandwich tern	PR	May - July	Cayo Lobito	Culebra archipelago
Sandwich tern	PR	May - July	Cayo Matojo	Culebra archipelago
Cayenne tern		May - July	Cayo Lobito	Culebra archipelago
Roseate tern	MA	May - July	Cayo Molinos	Culebra archipelago
Bridled tern	PR	April - August	Cayo del Agua	Culebra archipelago
Bridled tern	PR	April - August	Cayo Ratón	Culebra archipelago
Bridled tern	PR	April - August	Cayo Yerba	Culebra archipelago
Bridled tern	PR	April - August	Cayo Lobito	Culebra archipelago
Bridled tern	PR	April - August	Alcarraza	Culebra archipelago
Bridled tern	PR	April - August	Cayo Noroeste	Culebra archipelago
Bridled tern	PR	April - August	Cayo Molinos	Culebra archipelago
Bridled tern	PR	April - August	Cayos Geniquí	Culebra archipelago
Sooty tern	PR	April - August	Cayo Yerba	Culebra archipelago
Sooty tern	PR	April - August	Cayo Noroeste	Culebra archipelago
Sooty tern	PR	April - August	Cayo Molinos	Culebra archipelago
Sooty tern	PR	April - August	Alcarraza	Culebra archipelago
Sooty tern	PR	April - August	Peninsula Flamenco	Culebra archipelago

Appendix B: Human threats to marine ecosystems

VESSEL DAMAGE

Marine based damage from vessels was modeled using intensity of vessel traffic and occurrence of vessel groundings. Vessel traffic information was compiled from the U.S. Coast Guard (USCG) Automatic Identification System (AIS) for the year 2014 (Figure B1). Intensity of vessel traffic was calculated from raw AIS data and transformed using a custom-built R script to measure sum length (m) of ship tracks within 100 m pixels. Line segments with an elapsed time greater than 1 hour or average speed greater than 50 km were not included. The AIS data were log transformed and rescaled between 0 and 1. Vessel groundings were compiled from all reports to the USCG in the study area from 2009 to 2015. Given the uncertainty of grounding coordinates we buffered each coordinate by 200 m, approximately the average spatial uncertainty provided by the USCG across all coordinates (183 m). Areas within the vessel groundings buffer were given a value of 1 in the final marine vessel damage map.

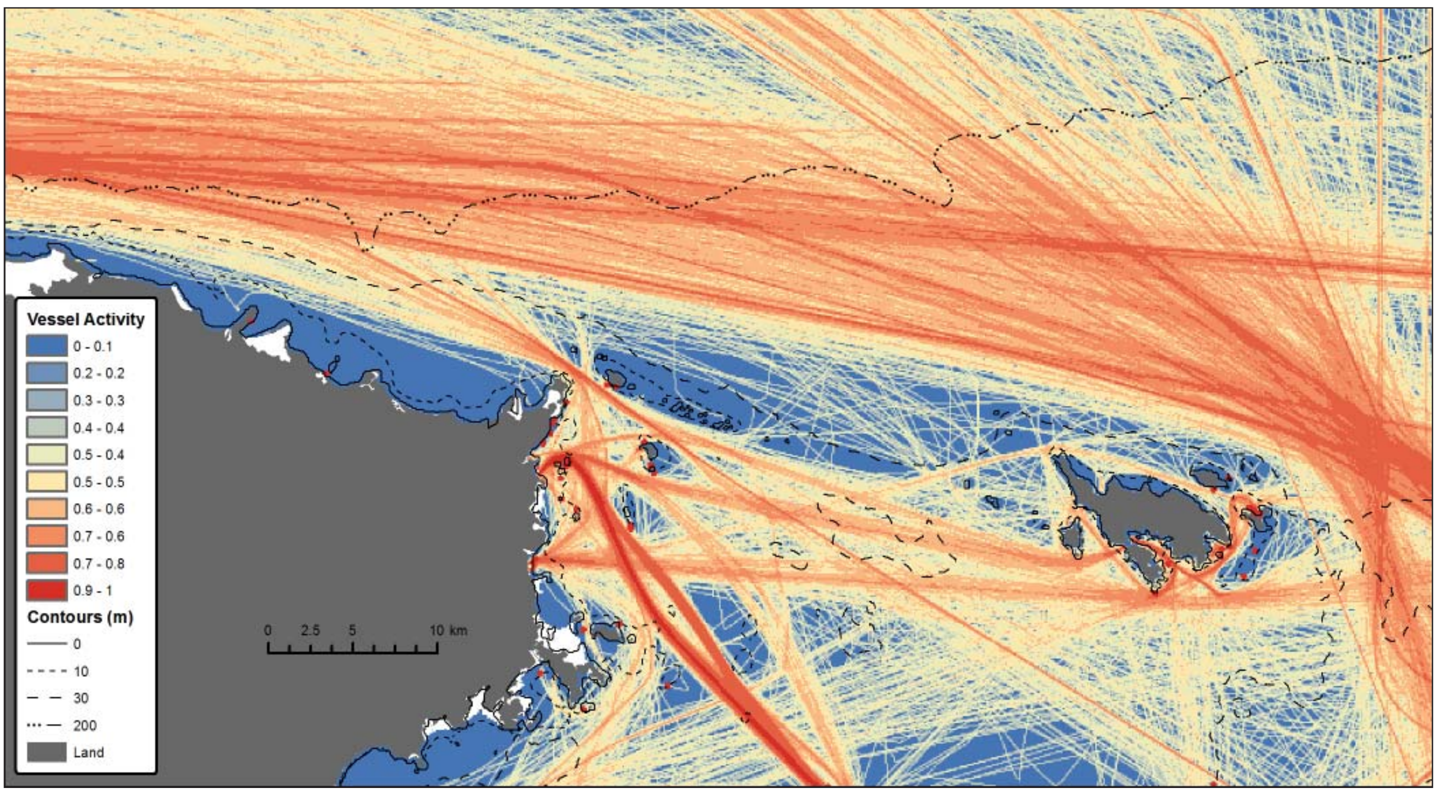


Figure B1. Vessel traffic intensity compiled from the U.S. Coast Guard Automatic Identification System (AIS) for the year 2014.

COASTAL INFRASTRUCTURE DAMAGE

Man-made structures in the ocean and along the shoreline can damage marine habitats directly through physical contact and resource extraction, as well as by disrupting connectivity of migrations or altering natural processes such as sedimentation. The threat of damage from benthic and coastal structures was modeled based on presence of boat ramps, docks, marinas, hardened shoreline, submarine cables, and anchorage areas. These man-made structures and areas of human activity are referred to here as coastal infrastructure. This threat was not intended to represent areas of ocean pollution, for which we have a separate threat layer. The sites of coastal infrastructure were gathered from various sources, including the 2015 NCCOS benthic habitat map and NOAA Nautical Charts. Each infrastructure site was buffered by 100 meters to identify impacts at and within a short distance of the man-made object (Figure B2). This buffer distance may not fully capture coarser scale impacts, such as changes to sediment transportation from piers and hardened shorelines.

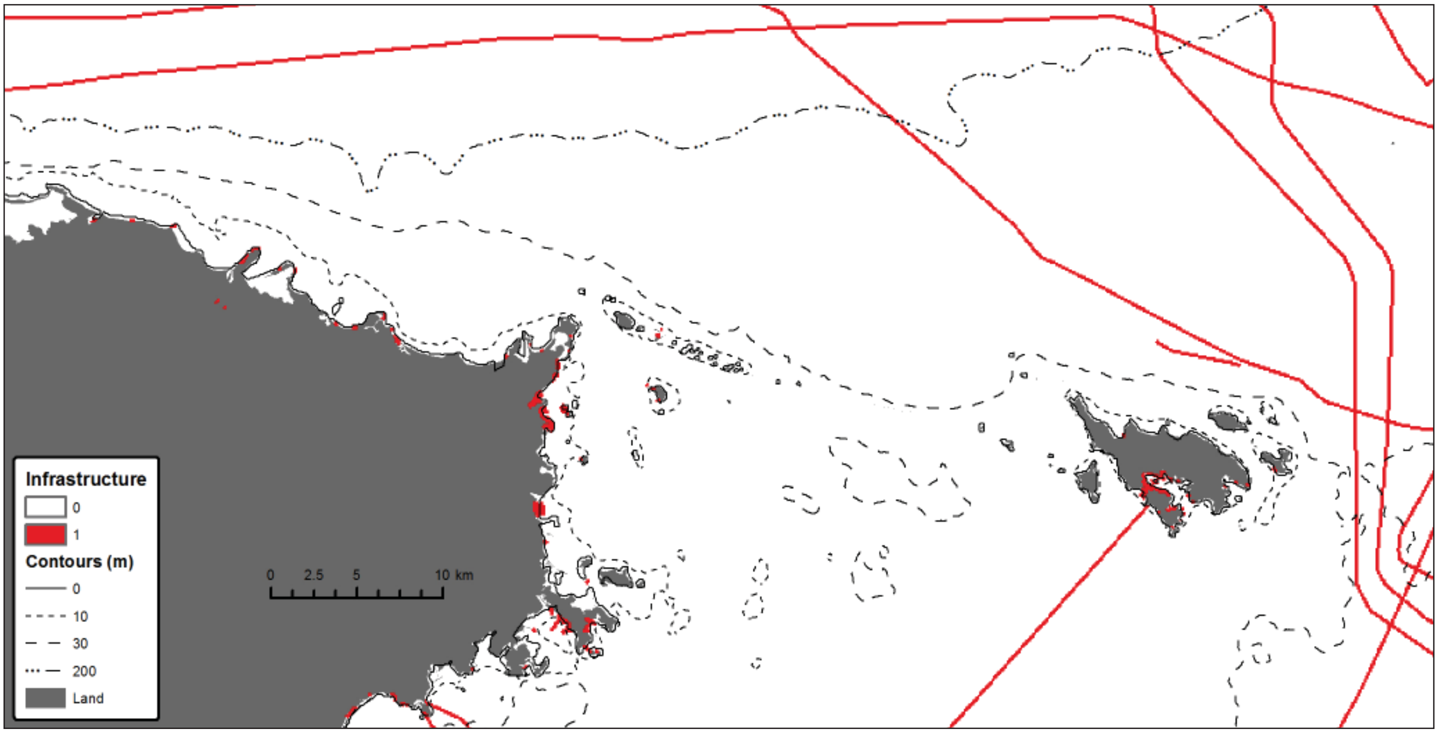


Figure B2. Coastal infrastructure, including presence of boat ramps, docks, marinas, hardened shoreline, submarine cables and anchorage areas.

COASTAL POPULATION PRESSURE

Areas with higher population density near the coast are expected to have more impacts to the marine environment (i.e. sewage discharge, trampling, etc.) than areas with lower population densities. Block-level population densities for the coastal counties within the study area were calculated and converted into a 100 meter-squared raster file. Focal statistics were calculated for 1 km, 2 km and 5 km circular neighborhoods and then the layers were summed to result in a cumulative population pressure layer. The values were transformed using a natural log function and re-scaled with the range of 0 to 1 (Figure B3).

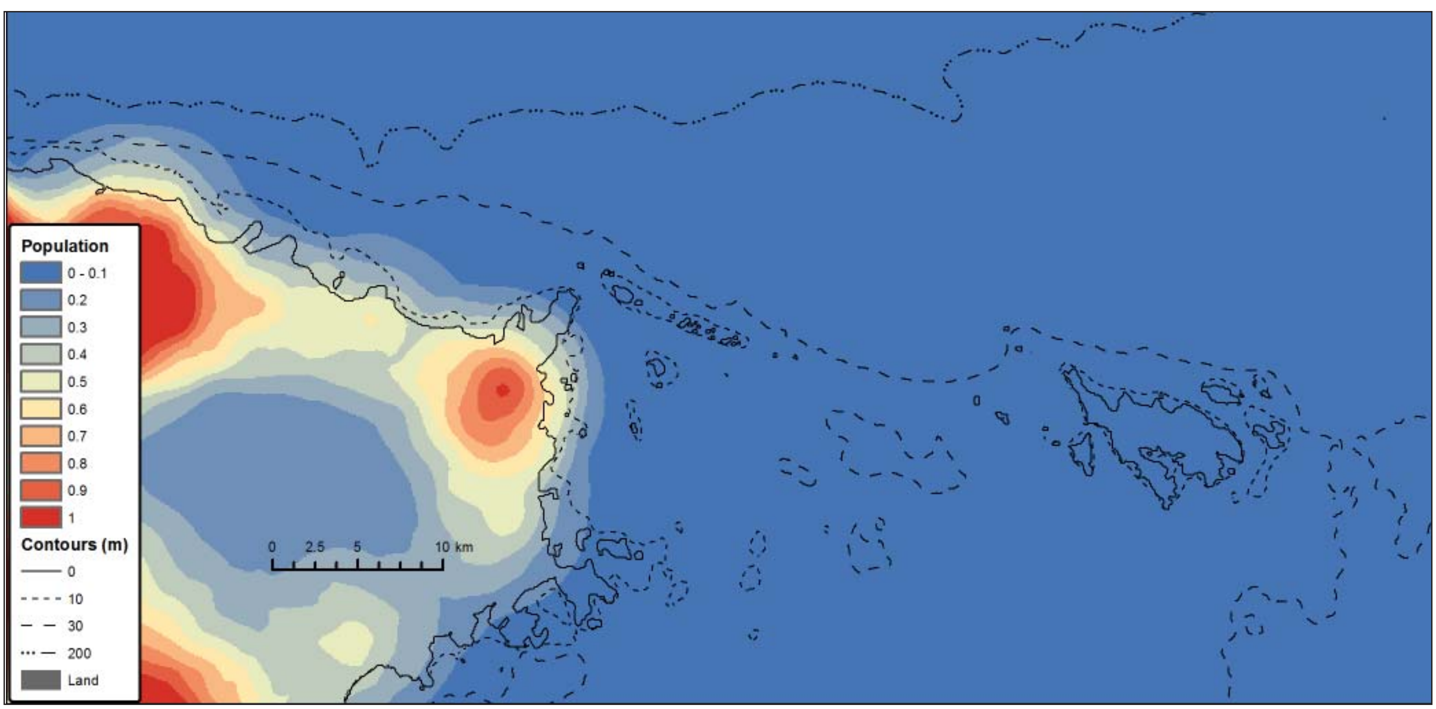


Figure B3. Human population density contours modeled from 2010 U.S. Census Bureau block-level data (Bureau, 2012).

LIGHT POLLUTION

Light pollution can affect the behaviors of photo sensitive animals, such as sea turtles and corals. Visible Infrared Imaging Radiometer Suite (VIIRS) monthly nightlight composites were downloaded from http://ngdc.noaa.gov/eog/viirs/download_monthly.html and light radiance between June 2014 and May 2015 were used to quantify light pollution. This monthly series provides a full annual cycle of light activity on the island. We used the data configuration which excludes any values impacted by stray light. Monthly composites were averaged to produce a single year-long composite. The values were re-scaled to the maximum value in water (Figure B4). Reviewers vetted the year-long composite and deemed it corresponded well to their recollection of light levels on visited beaches.

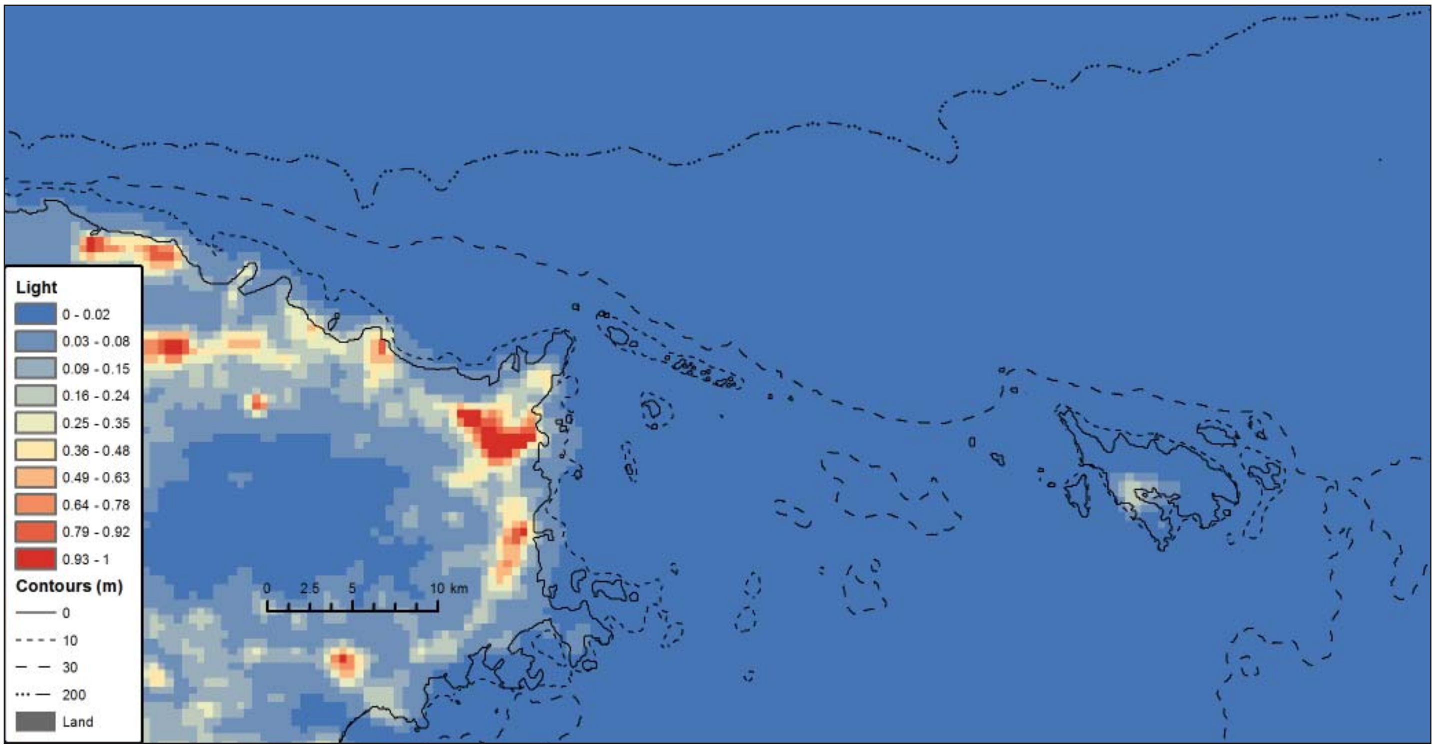


Figure B4. Light radiance from electric lighting acquired from night time satellite data between June 2014 and May 2015.

WATERSHED-BASED POLLUTION

The threat from watershed-based pollutants was quantified by the amount of non-point source nutrient and inorganic contaminant runoff reaching coastal habitats. Non-point source contaminants were estimated by the amount of agricultural and urban land cover within watersheds using existing land cover interpretations from Landsat TM imagery (Gould et al., 2007).

Agricultural land cover was designated by interpreted hay and row crops, and palm plantation land cover classes. Urban land cover was designated by low and high density urban area land cover classes. Both agricultural cover types were summed without weighting, whereas high density urban areas were weighted 10 times higher than low density urban areas to reflect recognized higher inorganic pollution delivery from high-density urban areas (Horner et al., 1994; EPA, 2014).

Pollution delivery to coastal habitats was calculated as the weighted sum of land cover in agricultural (Figure B5) or urban (Figure B6) land cover categories reaching coastal hydrological discharge sites. Discharge sites were determined based on hydrological flow modeled using ArcGIS's "Flow Accumulation" function and the Coastal Relief Model (NOAA National Geophysical Data Center; http://www.ngdc.noaa.gov/mgg/coastal/). Delivery to nearby habitats was extrapolated from discharge sites using overlapping 1 and 3 km buffers (Figures B5 and B6).

Appendices

The buffer distances were calibrated with observed pollution dispersion in the study area. Both buffers were attributed with the estimated discharge at each site, and then intersected to sum values at overlapping buffers. The effect was that coastal areas within 1 km of discharge sites were impacted twice as much as areas 1 to 3 km from discharge sites, and coastal areas could receive contributions from multiple discharge sites.

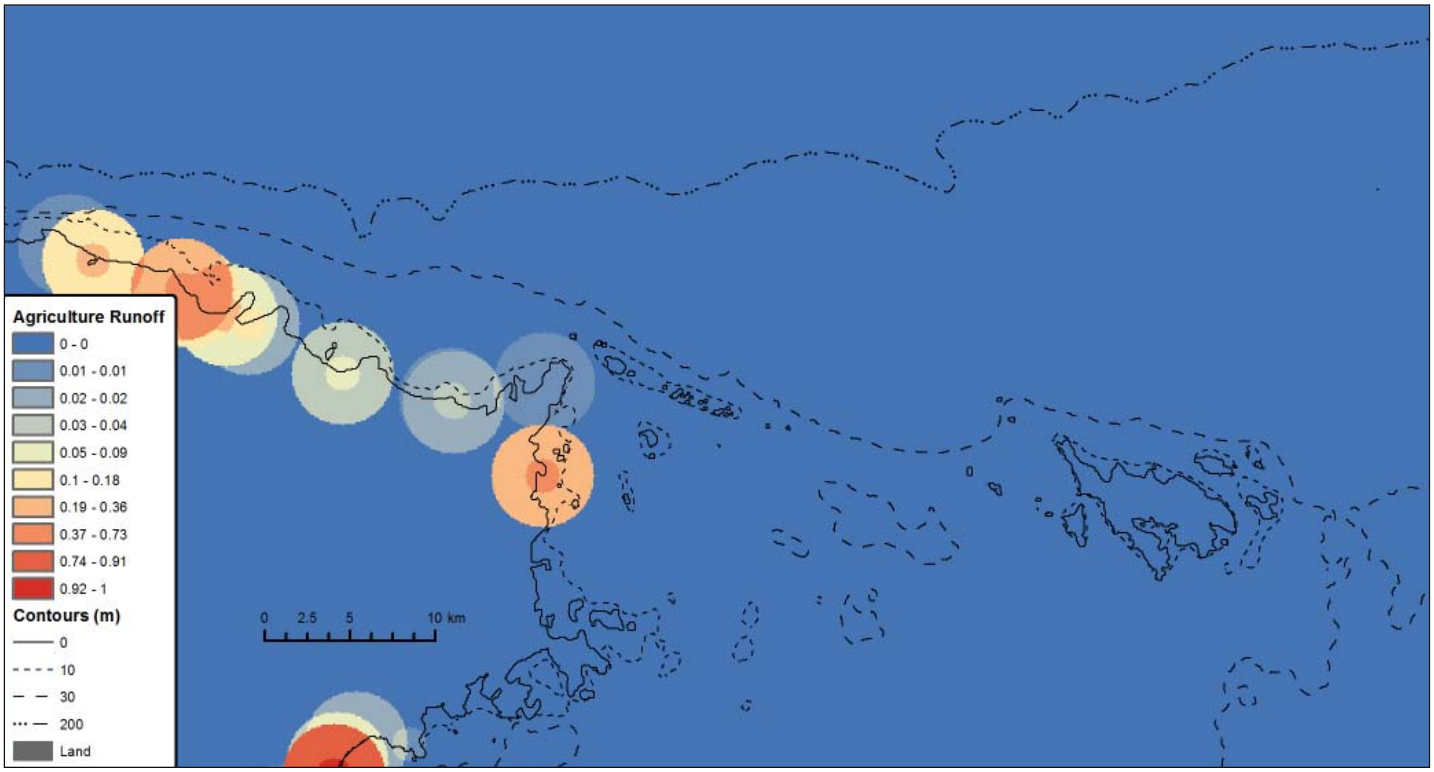


Figure B5. Pollution delivery to coastal habitats calculated as the weighted sum of land cover in agricultural land cover categories.

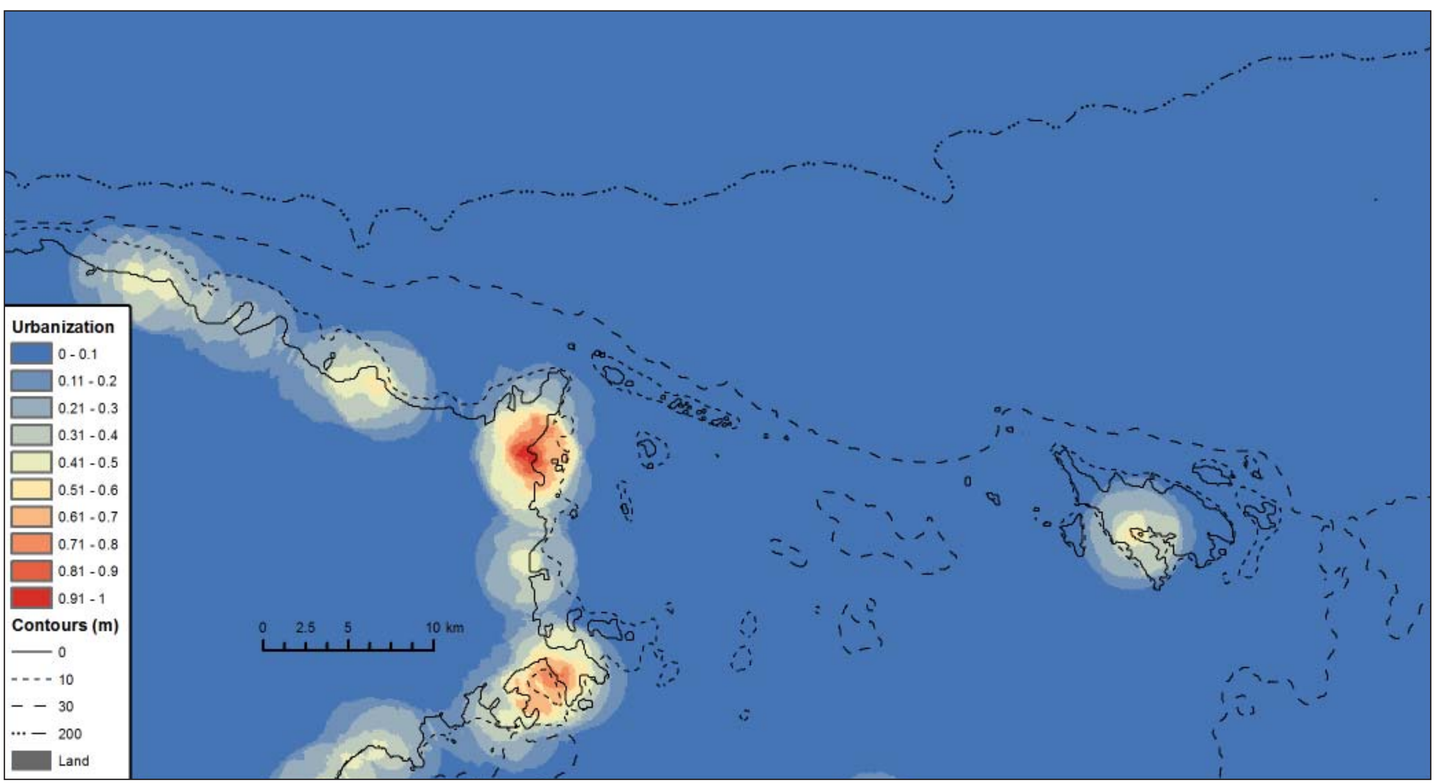


Figure B6. Pollution delivery to coastal habitats calculated as the weighted sum of land cover in urban land cover categories.

MARINE-BASED POLLUTION

Marine-based pollution threatens coastal and marine habitats through flaking anti-fouling paint, sewage discharge from boats, exhaust and oil discharge from engines, and dumping garbage. The threat of marine-based pollution was defined by distance to mooring buoys, docks, marinas, ports, and recreational areas; and the intensity of shipping traffic. Marine features and activities were collected from many geospatial data sources, and combined into an aggregate threat estimate (Figure B7).

The aggregate threat estimate was produced in a five step process. First, mean vessel activity (described above in the Vessel Damage section) was averaged across a 1 km neighborhood across the entire study area. This step created a relative estimate of pollution generated by vessels while underway, whereby more intense activity was estimated to create higher levels of pollution and areas within 1 km of vessel tracks received contributions of pollution. Second, two groups of anthropogenic features were created to define estimated pollution levels. Mooring buoys, docks, marinas, recreational areas, and small-sized ports were combined into a low-level pollution group. Medium-sized ports were separated out into a high-level pollution group. Third, the distance to the closest feature within each group was calculated and aggregated using a weighted sum of their reciprocals. The contribution of medium-sized ports was estimated to be higher than all other features, and the corresponding distance layer was weighted 10 times greater. Finally, the aggregated distance layer was multiplied with the vessel activity layer to produce the aggregate threat estimate of marine-based pollution.

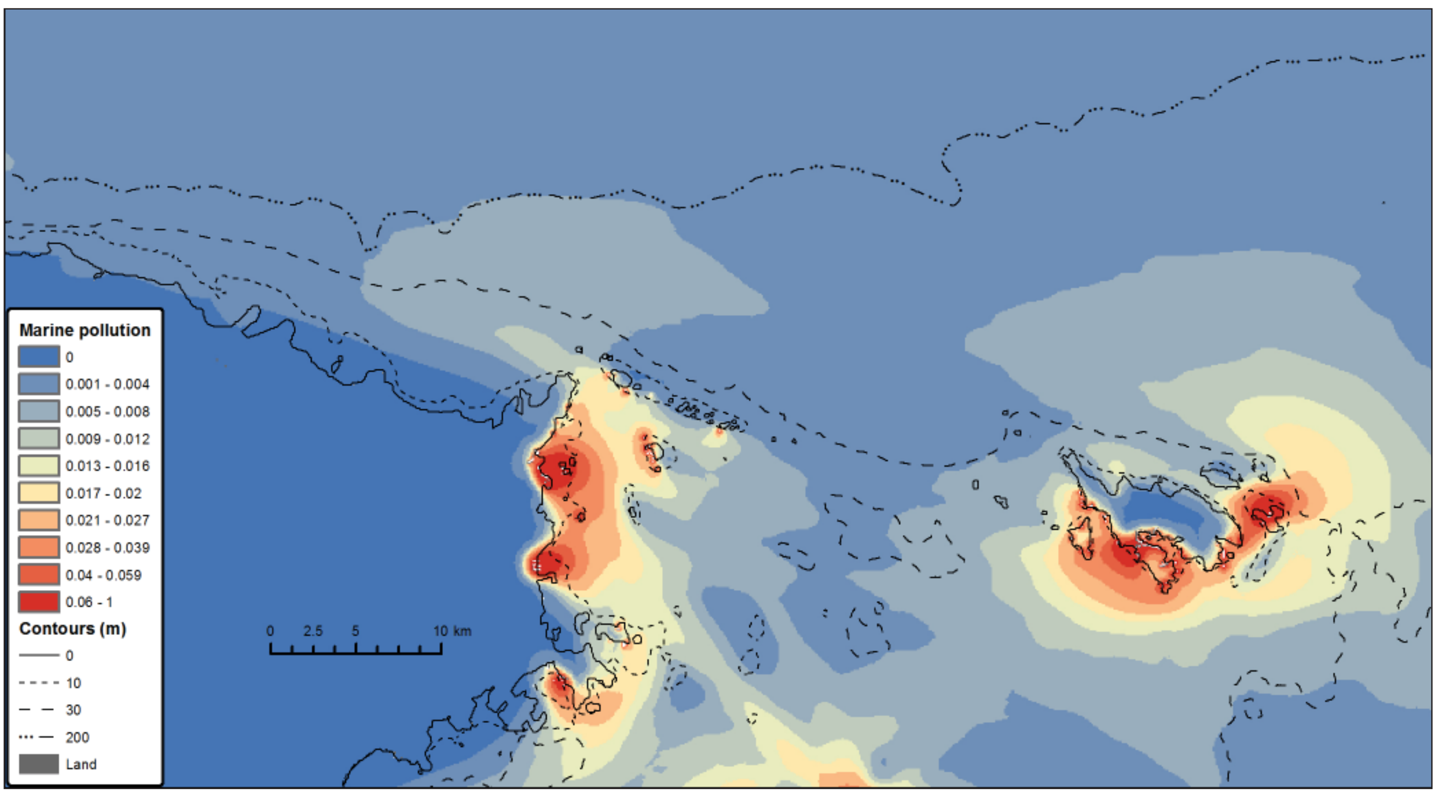


Figure B7. Potential for marine-based pollution defined by distance to mooring buoys, docks, marinas, ports, and recreational areas; and the intensity of shipping traffic.

Appendices

CORAL BLEACHING

Coral bleaching is a sign of coral stress. When water is too warm, corals will expel the algae (zooxanthellae) living in their tissues causing the coral to turn completely white. This is called coral bleaching. When a coral bleaches, it is not dead. Corals can survive a bleaching event, but they are under more stress and are subject to mortality.

Geospatial Caribbean coral bleaching alerts watches, and warnings data from 2013 and 2014 and at 5 km resolution were collected from the NOAA Coast Watch archive. The number of alerts, watches, and warnings were summed to identify areas of higher coral stress. The native resolution of bleaching data sets was used for the derived threat layer. The sum values were transformed using a natural log function and re-scaled with the range of 0 to 1 (Figure B8).

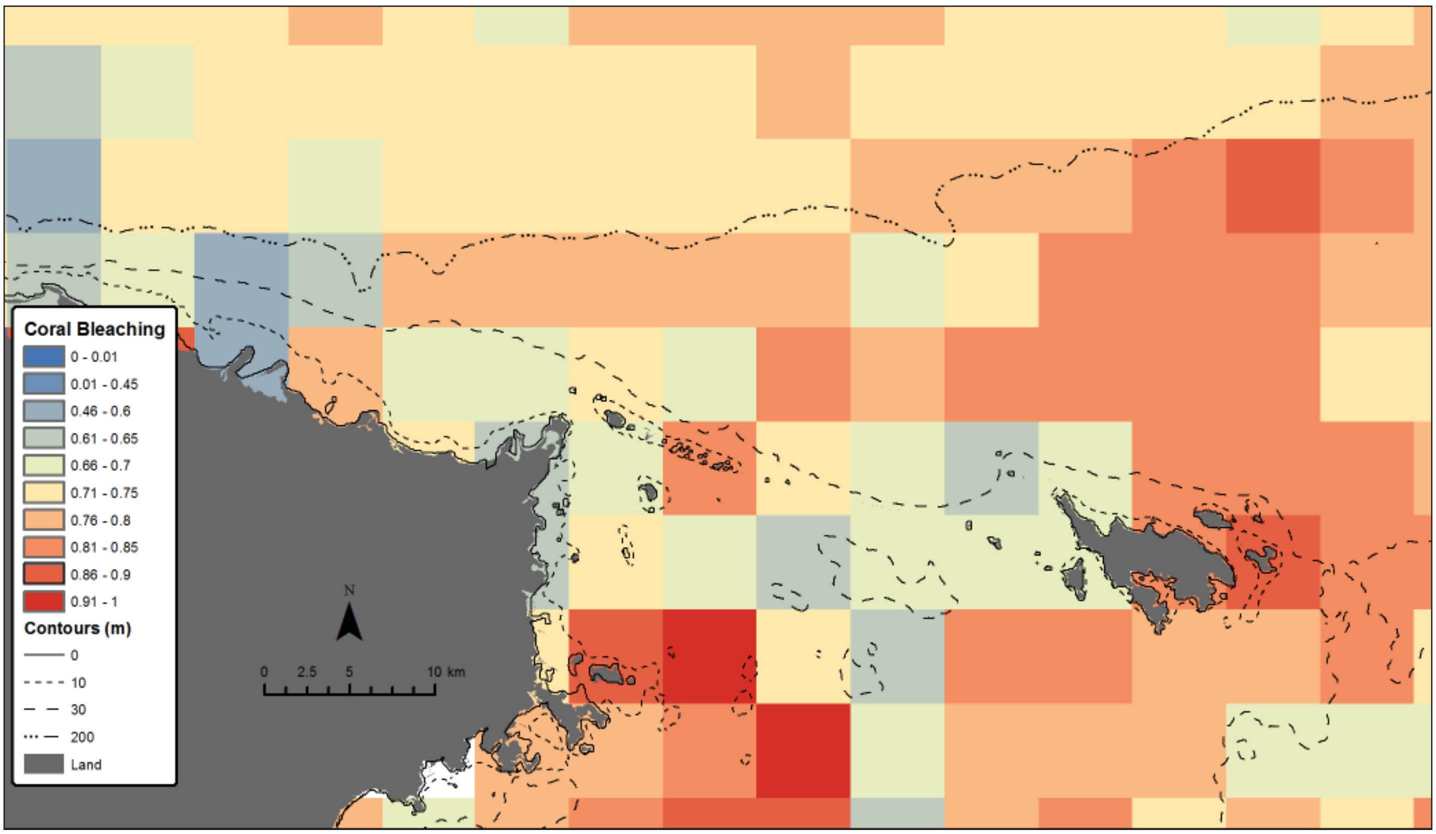


Figure B8. Normalized number of coral bleaching alerts watches, and warnings from 2013 and 2014.

Appendix C: Exploring spatial management designs using systematic decision support software

INTRODUCTION

When used to address a well-defined spatial planning problem, map-based spatial decision support tools can help with developing efficient solutions to complex spatial management problems and negotiating tradeoffs among competing space use patterns. In geographically complex areas, with many conservation features and many threats and stressors, site selection is generally more efficient with the use of software to identify the preliminary set of priority areas. In this section, we use the Marxan decision support tool (Ball and Possingham, 2000) to demonstrate a systematic planning approach to prioritizing sites in northeast Puerto Rico for natural resource management. Marxan is a spatial planning software that uses mathematical optimization for site selection to achieve feature representation goals in a spatially efficient manner with minimum costs (Ball and Possingham, 2000). Spatial solutions, or scenarios, from Marxan have been applied worldwide to evaluate and design protected area networks, zoning and to account for costs associated with human uses in spatial planning (Klein et al., 2010). Here, we apply Marxan to develop multiple prioritization scenarios using a range of different sets of management priorities and potential threats to marine ecosystem health. Together, these scenarios offer a portfolio of planning options for the efficient spatial configuration of priority areas that take account of management priorities and potential threats from human activities.

METHODS

To prioritize areas for management planning, we used the simulated annealing algorithm in Marxan software to find an optimal spatial configuration of ecologically important areas. Marxan selects planning units to meet specific management goals while considering cost such as the risk of being threatened by stressors and the connectedness of the selected units. By minimizing the value for an objective function, that combines cost tradeoffs, spatial design, and penalties for not meeting goals, we determined areas, which have particular ecological management significance. Lower values of the objective function indicate more suitable solutions, whereas higher values suggest less desirable configurations (Ball and Possingham, 2000):

$$Objective\ function = \sum_{PUs} Cost + \left(BLM * \sum_{PUs} Boundary \right) + \sum_{Features} (SPF * Penalty)$$

i. The Cost of the planning units in the scenario was interpreted as the opportunity costs resulting from protection or the risk of being affected by anthropogenic impacts.
ii. The Boundary Length Modifier (BLM) was used to determine how much emphasis should be placed on minimizing the overall boundary length (fragmentation level) for each component of the ecological priority area network. Fragmented scenarios have more exposed edge, which is less desirable for resource management purposes. We used a BLM that reduced fragmentation while favoring corridors.
iii. The Species Penalty Factor (SPF) is a penalty for each unmet ecological management objective.

With guidance from Puerto Rico's DNER, a diverse dataset of biological and ecological elements and an integrated map of cumulative human impacts was compiled (see Chapter 2 and Appendix A and B; Table C1), which included elements such as: spawning aggregations, coral species listed under the Endangered Species Act, key benthic habitats and Fajardo Bioluminescent Bay. The project area was divided into an analysis grid of 0.2 km^2 hexagonal planning units (22,402 units). The 0.2 km^2 planning unit size was selected to provide fine enough detail to resolve habitat within coastal features (especially within bays and estuaries), but did not exceed the resolution of the habitat data. To achieve a broader understanding of the ecological distributions of natural resources in the study area, we developed five different scenarios with different management objectives (referred to here as basic, human impact, required resources, coral-centric and no-manatees).

i. Basic scenario: we set the selection criteria for endangered coral species and spawning aggregations at 80%, with a constant cost for all the planning units.

ii. Human impact scenario: selection criteria were the same as the “basic” scenario, but we incorporated the cumulative human impacts (vessel damage, coastal infrastructure, light pollution, coral bleaching, marine-based pollution, agricultural pollution, urban pollution, coastal population) described in Section 2.2 as a cost.

iii. Required resources scenario: includes all the planning units of the bioluminescent bay area, turtles nest and hotspots sites, spawning aggregation and ESA species, while the remaining management objectives are derived from the “basic” scenario.

iv. Coral-centric scenario: takes into account four coral-focused elements which are associated with coral reefs (hardbottom, high topographic complexity, reefs with >10% coral cover and >50% cover). Numeric targets for these four features under each scenario are shown in Table C1. Costs are equal to area and kept constant at 200 per 0.2 km^2 planning unit.

v. No-manatees scenario: includes the basic scenario goals, all the elements except manatees, and costs remain constant for all the planning units. The no-manatees option was requested by DNER managers, because manatees receive specific attention under existing management plans.

For each of the scenarios, Marxan generated 100,000,000 alternative solution sets in each of 100 independent tests. We then identified the single efficient solution (the most efficient network of priority areas for management) from among the 100 independent tests.

Table C1. List of 17 categories of ecological elements represented in the study area and the selection criteria for each scenario.

	Targets (%) for each scenario				
Ecological Element	**Basic**	**Human impact**	**Locked In resources**	**Coral-centric**	**No manatees**
Coral cover >50%	80	80	80	80	80
Coral cover >10%	50	50	50	50	50
ESA listed coral	80	80	100	0	80
Hardbottom habitat	30	30	30	30	30
High topographic complexity	30	30	30	30	30
Manatee hotspots	30	30	30	0	0
Seagrass	30	30	30	0	30
Conch	50	50	50	0	50
Shelf edge	30	30	30	0	30
Shelf edge reef	30	30	30	0	30
Submarine canyon	30	30	30	0	30
Mangrove	50	50	50	0	50
Turtle nest	50	50	100	0	50
Turtle hotspot	30	30	100	0	30
Bird breeding	50	50	50	0	50
Bird hotspots	30	30	30	0	30
Fish spawning aggregation	80	80	100	0	80

RESULTS AND DISCUSSION

Here we present our spatial scenarios and summary descriptions using outputs from Marxan which are intended to support managers with exploration of five different scenarios. These numerical spatial products are the result of a mathematical approach to prioritizing ocean spaces for consideration in spatial planning. Although the configurations are mathematically optimized solutions, it is important to understand that these maps have not been reviewed by the management community and should be considered only as support for decision making rather than constituting any final decision. The scenarios are exploratory products and the data which fed into the process will have inherent bias and limitations which have not been quantified in this project.

Basic Scenario

The Basic scenario selected 1,697 (approximately 7%) of the available planning units to build the single most efficient solution (Figure C1). This solution is shown using a color scale, which represents the frequency with which each of the individual planning units was re-selected in 100 independent analyses. Clusters of planning units ranged in size from 20 to 9,060 ha. The largest cluster of contiguous units selected occurred around Culebra, and included most of the land and marine space around the island. Two smaller landward areas along the north shore were selected because they were identified as important bird nesting areas by local experts. Two bay areas in the southeast were selected because they were identified as manatee hotspots. The percentages and areas of representation for each of our biological and ecological criteria within this solution are listed in Table C2.

Table C2. Representation levels for each biological and ecological element within the Basic scenario *optimal solution.*

Ecological Element	Element Inside Scenario (%)	Hectares/ observations within scenario
Bioluminescent Bay	94.04	77
Coral cover >50%	80.97	102
Endangered corals	80.71	724 (observations)
Spawning aggregations	79.20	1002
Bird nesting areas	59.93	2075
Hardbottom	57.16	7286
Topographic complexity	51.78	136
Mangroves	50.27	1291
Coral cover >10%	50.08	4386
Turtle nesting areas	50.04	757
Bird concentration areas	50.02	2745
Conch hotspots	50.00	18731
Turtle feeding areas	32.09	1925
Seagrasses	30.12	6478
Shelf edge reef	30.10	1499
Manatee concentration areas	30.07	1678
Canyons	30.05	5552
Shelf edge	30.04	917

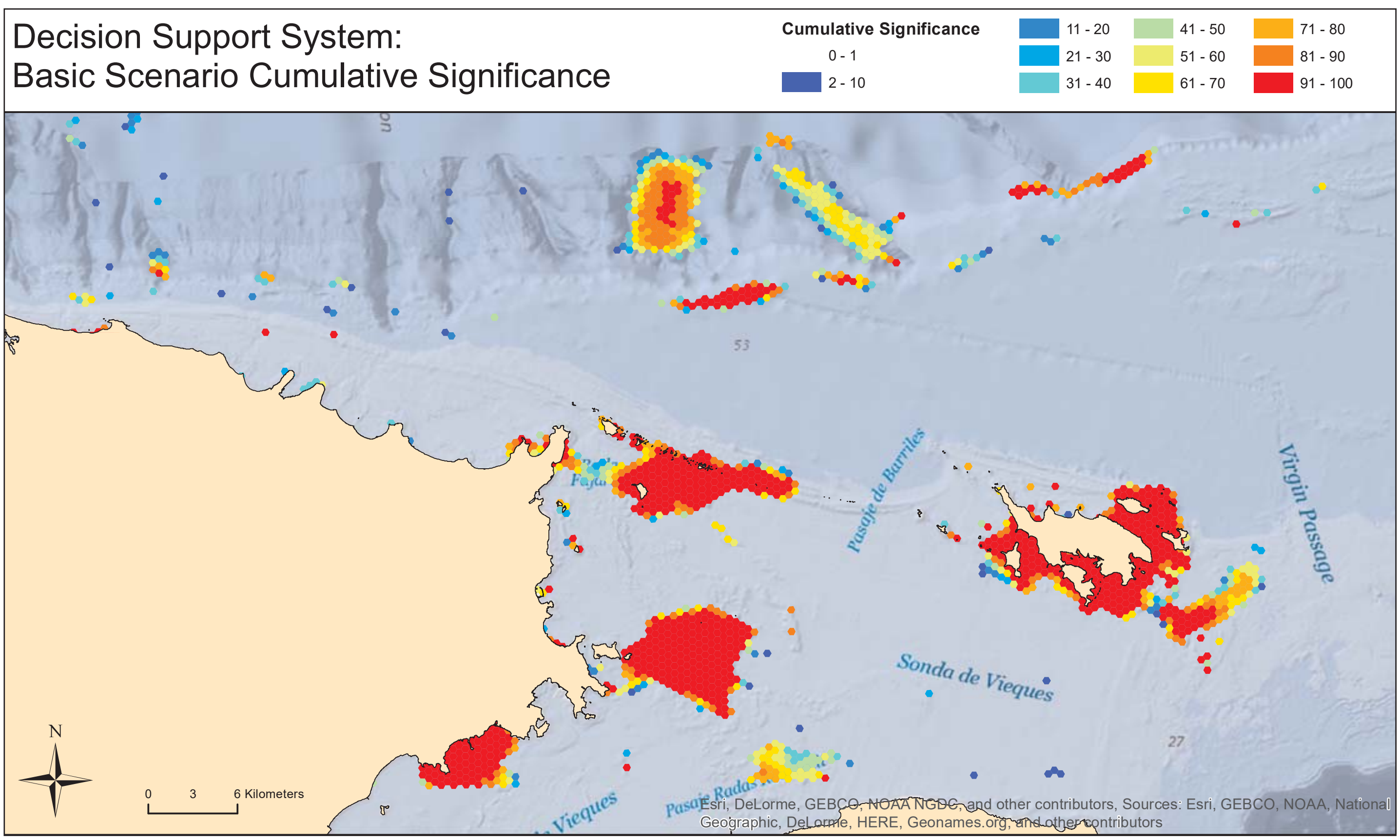


Figure C1. Results of the Basic scenario *analysis showing cumulative significance defined as the number of times an individual planning unit was selected in independent analyses.*

Appendices

Human impact scenario

The Human impact scenario selected 2,076 (approximately 10%) of available planning units to build the single most efficient solution (Figure C2). This solution is shown using a color-scale, which represents the frequency with which each of the individual planning units was re-selected in 100 independent analyses. Clusters of planning units ranged in size from 20 to 5,900 ha. Cells of highest cumulative significance (where priority ecological attributes existed with minimal threat from human activities) occurred primarily in offshore areas. The largest contiguous region of high cumulative significance was identified in the Sonda de Vieques between the islands of Culebra and Vieques. High significance was also calculated for the chain of cays within the Reserva Natural Arrecifes de la Cordillera, including Isla Palominos and Bajo Blake and the shallow nearshore waters around Culebra, particularly Isla Culebrita and the waters in and around Reserva Natural Canal Luis Peña. In addition, a large area of significance was identified in the region of Bajo Chinchorro del Sur and Isla Piñeros. Several deep-water offshore areas of high significance also emerged from the analysis along the shelf edge beyond the territorial sea boundary. Table C3 shows the representation levels for each of the biological and ecological elements within this scenario.

Table C3. Representation levels for each biological and ecological element within the human impacts scenario *optimal solution.*

Ecological Element	Element Inside Scenario (%)	Hectares/ observations within scenario
Coral cover >50%	80.20	101.25
Endangered corals	79.04	709 (observations)
Spawning aggregations	76.51	967.68
Hardbottom	50.82	6,479.02
Turtle nesting areas	50.02	756.22
Bird concentration areas	50.00	2,743.66
Conch hotspots	50.00	18,730.77
Coral cover >10%	50.00	4,379.41
Mangroves	50.00	1,284.62
Bird nesting areas	44.29	1,532.96
Topographic complexity	34.29	90.20
Bioluminescent Bay	33.05	27.22
Turtle feeding areas	30.43	1,825.25
Shelf edge	30.09	919.18
Canyons	30.00	5,542.43
Manatee concentration areas	30.00	1,673.93
Seagrasses	30.00	6,451.18
Shelf edge reef	30.00	1,494.94

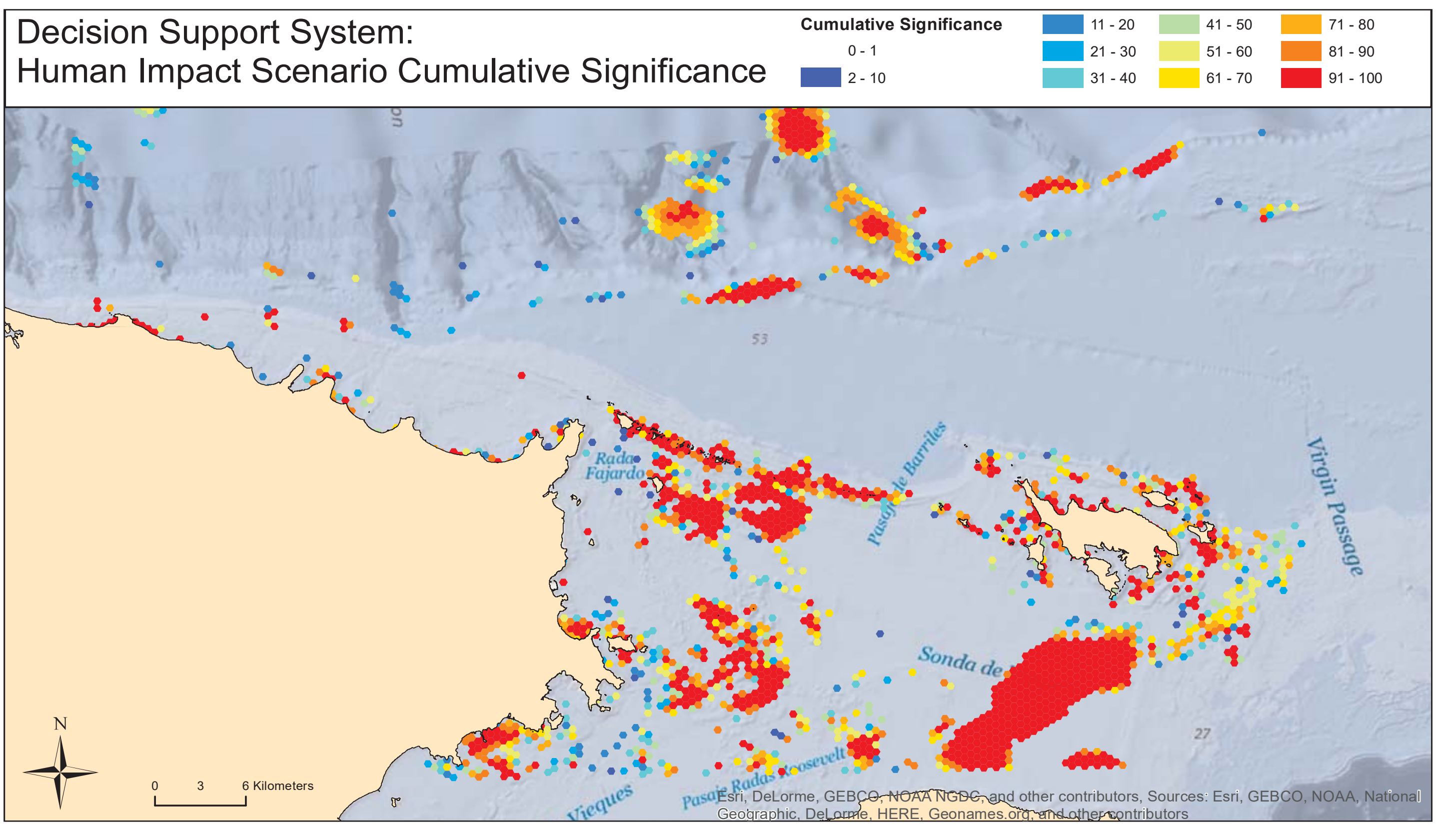


Figure C2. Results of the human impact scenario *analysis showing cumulative significance defined as the number of times an individual planning unit was selected in independent analyses.*

Required Resources scenario

The Required resources scenario selected 2,068 (~9%) of available planning units to build the single most efficient solution (Figure C3). This solution is shown using a color scale, which represents the frequency with which each of the individual planning units was re-selected in 100 independent analyses. Clustered planning units ranged in size from 20 to 10,940 ha. The spatial arrangement and configuration of clustered planning units were similar to that observed in the basic scenario, however, there was greater contiguity of planning units along the shoreline in the required resources scenario than was observed with the basic scenario. Table C4 shows the representation levels for each of the biological and ecological elements within this scenario.

Table C4. Representation levels for each biological and ecological element within the required resources scenario *optimal solution.*

Ecological Element	Element Inside Scenario (%)	Hectares/ observations within scenario
Bioluminescent Bay	100.00	82.37
Endangered corals	100.00	897 (observations)
Turtle nesting areas	100.00	1,511.94
Spawning aggregations	100.00	1,264.85
Coral cover >50%	88.74	112.03
Topographic complexity	68.10	179.12
Mangroves	53.44	1,372.90
Bird nesting areas	50.98	1,764.78
Coral cover >10%	50.04	4,382.56
Conch hotspots	50.01	18,734.39
Bird concentration areas	50.00	2,743.67
Manatee concentration areas	49.83	2,780.56
Turtle feeding areas	48.31	2,897.98
Hardbottom	42.66	8,296.20
Seagrasses	30.53	6,564.55
Shelf edge reef	30.05	1,497.21
Shelf edge	30.03	917.19
Canyons	30.02	5,545.32

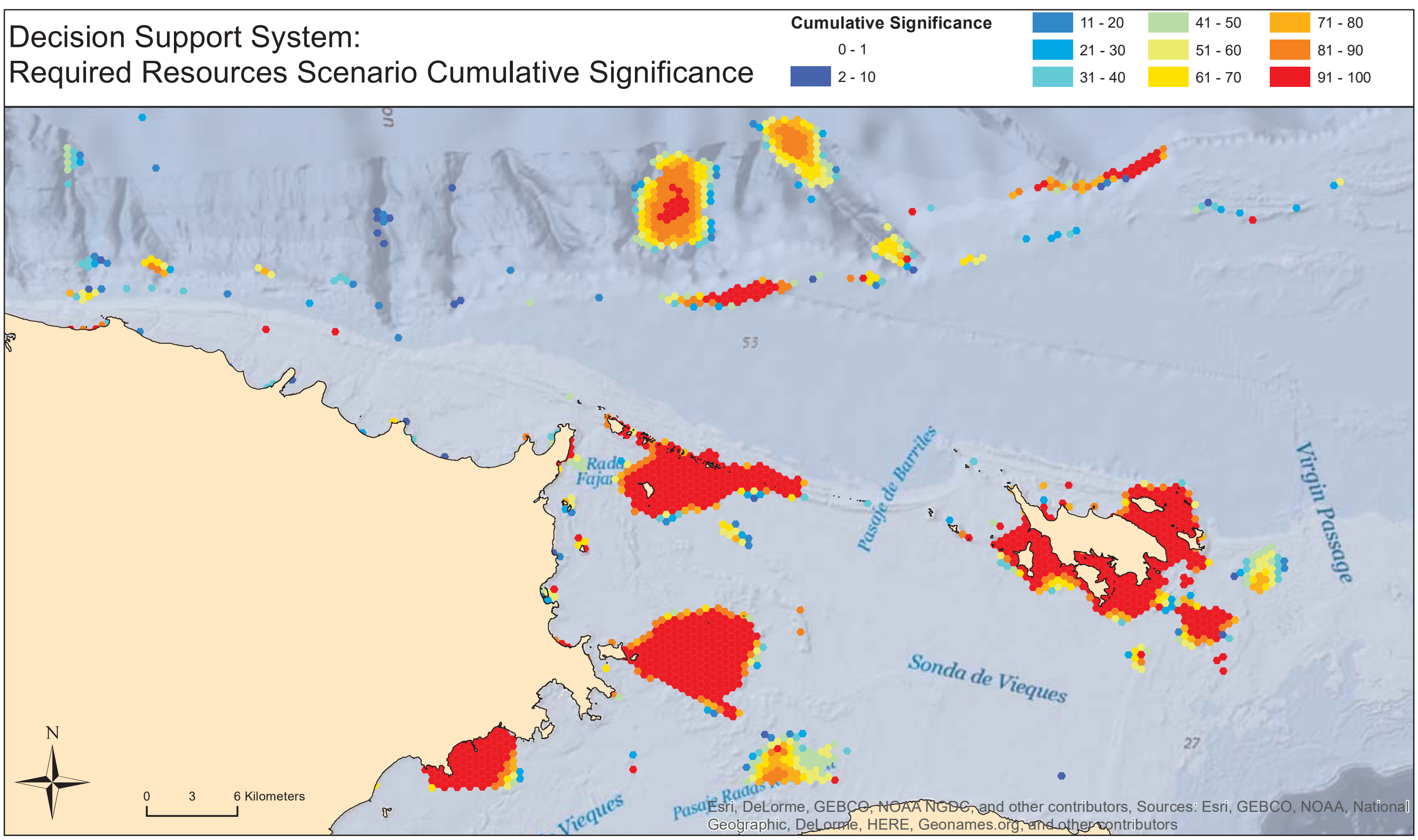


Figure C3. Results of the required resources scenario analysis *showing cumulative significance defined as the number of times an individual planning unit was selected in independent analyses.*

Coral-centric scenario

The Coral-centric scenario selected 345 (2%) of available planning units to build the single most efficient solution (Figure C4). This solution is shown using a color scale, which represents the frequency with which each of the individual planning units was re-selected in 100 independent analyses. Clusters of planning units ranged in size from 20 to 5,600 ha. The largest contiguous area selected by the algorithm encompassed coral reefs south east of Culebra in the region surrounding Arrecife Culebrita and extending offshore to the shoals of Bajos Grampus, a priority area which is mostly outside of any existing protected areas. Two smaller clusters of high significance cells also existing outside of protected areas were selected in the region between Bajo Chinchorro del Sur and Bahía de Puerca off the east coast of Puerto Rico and in the region of the Canal de Cayo north of Bahía Flamenco and Bahía de Marejada along the north coast of Culebra. Table C5 shows the representation levels for each of the biological and ecological elements within this scenario.

Table C5. Representation levels for each biological and ecological element within the coral-centric scenario *optimal solution.*

Ecological Element	Element Inside Scenario (%)	Hectares/ observations within scenario
Coral cover >50%	80.23	101
Coral cover >10%	50.00	4380
Hardbottom	45.77	5835
Topographic complexity	30.07	79
Spawning aggregations	17.58	222
Endangered corals	14.38	129 (observations)
Conch hotspots	4.74	1775
Seagrasses	1.55	333
Turtle feeding areas	0.84	50
Turtle nesting areas	0.72	11
Bird nesting areas	0.01	0
Bioluminescent Bay	0.00	0
Bird concentration areas	0.00	0
Canyons	0.00	0
Manatee concentration areas	0.00	0
Mangroves	0.00	0
Shelf edge reef	0.00	0
Shelf edge	0.00	0

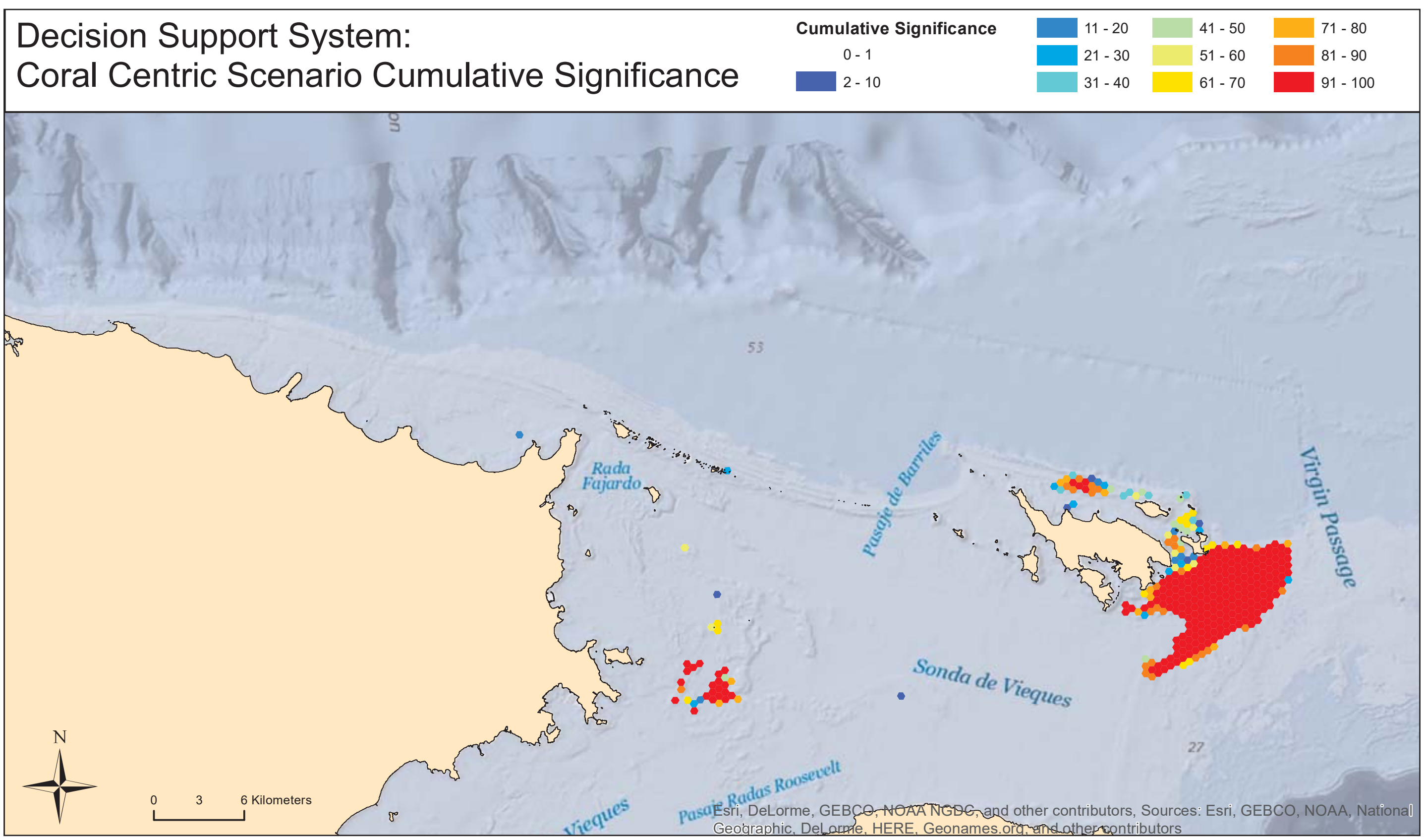


Figure C4. Results of the coral-centric scenario *analysis showing cumulative significance defined as the number of times an individual planning unit was selected in independent analyses.*

No-manatee scenario

The No-manatee scenario selected 1,684 (~8%) of available planning units to build the single most efficient solution (Figure C5). This solution is shown using a color scale, which represents the frequency with which each of the individual planning units was re-selected in 100 independent analyses. Clusters of planning units ranged in size from 20 to 8,000 ha. The main clusters of high cumulative significance differ only slightly when compared with the Basic scenario. Table C6 shows the representation levels for each of the biological and ecological elements within this scenario.

Table C6. Representation levels for each biological and ecological element within the no-manatee scenario *optimal solution.*

Ecological Element	Element Inside Scenario (%)	Hectares/ observations within scenario
Bioluminescent Bay	92.09	75.86
Bird concentration areas	50.07	2,747.27
Bird nesting areas	65.74	2,275.74
Canyons	30.00	5,542.84
Conch hotspots	50.00	18,730.78
Coral cover >10%	50.02	4,381.02
Coral cover >50%	82.52	104.18
Endangered corals	81.27	729 (observations)
Hardbottom	37.28	7,249.17
Manatee concentration areas	25.16	1,403.86
Mangroves	50.05	1,285.83
Seagrasses	30.01	6,452.42
Shelf edge reef	30.03	1,496.03
Shelf edge	30.10	919.30
Topographic complexity	46.88	123.33
Turtle feeding areas	32.23	1,933.16
Turtle nesting areas	50.02	756.26
Spawning aggregations	81.01	1,024.61

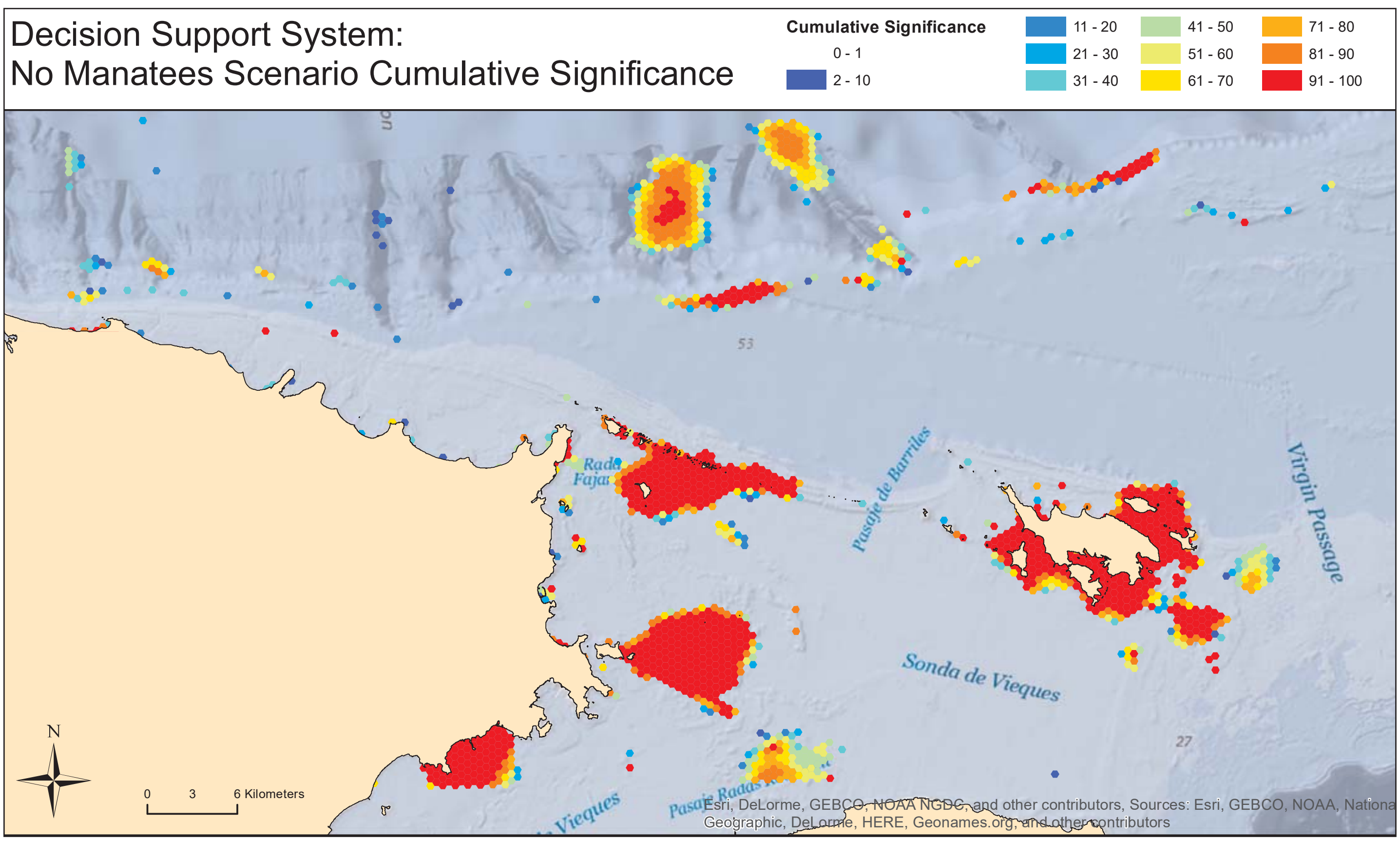


Figure C5. Results of the no-manatees scenario *analysis showing cumulative significance defined as the number of times an individual planning unit was selected in independent analyses.*

Areas of Special Interest

We also used the Marxan decision support system to analyze the 11 areas of special interest (ASIs) identified in Chapter 3 of this report. In order to evaluate the 11 areas of special interest against the efficient portfolio design approach provided by the Marxan decision support system, we identified areas which were included in 80% of efficient portfolio designs as "hotspots" then determined the level of representation of these hotspots within the areas of special interest. In our basic scenario, 72% of the hotspots were represented in the areas of special interest (Figure C6). In our required resources scenario, 69% of the hotspots were represented in the areas of special interest (Figure C7). The 11 areas of special interest combined represented approximately 10% of the project area. When these areas were evaluated for ecological representation, we found that some of our ecological elements were well represented while others were not. For example, the bioluminescent bay, turtle feeding areas, areas with coral cover greater than 50%, and areas of high topographic complexity are very well represented. Whereas, shelf edge reef, canyons, and the shelf edge were poorly represented (Table C7).

Table C7. Representation (%) of ecological elements inside and outside of the areas of special interest (ASIs).

Ecological Element	Element Inside Scenario (%)	Hectares/ observations within ASI
Bioluminescent Bay	100.00	82
Turtle feeding areas	98.33	5899
Coral cover >50%	97.58	123
Endangered corals	85.73	769 (observations)
Manatee concentration areas	83.82	4677
Topographic complexity	79.39	209
Turtle nesting areas	71.43	1080
Spawning aggregations	57.08	1271
Hard bottom	55.06	7694
Mangroves	48.53	1247
Seagrasses	45.39	9761
Conch hotspots	44.27	16583
Bird nesting areas	37.20	1288
Coral cover >10%	34.07	2984
Bird concentration areas	21.08	1157
Canyons	5.82	1075
Shelf edge	5.82	178
Shelf edge reef	0.75	37

We also evaluated the 11 areas of special interest based on the four determinants, which were used in the design of these areas. They were: areas with greater than five ecologically important elements defined by biophysical data; areas with greater than one ecologically important element defined by expert knowledge; areas having both of the former criteria; and off-shore areas with greater than two ecologically important elements. The 11 areas of special interest captured 94% of the areas identified as having more than five ecologically important elements, 85% of the areas identified as having more than one ecologically important element by expert knowledge, 97% areas having both, and 42% of areas off-shore with greater than two ecologically important elements.

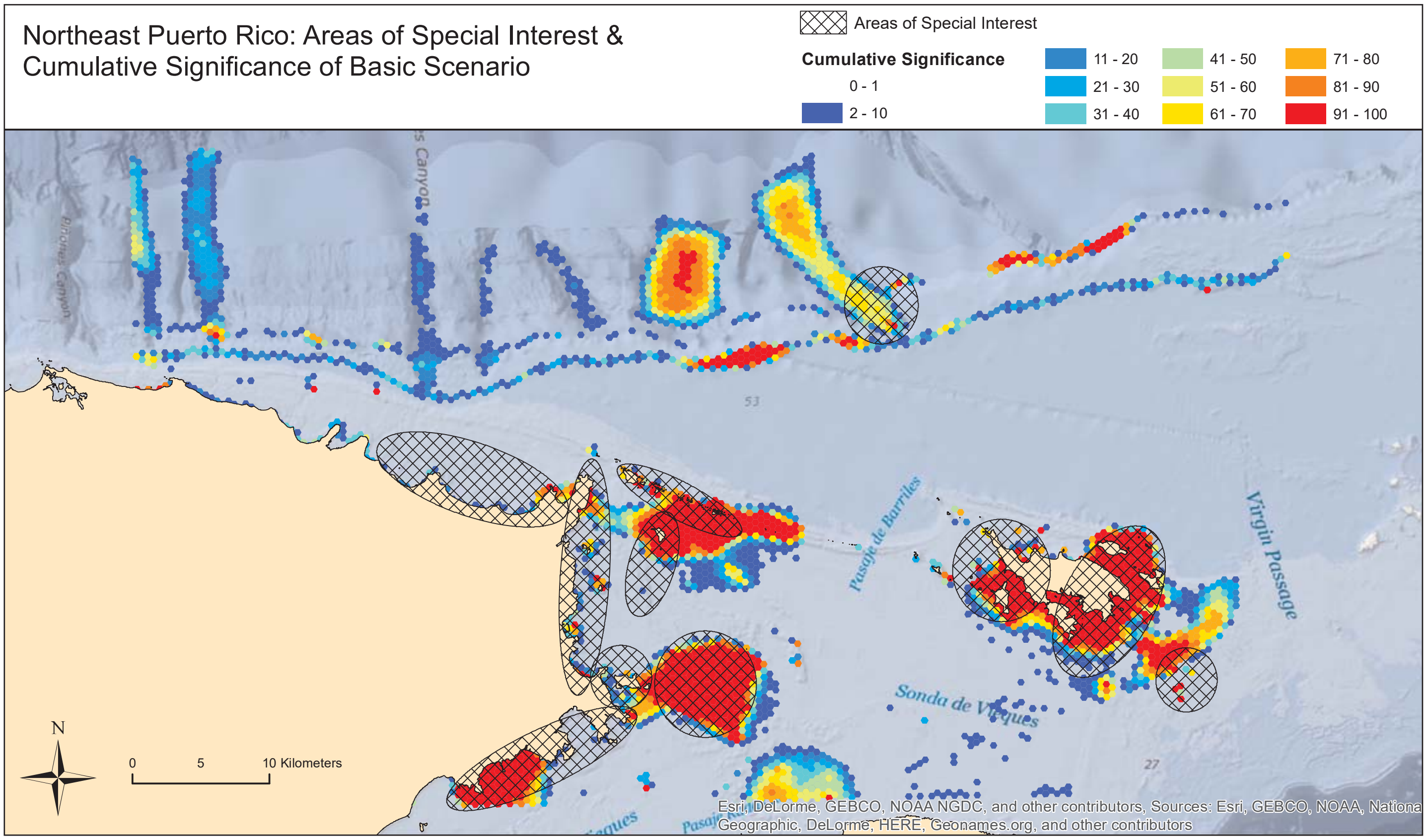


Figure C6. Spatial comparison between areas of special interest identified by integrating local expert knowledge with empirical data and areas of high cumulative significance selected by Marxan software running the Basic scenario.

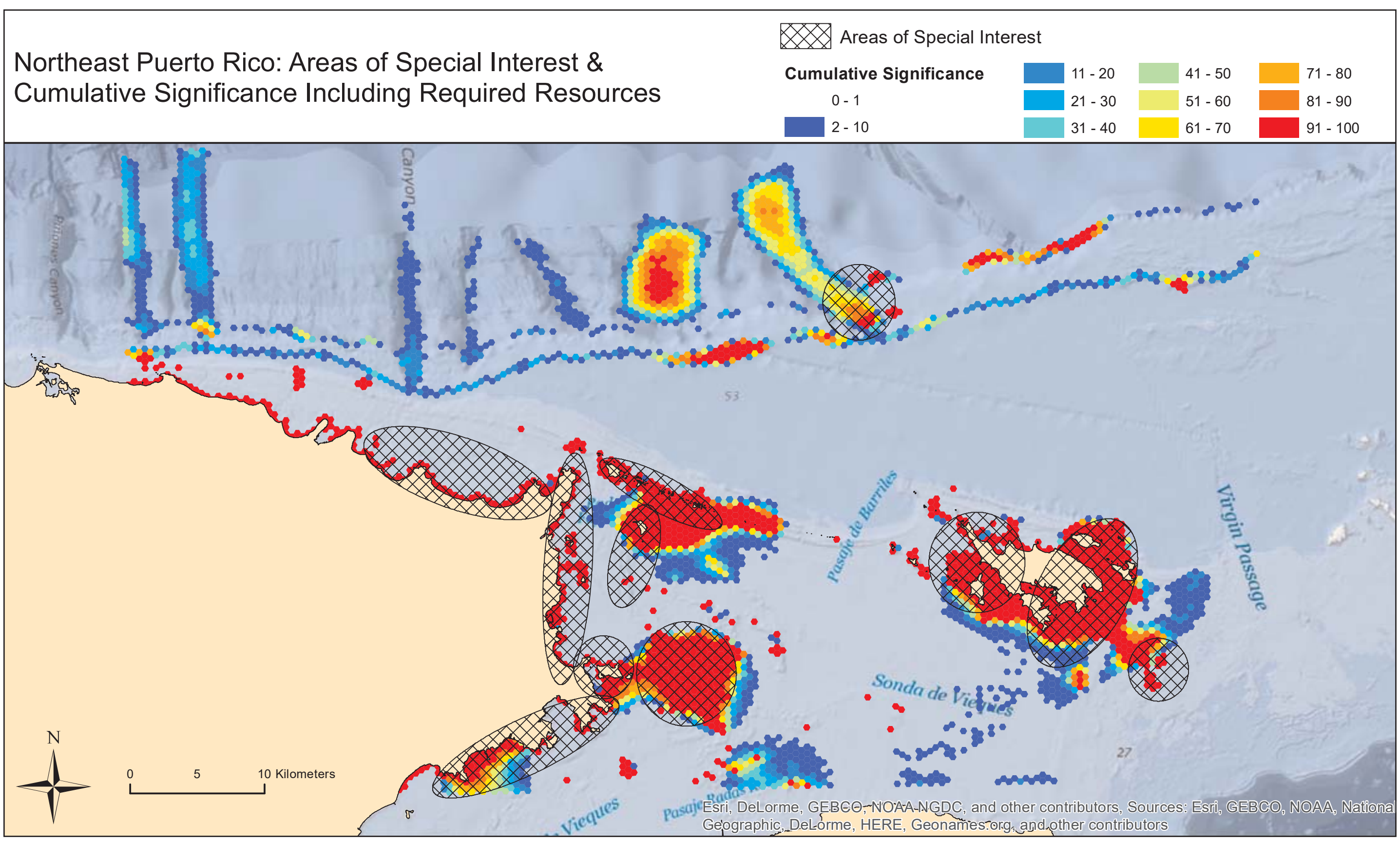


Figure C7. Spatial comparison between areas of special interest identified by integrating local expert knowledge with empirical data and areas of high cumulative significance selected by Marxan software running the Required Resources scenario.

U.S. Department of Commerce

Wilbur L. Ross, Jr., *Secretary*

National Oceanic and Atmospheric Administration

Benjamin Friedman, *Acting Under Secretary for Oceans and Atmosphere*

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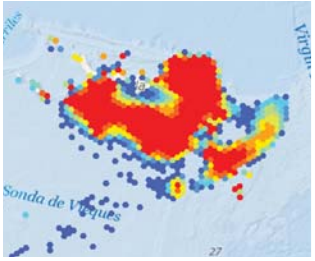

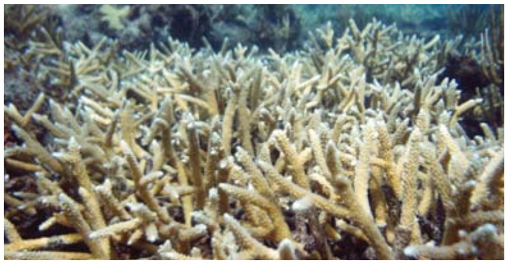

Mapping Ecological Priorities and Human Impacts to Support Land-Sea Management of Puerto Rico's Northeast Marine Corridor