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Modeling Coastal Vulnerability for Insight into Mangrove and Coral Reef Conservation Efforts in Cuba

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ABSTRACT

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Cuba's expansive coral reefs and mangrove habitats provide a variety of ecosystem services to coastal communities including nursery grounds for fisheries, shoreline stability, and storm and flood protection. While Cuba's coastal habitats are some of the most preserved in the Caribbean, they are under increasing threat of degradation from the impacts of climate change, increased tourism, and coastal development. With the goal of sustainable development, Cubans need to assess the storm and flood protection benefits these coastal habitats provide, and integrate this information into future expansion and management plans within the National Protected Areas System (SNAP). Using the open source software, Integrated Valuation on Ecosystem Services and Tradeoffs (InVEST), a national-scale coastal vulnerability model was developed to provide quantitative estimates of coastal exposure and the protective role of coastal habitats during storm events. This model integrates storm information with bathymetry and coastline geomorphology, coupled with coastal habitat data to estimate the influence of these habitats in reducing vulnerability to storms and flooding. By combining these results with human population data, the model identifies where coastal communities are most vulnerable to wave energy and storm surge, and where coral reefs and mangroves provide the most protection by reducing impacts to these communities. We classify these regions as areas of conservation priority. We observed that fifty percent of the areas identified as areas of conservation priority lack any form of environmental protection. We recommend including these key habitats within the National System of Protected Areas. This will permit decision makers to more effectively concentrate restoration and conservation efforts in areas where people and natural resources will experience greater benefit from valuable ecological services.

Keywords: coastal vulnerability, ecosystem services, marine conservation, coral reef, Mangrove, GIS, Natural Capital Project, climate change adaptation.

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INTRODUCTION

Cuba, a tropical ecosystem located in the Insular Caribbean, supports critically important marine environments, harboring 13 percent of the region's coral reef (Burke et al., 2011) and 80 percent of the mangrove forest (Huggins et al., 2007; Keel et al., 2007). It is home to some of the healthiest Caribbean coral reefs (Linton et al., 2002) and maintains the largest mangrove forest in the region (Bordács & Borhidi, 1993). These habitats provide benefits that promote human well-being, often referred to as ecosystem services (Board 2005). Coral reefs and mangroves provide multiple ecosystem services such as nursery grounds for fisheries (Nagelkerken et al., 2000), shoreline stability, opportunities for tourism development (Moberg & Folke, 1999) and coastal protection by reducing erosion and flooding that result from severe and frequent storms (Ferrario et al., 2014).

Cuba has put great effort in protecting and conserving its marine and coastal environments. The country has declared 25 percent of the marine shelf (<200m depth) area within the country's Marine Protected Area Network (MPAN; CNAP, 2014). However, increasing threats from climate change and tourism development put Cuban marine habitats at risk (Burke, Reytar et al., 2011). As Cuba seeks to promote sustainable development, there is an urgent need to maximize the efficiency of the current MPAN. Ensuring that the ecosystems that provide the most services to the coastal communities are included within the MPAN will help Cuba achieve its goal.

Geographic Background

The Cuban archipelago spans more than 1,500 islands and cays covering a total area of 111,000 km^2 (Baez 1977). The coastline length of the entire archipelago is approximately 5,750 km. The Cuban shelf (<200m depth) covers an area of 67,831 km^2 (Núñez Jiménez 1982) and consists of four primary shallow gulfs that are bordered by extensive coral reef systems, with each area separated by long, narrow shelf stretches (Claro and Lindeman 2008). Two of the wide-shelf areas occur on the south coast, the Batabano Gulf to the west, and the area including the Gulf of Ana Maria and the Gulf of Guacanayabo to the east, and two occur on the north coast, the Archipelago of los Colorados in the northwest, and the Archipelago of Sabana-Camagüey in the northcentral region (MAP 1). These gulf areas are characterized by sandy and muddy bottoms with extensive seagrass beds and bordering cays and coral reef systems that extend from the channels to the shelf edge (Claro and Lindeman 2003).

More than 98 percent of Cuba's continental shelf is fringed by coral reefs (CNAP 2014; MAP 2). It is estimated that Cuba's coral reefs cover an area of 3,781 km^2, constituting 36 percent of all Insular Caribbean coral reefs (Alcolado, Claro-Madruga et al., 2003). As of 2017, Cuba currently includes 34.5 percent of its coral reefs within their national system of marine protected areas (TNC, 2017), however, it is estimated that 90 percent of the corals in the area are already threatened due to coastal development and climate-related threats (Burke, Reytar et al., 2011). Although Cuba is considered to be home to the healthiest coral of the Caribbean (Linton et al., 2002), at least 10 percent of the coral cover of the island has deteriorated, meaning the corals are dead but the coral skeleton is still standing, leaving the opportunity for coral to reestablish and grow (Iturralde-Vinent and Méndez 2015).

Mangrove forests cover 7,337 km^2 of the Cuban shoreline, spanning more than 50 percent of the Cuban coastal areas (Ortiz and Lalana 2013; MAP 2). These mangroves represent 20 percent of the total forest cover in Cuba. Mangrove forests are one of the most important ecosystems in Cuba as they protect the coast from erosion, filter pollutants and sediments, provide nursery for fisheries, and protect the coast against storms and flooding (Brown, Corcoran, Herkenrath, & Thonell, 2006). Mangroves are predominantly found along the southern side of the island. The Zapata Swamp, located within the Matanzas Providence, is home to the largest mangrove forest in the entire Caribbean region, covering 450 km^2 (Rodríguez, Pérez et al., 2001). Cuba's mangrove forest is made of four species; *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove) and *Conocarpus erectus* (button mangrove) (Padrón, Llorente, Menendez, & Menendez, 1993). Threats to Cuban mangroves include channel and dam construction, livestock grazing, agriculture, urbanization, and pollutants (Iturralde-Vinent and Méndez 2015).

To protect and manage coral reef and mangrove habitats and to conserve marine biodiversity, Cuba has established an effective system of marine protected areas. As of 2017, Cuba's protected area network has included 211 protected areas that have been officially recognized since 2003 (MAP 1). One hundred and four protected marine habitats cover 25 percent of the Cuban shelf (<200m depth) and 4 percent of the entire Cuban exclusive economic zone (portion of the ocean to which the country claims exclusive rights for fishing, drilling and other economic activities). Conservation and research projects have been mostly focused on coral reefs, mangroves and seagrasses which are considered ecosystems of primary importance because of their key role in maintaining ecological stability and provision of ecosystem services (Yahumila 2015).

Importance of Ecosystem Services Protection

Cubans are highly dependent on the countries rich biodiversity and natural capital that provides a wide range of ecosystem services that support livelihoods and human health. These ecosystem services can be divided into four different categories: provisioning services, regulating services, cultural services, and supporting services (Board 2005; FIGURE 1).

Provisioning services are the products obtained from ecosystems, such as food, water, timber, and fiber. Regulating services are the benefits obtained from the regulation of ecosystem processes that affect climate, floods, disease, wastes, and water quality. Cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences. Supporting services are those necessary to produce all other ecosystem services, such as soil formation, photosynthesis, and nutrient cycling. In the past decade as scientists have come to better understand ecosystem services, there has been an increasing push to expand protection beyond biodiversity, concentrating efforts on quantifying and including valuable ecosystem services within protected area systems. An ecosystem services approach to conservation focuses on protecting and maintaining the link between nature and people and is more likely to be adopted and successfully implemented by government decision makers since it emphasizes important economic and social benefits to people (Figure 2).

Cuba is located in an area that makes it highly vulnerable to tropical storms (Jáuregui, 2003). In the past two centuries Cuba was affected by 180 tropical storms and 109 hurricanes, 32 of those above category five, the highest category hurricane with winds of 157 mph or higher (Schott et al., 2012). These intense meteorological events are likely to occur at least every two years (Gonzalez and Vilaboy 2015), potentially devastating coastal populations by extensive flooding, damage to infrastructure and the disruption of natural habitats. In some cases, these storms have resulted in the loss of human life and severe economic disruption.

Coral reefs dissipate wave energy by breaking waves at the seaward edge and creating bottom friction as the waves move across the reefs (Botello, Gutiérrez et al., 2010). It has been estimated that coral reefs can reduce wave energy by up to 97 percent (Ferrario, Beck et al., 2014). Mangroves can also significantly attenuate wave energy, as wave height can be reduced by 13 to 66 percent over a 100-meter-wide mangrove belt, and by 50 to 100 percent over a 500-meter-wide mangrove belt (Guannel, Arkema et al., 2016). Wave height reduction within a mangrove forest depends on the width of the forest, mangrove tree morphology, water depth, topography, and wave height. The mangrove vegetation also reduces wind speeds over the water surface, lessening the likelihood of waves increasing in height within mangrove areas. This research looks at where coral reefs and mangroves are providing wave protection along the coast of Cuba.

Threats to Coastal Protection Services in Cuba

As with other Caribbean nations, sea level rise, extreme meteorological events, and warmer ocean temperatures are increasingly threating Cuba's coastal ecosystems. Sea level rise alters sedimentary processes which smother coral reefs. The alteration in sedimentary processes can also disturb other important coral processes like feeding and photosynthesis (Buddemeier & Smith, 1988). Mangrove systems do not keep pace with changing sea-level when the rate of change in elevation of the mangrove sediment surface is exceeded by the rate of change in relative sea-level and are highly threaten if there is no space to retreat (Gilman, Ellison, Duke, & Field, 2008). In addition, the intensification and frequency of severe storm events has the potential to seriously damage the structure of both coral reef and mangrove habitat. Across the Caribbean, coral cover is reduced by ~7%, on average, in the year following a hurricane (Gardner, Cote, Gill, Grant, & Watkinson, 2005). The increased intensity and frequency of storms has the potential to increase damage to mangroves through defoliation and tree mortality (Gilman et al., 2008). Warmer temperatures also threaten coral reefs and mangroves and rising sea temperatures stress corals. Overheated corals expel most of their pigmented microalgal endosymbionts (zooxanthellae), and become pale. If thermal stress is prolonged, corals may bleach, and many may die (Hughes et al., 2003). Increasing water temperatures also decrease mangrove productivity (Field 1995). In addition to the impacts of climate change, shifts in U.S. – Cuba diplomatic relationships brings an increased potential for development within coastal habitats. After December 17, 2014, when both countries announced their intention to start normalizing relations, Cuba experienced tourism growth – up to 3.5 million visitors in 2015, a 17% increase when compared to visitors in 2014 (Feinberg and Newfarmer 2016). Consequently, the Cuban government drafted a new foreign investment policy and development plan for 2030, with a specific focus on tourism development as a strategic sector. The plan seeks to expand hotels and resorts, with a target of accommodating 10 million foreign visitors by 2030 – not including the additional 5 million in cruise passengers that are expected (Feinberg and Newfarmer 2016). Unless properly mitigated, these ambitious development plans may have unintended consequences to the health of coastal and marine ecosystems, which are usually targeted by Caribbean tourism development and foreign investments.

The objectives of this research are first, to identify where coastal communities are most vulnerable to inundation and erosion caused by storms. Second, to identify where mangroves and coral reefs are providing significant protection from inundation and erosion. And third, to identify mangroves and coral reefs that provide significant protection against storms that are not part of the Cuban MPAN. Our hope is that our finding will help Cuban conservation managers make informed decisions that will maximize the efficiency of their conservation efforts.

We used the open source software, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Sharp, Tallis et al., 2014), to develop a national-scale coastal vulnerability model. This model integrates storm information with bathymetry and coastline geomorphology, coupled with coastal habitat. By combining these results with human population distribution and density information, this model identifies where coastal communities are most vulnerable to wave energy and storm surge, and where coral reefs and mangroves provide a significant protection to these communities. Consequently, recommendations can be made to include these key habitats within the national system of marine protected areas, permitting decision makers to more effectively concentrate restoration and protection efforts in areas where people benefit from ecosystem services.

METHODS

InVEST

To achieve our objectives, we needed to identify the level of protection that marine habitats provide the Cuban coast. To accomplish this, we used the Coastal Vulnerability Model (CVM) from the Integrated valuation of ecosystem services and tradeoffs (InVEST) software. InVEST is a software program that develops models that identify the value of ecosystem services fundamental to conservation (Sharp, Tallis et al., 2014). This software contains a suite of free, open source, non-encrypted models developed by Stanford University, The Nature Conservancy (TNC) and World Wildlife Fund. The software includes a set of eighteen geospatial models designed to valuate ecosystem services for terrestrial, freshwater, marine and coastal ecosystems. The different models answer questions regarding the value of different ecosystem services like fisheries productivity, coastal vulnerability, recreation, sediment retention and crop pollination. InVEST uses science based geospatial tools to account for the changes in the ecosystems and their impact on human well-being. These tools model conservation and development scenarios that enable decision makers to assess tradeoffs with alternative management choices, identifying areas where investment in natural capital enhance human development and conservation.

The Coastal Vulnerability Model

The InVEST Coastal Vulnerability Model (CVM) quantifies the influence that coastal habitats have in reducing the risk of communities to coastal hazards and in providing storm protection. It computes a shoreline index representing the relative exposure of the shoreline to coastal hazards based on characteristics such as the presence of terrestrial and marine habitats (e.g., coral, mangroves), elevation, wind speed, wave energy, shoreline type, sea-level rise, and storm surge potential (the potential for abnormal rise in seawater level during a storm) (Table 1). CMV index values range from 1 (very low exposure) to 5 (extreme exposure). The index is coupled with social and economic data on population density and demographics, property, and urban infrastructure (depending on data availability) to denote where human settlements and critical infrastructure are most vulnerable to storm waves and surge over time. This information is combined with other model outputs (i.e. Exposure Index, Habitat Role) to estimate the number of people receiving protection benefits from coral reefs and mangroves.

The model divides the shoreline into of an assigned length. We divided the coastline of Cuba into 1 km segments. Each segment was assigned a rank from 1 to 5 on each variable depending of the geophysical characteristics of every segment of the coastline. The ranks were assigned based on the guidelines used by the Invest users guide (Sharp et al., 2014). The model calculates the exposure index (EI) for each shoreline segment as the geometric mean of all the variable ranks:

$$EI = ({}_{R}Geomorphology\, {}_{R}Relief\, {}_{R}Habitats\, {}_{R}SLR\, {}_{R}WindExposure\, {}_{R}WaveExposure\, {}_{R}Surge)^{1/7}$$

The outputs of the model are rasters that overlay the shoreline in the shoreline of Cuba. The model generates two different exposure indices, the index of exposure of coastal areas when marine habitats are presents and the index of exposure when habitats are absent. The model identifies where marine habitats are reducing exposure as it compares the two different indices; areas with a larger difference of exposure indicating a higher relative habitat influence in coastal protection.

Study Site

The CVM was executed along the entire coast of Cuba's main island, Isla de la Juventud and keys at a 1km resolution using four different scenarios: a) mangrove and coral reef habitat present; b) mangroves only; c) coral reef only; and d) no habitats present. The difference in results helps identify the specific contribution provided by each habitat type both individually and in combination with other types in reducing the risk of inundation and erosion.

Input Data

To calculate the coastal vulnerability exposure index, the model requires data on geomorphology, elevation, coastal habitats, bathymetry, sea-level rise, and population density. The software provides global data sets for wind and wave exposure as well as the continental shelf used to calculate storm surge potential. These six layers were either produced for this study, or obtained from external sources. The data type and its source is described as follows:

- **Geomorphology** (coast type): Using Google Earth satellite imagery, the geomorphology classes of the entire island were interpreted and manually digitized.
- **Elevation**: A digital elevation model at 30x30m spatial resolution was developed using the Shuttle Radar Topography Mission (SRTM) version 3.0 Global 1 arc second (Radar and Data 2008).
- **Bathymetry**: The bathymetry was interpolated using the GEBCO global bathymetric dataset as well as digitized depth points from nautical charts at various scales.

- **Coral Reefs**: Coral reef data are from the Millennium Coral Reef Mapping Project (Andrefouet, Muller-Karger et al., 2006).
- **Mangroves**: Mangroves were interpreted and manually digitized using Google Earth imagery by The Nature Conservancy in 2011.
- **Population**: LandScan 2012 global population distribution dataset was used with a spatial resolution of 1x1km (Bright, Rose et al., 2012).

Model Limitations

When interpreting the output of the InVEST Coastal Vulnerability model, users should understand the limitations of the model. Coastal interactions are complex and dynamic processes and the model simplifies these processes into seven variables. In addition, the interaction between these variables in this study is not considered and all habitats are treated with equal quality and condition. Verification and validation of input datasets is critical as the quality of these data can greatly influence model results. Users should strive to obtain the best available data within time and budget constraints. For example, field data coupled with high-resolution satellite imagery can be used to improve the accuracy of the spatial distribution of benthic habitats.

RESULTS

Exposure Index

The Exposure Index represents the level of coastline exposure to erosion and inundation for user-defined segments. The Cuba model estimated exposure index values for 28,552 points along the coast, each separated from the next by 1 km. Index values varied depending on geophysical conditions along the coastline. For example, steep elevation and bathymetry areas, such as the southeast section of the island, showed significantly less exposure compared to the Batabano Gulf a relatively flat area with estimated high levels of exposure. These results confirm that areas characterized by wide and shallow coastal shelfs, with low topographic coastal variability, are more vulnerable to storms and flooding than steep and deep areas that are found along the southeast coast. The average Exposure Index for the entire island was calculated to be 2.8, which represents a moderate level of exposure. Six percent of the coast was classified as extremely exposed and another 44 percent was classified as highly exposed, indicating that half of the country's coastline is at high risk of erosion and inundation (Figure 1).

The province of Mayabeque was identified as having the highest level of exposure with an average index value of 4. Eleven out of the sixteen provinces of Cuba were estimated to have an average exposure index higher than 3.0, indicating that 70 percent of Cuban provinces have high levels of exposure (See appendix for reference map). MAP 3 shows the average exposure index value for each province and TABLE 2 ranks the average exposure index value for all coastal municipalities from highest to lowest.

The role of coastal habitats in reducing exposure can be evaluated by comparing model results with and without these habitats. When habitats are removed, the average exposure index increases from 2.8 (Medium) to 3.0 (High). The Gulf of Ana Maria and the Archipelago of Camaguey area showed significant increases in exposure levels (See MAP 4 and MAP 5). Figure 2 shows a comparison between the average exposure index with and without the presence of habitats across different provinces. In most provinces there was an increase of exposure when these habitats were removed from the model. The provinces of Santiago de Cuba, Ciudad de la Habana and Cienfuegos do not show any change since those areas are highly populated and coastal habitats are mostly absent.

Habitat Role

The habitat role index estimates the level of exposure reduction that coastal habitats provide. It does this by computing the difference between model results that were developed both with and without habitats. These results can be visualized under different scenarios to provide a more clear understanding of the level of protection provided at each habitat location. MAP 6 shows the habitat role when coral reefs and mangroves are combined and used in the model. MAP 7 show the results of the model considering only coral reefs while MAP 8 considers only mangroves. As expected, coral reef and mangrove habitats demonstrated coastal exposure reduction benefits across different geographic areas of the island. Coral reefs were shown to have a significant exposure reduction role in the areas of the Archipelago of Canarreos, Gulf of Ana Maria, Gulf of Guacanayabo and a small region of the Zapata Swamp. Coral reefs show less of a role in reducing exposure along the northern side of the island. On the contrary, mangroves showed to have major protective influence along the Archipelago of Camaguey on the northern side of the island. On the southern side of the island, mangroves show an exposure reduction role within limited area around the Inglesitos Cays and the Zapata Swamp.

A summary of the average habitat role index value by province for the coral reef and mangrove only scenarios is shown in GRAPH 3. This graph indicates which type of habitat is providing greater protective benefits within each province. Sancti Spiritus scored the highest in terms of the most benefits received from habitats, however the graph shows that most of the protection benefits are derived from coral reefs. The provinces of Mayabeque, Artemisa, and Villa Clara receive most of the protection benefits from mangroves. Due to the low levels of mangroves and coral reef habitats, the provinces of Santiago de Cuba, Ciudad de la Habana, and Cienfuegos receive very low levels of protective benefits from coastal habitats. A summary of the top ten municipalities that receive significant protection benefits from coastal habitats are listed in TABLE 3.

Population

According to the model, approximately 1.5 million people live within one kilometer of the coast (coastal population), from which about 60 percent of this coastal population were identified as living in highly exposed areas. Only 5 percent of the total coastal population are receiving protective benefits from mangroves and coral reefs. MAP 9 shows the total coastal population by province and is classified into different exposure rankings.

These results demonstrate that the majority of the 1.5 million people living along the coast inhabit areas of high exposure where protective benefits from coral reefs and mangroves are scarce or absent. For example, Ciudad de la Habana, with 400,000 people living within 1 kilometer of the coast, represents 27 percent of the total coastal population. This province has an Exposure Index of 3.4, indicating high levels of exposure, while the habitat role index is zero.

The Marine Protected Area Network

One of the main goals of this research is to provide Cuban managers with information that can assist them in their efforts to expand their protected are network efficiently. We attempted to do so by identifying coastal areas where populations are highly exposed to wave energy and storm surge but where coastal habitats play a significant role in reducing their impacts. We standardized and added together the indices of exposure, habitat role and population and created a new index we titled "Index of Conservation Priority". All areas with a conservation priority index above the mean where considered areas with high conservation priority.

Fifty percent of the country falls into the high conservation priority range. We overlaid these areas with the current protected area network boundaries. This allows us to locate areas of high conservation priority that remain unprotected (See MAP 10). Forty six percent of those high conservation priority areas are already part of the Cuban protected area network. However only seven percent of the population within the high conservation priority areas lives in those protected areas. The results of our analysis show candidate sites for conservation actions. For example, the area of the Gulf of Ana Maria shows high habitat value for coastal protection and is not included within the national protected area network. Interestingly, the area of Artemisa has already been included in the ecosystem based adaptation project "Manglar Vivo", a project aimed at restoring and protecting mangroves to reduce flooding caused by severe storms.

The impacts of Hurricane Irma were used as a case study to validate the results of the coastal vulnerability model. No official report of the specific economic and infrastructure damages was published; consequently, an official statistical test on the accuracy of our results of the model and the damaged cause by hurricane Irma could not be conducted. However, we reviewed news reports and interviewed locals to map the areas that suffered the most damage (MAP 11). We observed that many of high impact areas were identified as having the potential for high exposure in our model. Based on this assessment, our results appears to have successfully identified areas along the coastline susceptible to the impacts of severe weather.

The Effects of Improving Spatial Data

As part of the project, an experiment was conducted to determine how refining and improving the accuracy and quality of the habitat data would influence the results of the InVEST Coastal Vulnerability model. Working directly with the Cuban experts, the differences in the accuracy of model output was compared using global habitat datasets vs. the same data that was refined and corrected by local experts for the areas around Isla de la Juventud (Isle of Youth). The local Cuban experts edited and provided more detailed habitat data, improved existing data on geomorphology, and validated the accuracy of the model results based on their local knowledge. When comparing model output using the two habitat datasets, differences were identified in both levels of exposure and habitat role. FIGURE 2 and FIGURE 3 compare the results of the model outputs using both the global data vs expert refined data. An expert review of these results concluded the refined and improved habitat data yielded more realistic and greater accuracy that would lead to more practical and useful management actions.

DISCUSSION

Ecosystem service models can be used to spatially identify the value of habitats and the benefits they provide to people. The inclusion of ecosystem services in conservation planning is increasingly highlighting tangible values that governments can use to prioritize, maintain, and restore the natural benefits that people receive from a healthy and functioning environment. In fact, these models can be used as decision-support products to promote the conservation and protection of identified high priority habitats. For example, our Cuba coastal vulnerability model results indicate that 50 percent of the coastline is highly exposed to the effects of storms. Of the approximately 1.5 million people living within one kilometer of the coast, 60 percent were identified as living in highly exposed areas with only 5 percent benefiting from the protective services of coastal habitats. These numbers highlight the vulnerable situation of Cuba's coastal communities and a call for strategic planning.

However, these natural habitats protect not only people from storms, but they also protect infrastructure, agricultural land, and a variety of other land use types. The economic value of tourism infrastructure and agricultural lands plays a critical role for both the provincial and national economy. For instance, many areas that are economically important for tourism and agriculture, such as those located within the provinces of Villa Clara, Sancti Spiritus, Ciego de Avila and Camaguey, contain extensive areas of coral reefs and mangroves that were identified as having significant habitat role index scores, highlighting the protection value of these important (critical?) habitat types.

Often, natural habitats provide multiple ecosystem services, and protection can be further prioritized by the number of overlapping benefits that a particular habitat provides. For example, our results estimate that 8,700 Cubans are receiving coastal protection benefits from adjacent coral reefs. A recent study on tourism ecosystem services calculated that the total dollar tourism value of the coral reefs in Cuba is approximately US$276,150,000 per year (Spalding, Burke et al., 2017). Combining information on the value of different ecosystem service benefits can add significant insight that can positively influence conservation strategies and focus management where habitats are providing multiple benefits. These habitats should be protected and monitored so they continue to provide benefits to people.

Ecosystem service models can also provide guidance and insight for designing and implementing climate change adaptation plans. Consider the category five hurricane Irma that battered the Caribbean, including the northern coast of Cuba, on Friday September 8th, 2017 for seventy-two hours. Strong winds, high waves, and powerful storm surge took the lives of ten people and left cities without power and running water for several weeks. Approximately 150,000 homes were severely damaged and an estimated 338,000 hectares of plantain and sugar cane fields were partially lost. Flooding, caused by stormed surge, reached five feet and took several weeks to clear up the destruction (Times, 2017). According to a state media radio station, Irma was the first Category 5 hurricane to hit the province of Camaguey in 85 years. As Cuba is expecting an increase in more violent and frequent tropical storms, the inclusion of the protection benefits of coastal habitats and the ecosystem services they are providing can assist with strategic climate adaptation planning. As we compared the results of the model with the areas that suffered devastation after the hurricane, we observed that many of the impacted areas were identified as areas of high exposure in our model. Based on this comparison we can presume that accounting for ecosystem services could effectively provide guidance for climate change adaptation planning.

Exploring how natural solutions can enhance coastal resilience is an important part of efficiently planning for climate change adaptation in island countries prone to the impacts of storms. These models can be used to simulate different habitat restoration scenarios to determine if the recovery of habitat, in combination with all other geophysical variables, will be successful in reducing exposure to flooding and erosion. Investigations into the effectiveness of different types and designs of green infrastructure can also be explored, which is typically more cost-effective than investments in gray infrastructure, such as seawall, groynes, and breakwaters. Green infrastructure solutions provide additional benefits to the area such as promoting fisheries, habitat for other species, and recreational opportunities while gray infrastructure tends to be expensive and require costly maintenance.

Identifying areas of high exposure combined with population data can provide vital information to emergency response managers helping them prioritize areas of high risk. Habitat role data can be used to determine where, and if, investing in green infrastructure will be feasible and effective in reducing vulnerability. For example, areas characterized by having exposed large coastal populations and low abundance of coastal habitats (such as Cienfuegos, Ciudad de la Habana, and Guantanamo) are candidate sites for storm protection measures. Possible solutions that could be implemented by governments include gray (e.g. construction of seawalls) or green (e.g. restoration of natural habitats) projects. Ecosystem service models could be used to simulate different habitat restoration scenarios to determine if the recovery of habitat, in combination with all other geophysical variables, will be successful in reducing exposure to flooding and erosion (Beck, 2018). The same procedure can be done when considering the effectiveness of gray infrastructure. While investing in green solutions is often more cost- effective, a hybrid approach can be used if the natural infrastructure is in poor condition. Green solutions provide additional benefits to the area such as fisheries production, habitat for other species, and recreational opportunities.

In cooperation with the Minister of Science, Technology and Environment (CITMA), TNC's Cuba program is currently developing an Ecosystem-Based Adaptation plan to increase coastal resilience and reduce vulnerability to climate change, particularly in highly exposed coastal areas where degraded or absent coastal ecosystems exist. A program to restore and monitor key coral populations in vulnerable areas will be implemented, supporting healthy coastal ecosystems that will build resilience in Cuba.

Additionally, as new development opportunities open to Cuba, studying ecosystem services can provide information to decision makers and guide development plans in a more sustainable manner. Analyzing the value of different ecosystem services provides a way to assess tradeoffs and discover mechanisms where both people and nature receive benefits. By comparing the cost and benefits of the different uses of the coastal environment, planners and resource managers can better understand the tradeoffs of the various scenarios. Ecosystem service modeling can raise awareness of the value of habitats and identify areas of development along the coastline that should be avoided due to their exposure and level of vulnerability. Modeling can also help identify areas of high ecosystem value that should be protected. Such is the case of the province of Sancti Spiritus, where highly vulnerable coastal populations and infrastructure exist that greatly rely on the protection benefits provided by coral reefs. Any further development in this area should be aware of the potential consequences of the loss of coral reef and efforts should be made to avoid or mitigate any damage to these habitats.

CONCLUSION

Our research attempts to demonstrate how analyzing ecosystem services can assist strategy development in conservation planning, climate change adaptation, and sustainable development. Our national scale analysis on the coastal protective services provided by coral reefs and mangroves in Cuba, provides insight into the protection prioritization of these habitats. Our results are intended to help guide restoration actions across Cuba by highlighting areas where natural habitats are reducing exposure to erosion and protecting populations and infrastructure from inundation. It is hoped that this information will be of great value to Cuba, guiding and promoting investments in coastal green infrastructure and habitat restoration as an essential part of a national climate adaptation plan.

While our research only focuses on coastal protection ecosystem services, this type of analysis can be done for other important marine ecosystem services, such as sediment retention, fisheries production, carbon sequestration, or tourism and recreation. Our hope is that additional ecosystem service analyses be performed so conservation actions can be directed to areas where multiple ecosystem services are providing benefits to people. These types of models provide key information to decision-makers since benefits and tradeoffs can be quantified and used to guide policy. Cuba is in a unique position to build a sustainable future and development strategy, where both people and nature win. As pressures increase to develop coastal areas, it is important that future conservation efforts focus on maintaining and restoring healthy and functioning coastal ecosystems to safeguard the benefits provided to coastal communities. By doing so, the efficiency of the protected area network can be increased, and the economic and social benefits of these habitats can be secured.

LITERATURE CITED

Alcolado, P. M., et al. "The Cuban coral reefs." Latin American coral reefs. 2003. 53-75.

Andrefouet, S., et al. (2006). Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. Proceedings of the 10th International Coral Reef Symposium, Japanese Coral Reef Society Okinawa, Japan.

Baez, V. (1977). La enciclopedia de Cuba, PR Enciclopedia y Clásicos Cubanos.

Brown, C., Corcoran, E., Herkenrath, P., & Thonell, J. (2006). Marine and coastal ecosystems and human well-being: synthesis.

Board, M. A. (2005). "Millennium ecosystem assessment." Washington, DC: New Island 13.

Bordács, M. and A. Borhidi (1993). "Preliminary studies of possible Ni-hyperaccumulators in the serpentine flora of Cuba. II." Acta Botanica Hungarica 38: 447-454.

Botello, A. V., et al. (2010). Vulnerabilidad de las zonas costeras mexicanas ante el cambio climático (Vulnerability of the Mexican coastal zones during Climate Change).

Bright, E. A., et al. (2012). "LandScan 2012."

Buddemeier, R., & Smith, S. (1988). Coral reef growth in an era of rapidly rising sea level: predictions and suggestions for long-term research. *Coral Reefs, 7*(1), 51-56.

Burke, L., et al. (2011). Reefs at risk revisited, 114 p." World Resources Institute (2011).

Claro, R. and K. C. Lindeman (2003). "Spawning aggregation sites of snapper and grouper species (Lutjanidae and Serranidae) on the insular shelf of Cuba." Gulf and Caribbean research 14(2): 91-106.

Claro, R. and K. C. Lindeman (2008). "Biología y manejo de los pargos (Lutjanidae) en el Atlántico occidental." La Habana: Instituto de Oceanología.

CNAP, C. N. d. A. P. (2014). "Plan del Sistema Nacional de Áreas Protegidas 2014-2020." 7.

Feinberg, R. E. and R. S. Newfarmer (2016). "Tourism in Cuba: Riding the Wave toward Sustainable Prosperity." Brookings Institute, Latin American Initiative.

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nature communications, 5, 3794.

Field, C. D. (1995). "Impact of expected climate change on mangroves." Hydrobiologia 295(1): 75-81.

Gardner, T. A., Cote, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2005). Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline. *Ecology, 86*(1), 174-184.

Gilman, E. L., Ellison, J., Duke, N. C., & Field, C. (2008). Threats to mangroves from climate change and adaptation options: a review. Aquatic botany, 89(2), 237-250.

Gonzalez, R. and S. G. Vilaboy (2015). Cuba a la mano: Anatomía de un país, Universidad del Norte.

Guannel, G., et al. (2016). "The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience." PloS one 11(7): e0158094.

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., . . . Kleypas, J. (2003). Climate change, human impacts, and the resilience of coral reefs. *science, 301*(5635), 929-933.

Huggins, A., et al. (2007). "Biodiversity conservation assessment of the insular Caribbean using the Caribbean Decision Support System." Arlington (VA): The Nature Conservancy, summary report.

Iturralde-Vinent, M. and H. S. Méndez (2015). Peligros y vulnerabilidades de la zona marino-costera de Cuba: estado actual y perspectivas ante el cambio climatico hasta el 2100, Editorial Academia.

Jáuregui, E. R. N. E. S. T. O. (2003). Climatology of landfalling hurricanes and tropical storms in Mexico. Atmósfera, 16(4), 193-204.

Linton, D., Smith, R., Alcolado, P., Hanson, C., Edwards, P., Estrada, R., . . . Mccoy, C. (2002). 15. Status Of Coral Reefs in the Northern Caribbean And Atlantic Node of the Gcrmn.

Moberg, F., & Folke, C. (1999). Ecological goods and services of coral reef ecosystems. Ecological economics, 29(2), 215-233.

Nagelkerken, I., Van der Velde, G., Gorissen, M., Meijer, G., Van't Hof, T., & Den Hartog, C. (2000). Importance of mangroves, seagrass beds and the shallow coral reef as a nursery for important coral reef fishes, using a visual census technique. Estuarine, coastal and shelf science, 51(1), 31-44.

Núñez Jiménez, A. (1982). "El Archipiélago-Cuba: La Naturaleza y el Hombre." La Habana: 123.

Ortiz, M. and R. Lalana (2013). "Marine biodiversity of the Cuban archipelago: An overview." Caribbean marine biodiversity: The known and the unknown. DEStech Publications, Lancaster, PA, USA. http://cbm. usb. ve/CoMLCaribbean/pdf/I-03_Cuba_final. pdf. Accessed 7.

Padrón, C. M., Llorente, S., Menendez, L., & Menendez, L. (1993). Mangroves of Cuba. *Conservation and Sustainable Utilization of Mangrove Forests in Latin America and Africa Regions, Part I-Latin America"(LD Lacerda, ed)*, 147-154.

Radar, I. S. A. and S. W. B. Data (2008). "Shuttle Radar Topography Mission."

Rodríguez, C., et al. (2001). "Los asentamientos humanos, el uso de la tierra y los cambios globales en Cuba." Instituto de Planificación Física.

Schott, T., Landsea, C., Hafele, G., Lorens, J., Taylor, A., Thurm, H., . . . Zaleski, W. (2012). The Saffir-Simpson hurricane wind scale. NOAA/National Weather Service [Internet], 1-4.

Sharp, R., et al. (2014). "InVEST user's guide." The Natural Capital Project, Stanford.

Spalding, M., et al. (2017). "Mapping the global value and distribution of coral reef tourism." Marine Policy 82: 104-113.

Tallis, H. and S. Polasky (2009). "Mapping and valuing ecosystem services as an approach for conservation and natural-resource management." Annals of the New York Academy of Sciences 1162(1): 265-283.

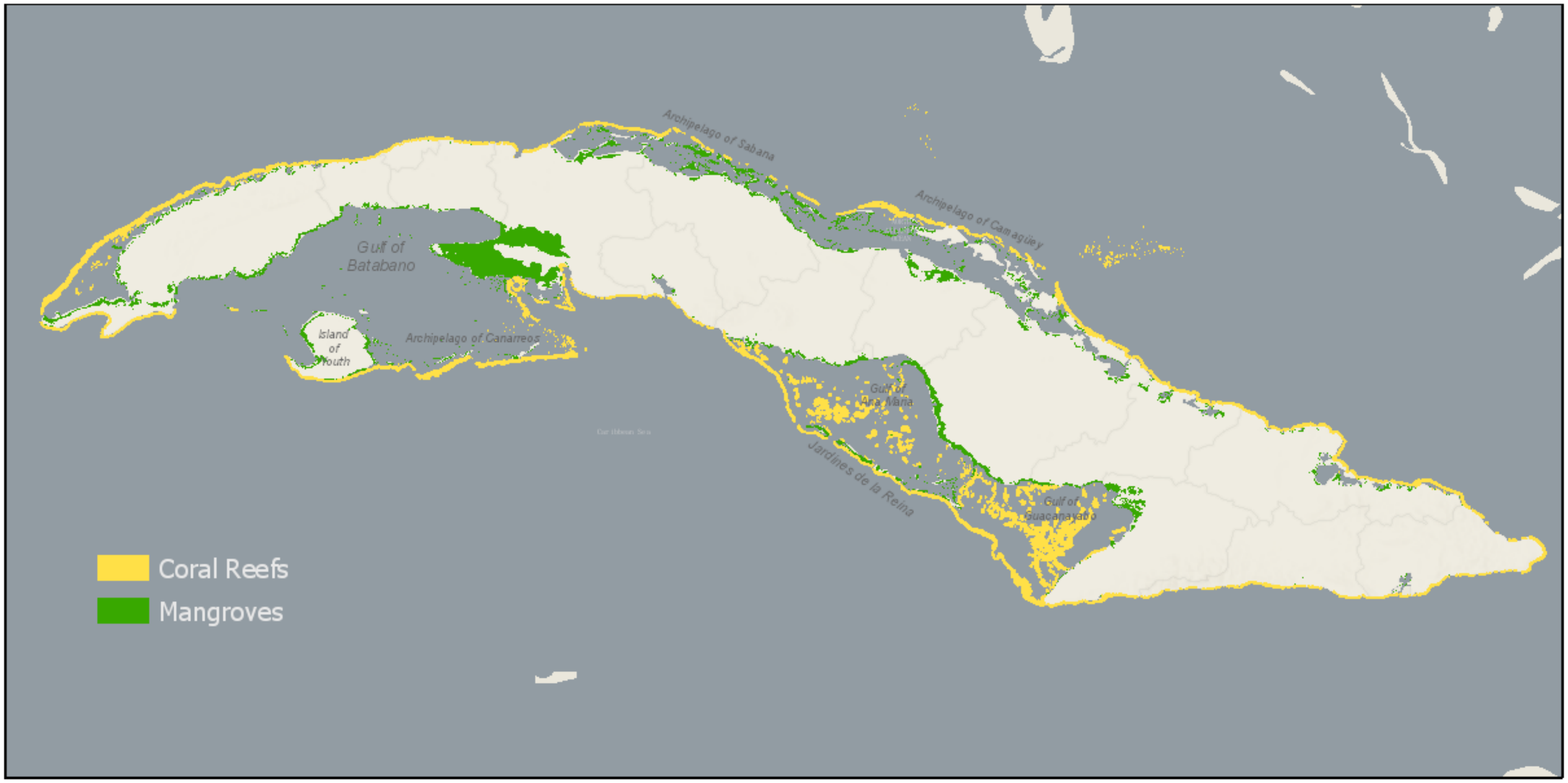
Waite, R., et al. (2014). Coastal capital: ecosystem valuation for decision making in the Caribbean, World Resources Institute.

Whittle, D. and K. Lindeman (2004). Protecting coastal resources in Cuba: a look at current laws and institutions. Proceedings of the coastal society 19th international conference proceedings, Rhode Island, Citeseer.

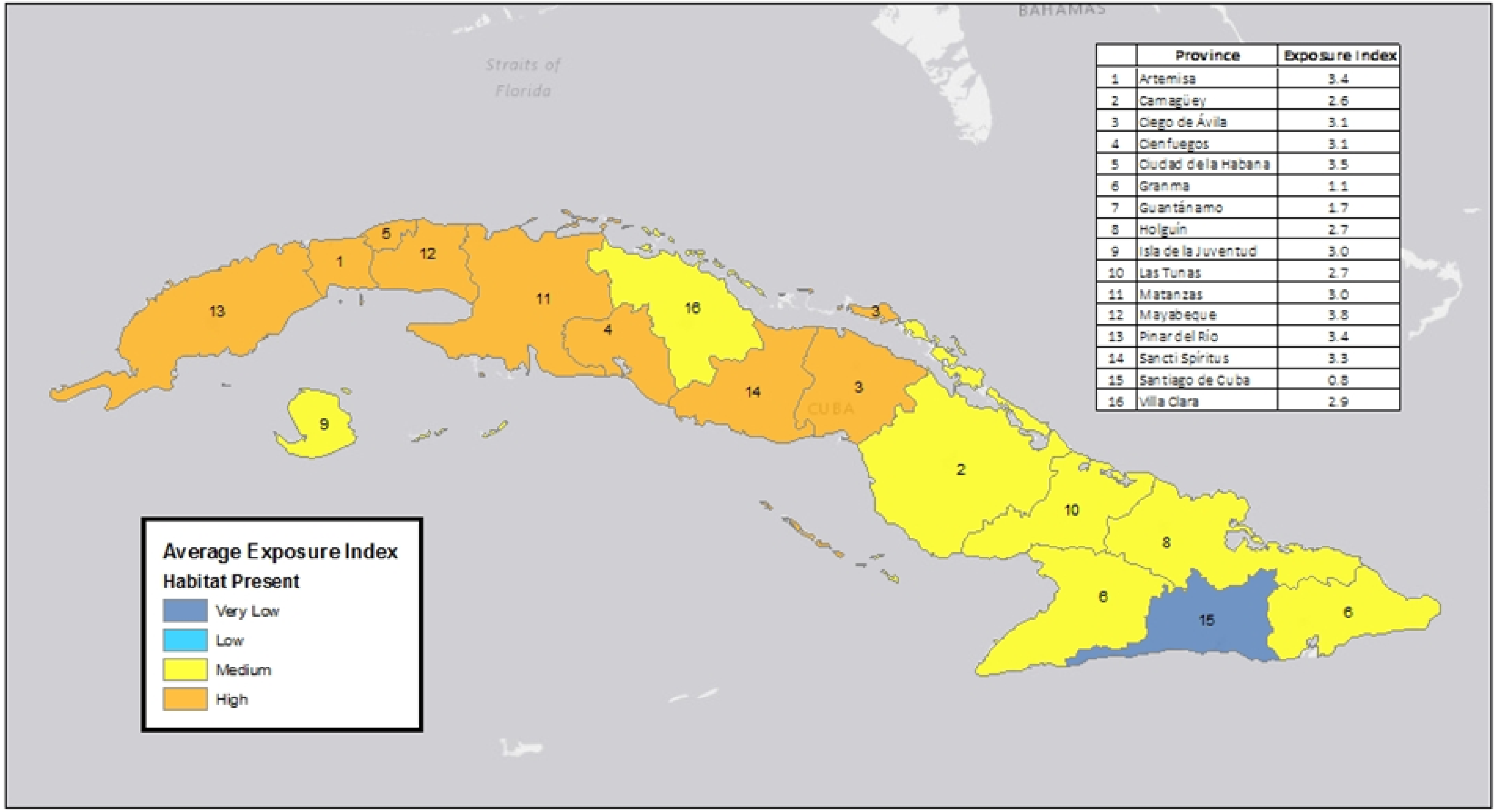
Yahumila, H. (2015). "Areas Marina Protegidas en Cuba: importantes elementos de un sistema nacional para la conservacion. ."

MAPS

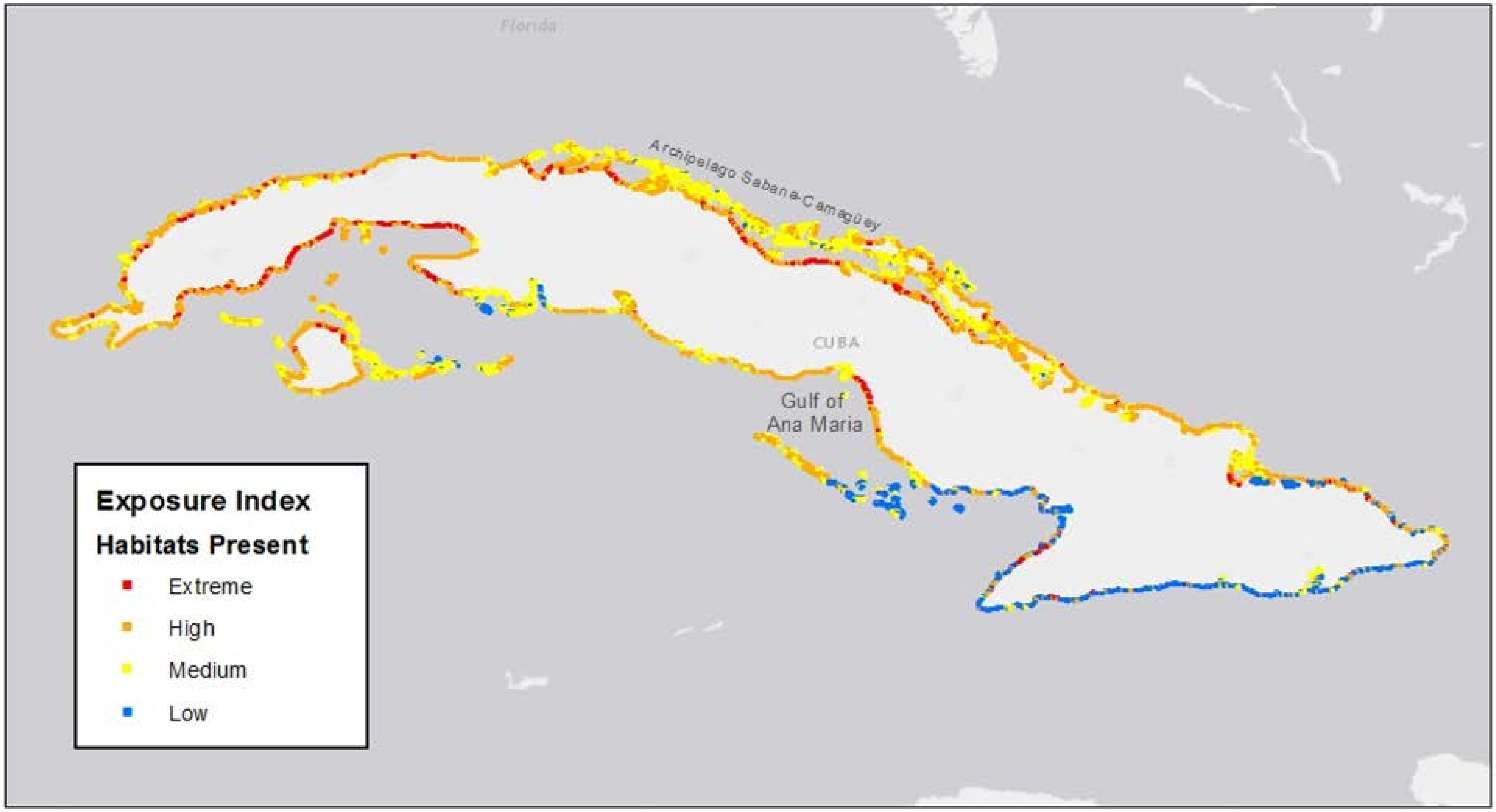
MAP 1 – Map with key gulfs and archipelagos of Cuba. Main gulfs and archipelagos are listed in the map. The map also defines Cuba's National Protected Area System, as in the National Plan of the National Center for Protected Areas from 2014 -2020.



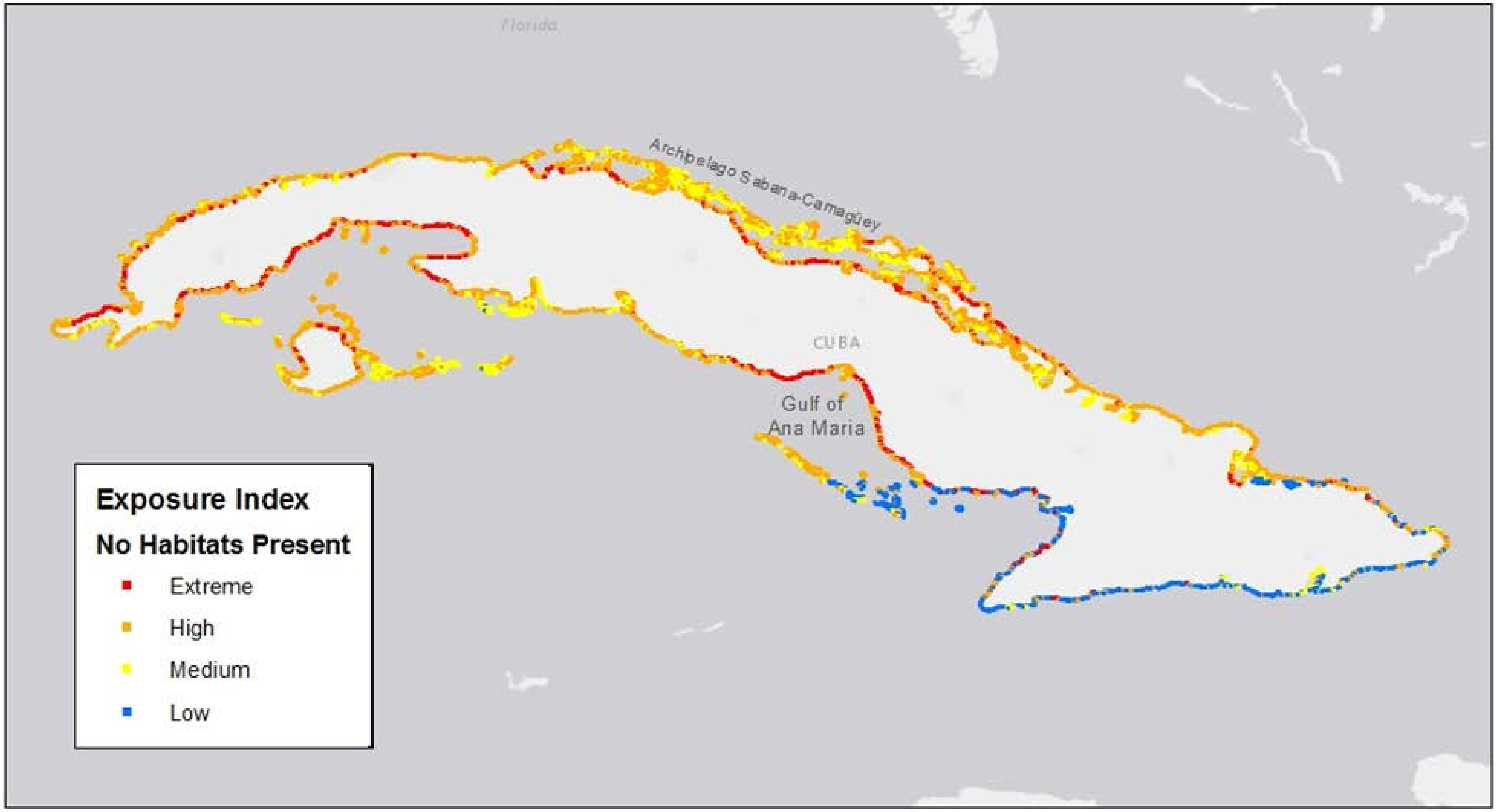
MAP 2 - Cuba's coral reefs cover an area of 3,781 km2, constituting 36 percent of all insular Caribbean coral reefs. Mangrove forest cover 7,337 km2 of Cuba, spanning more than 50 percent of the Cuban coastal areas and representing 20 percent of the total forest cover in Cuba.



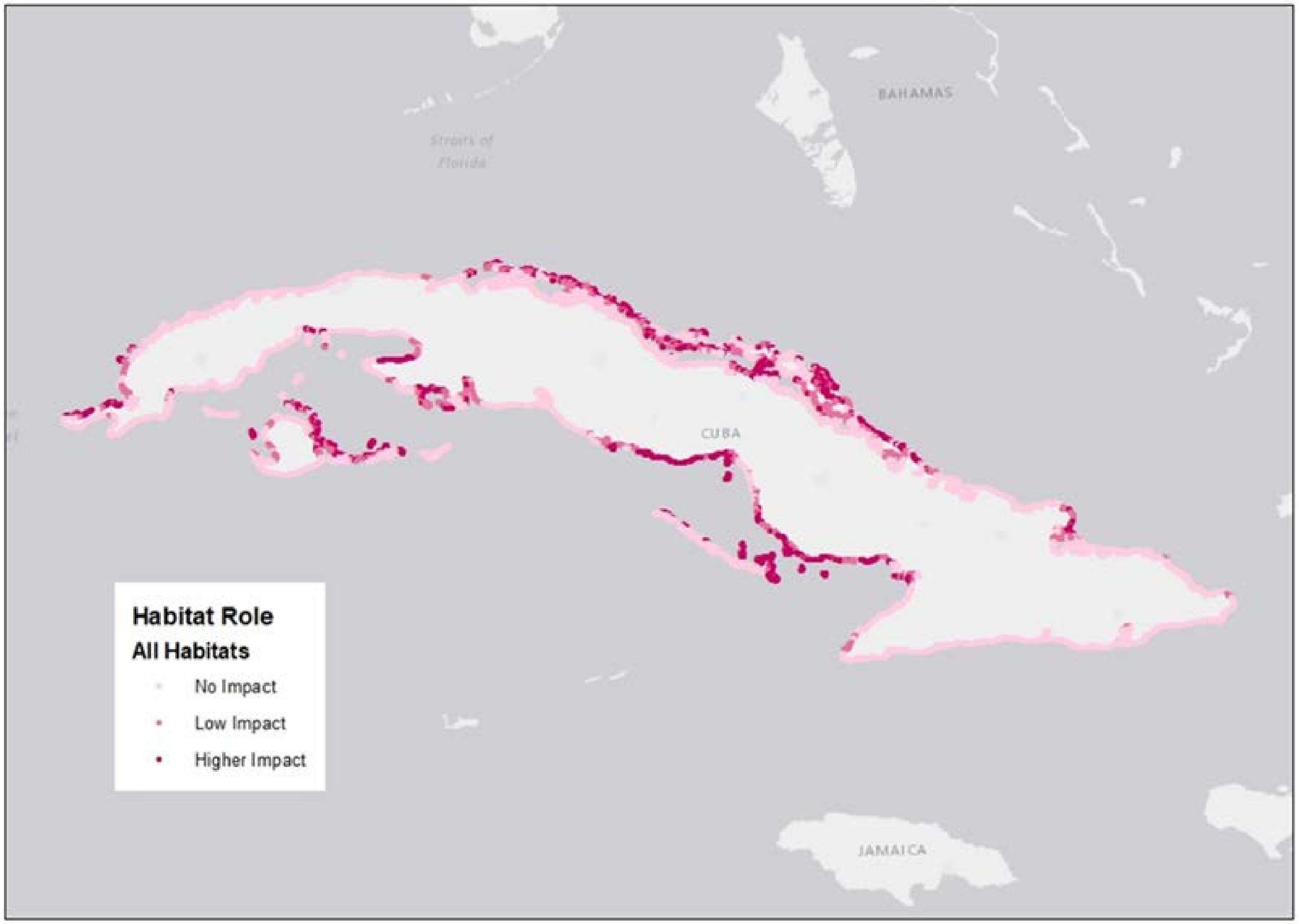
MAP 3- Average exposure index value per providence for all 16 provinces in Cuba. Ranges from very low to high indicated by the colors in the map legend.



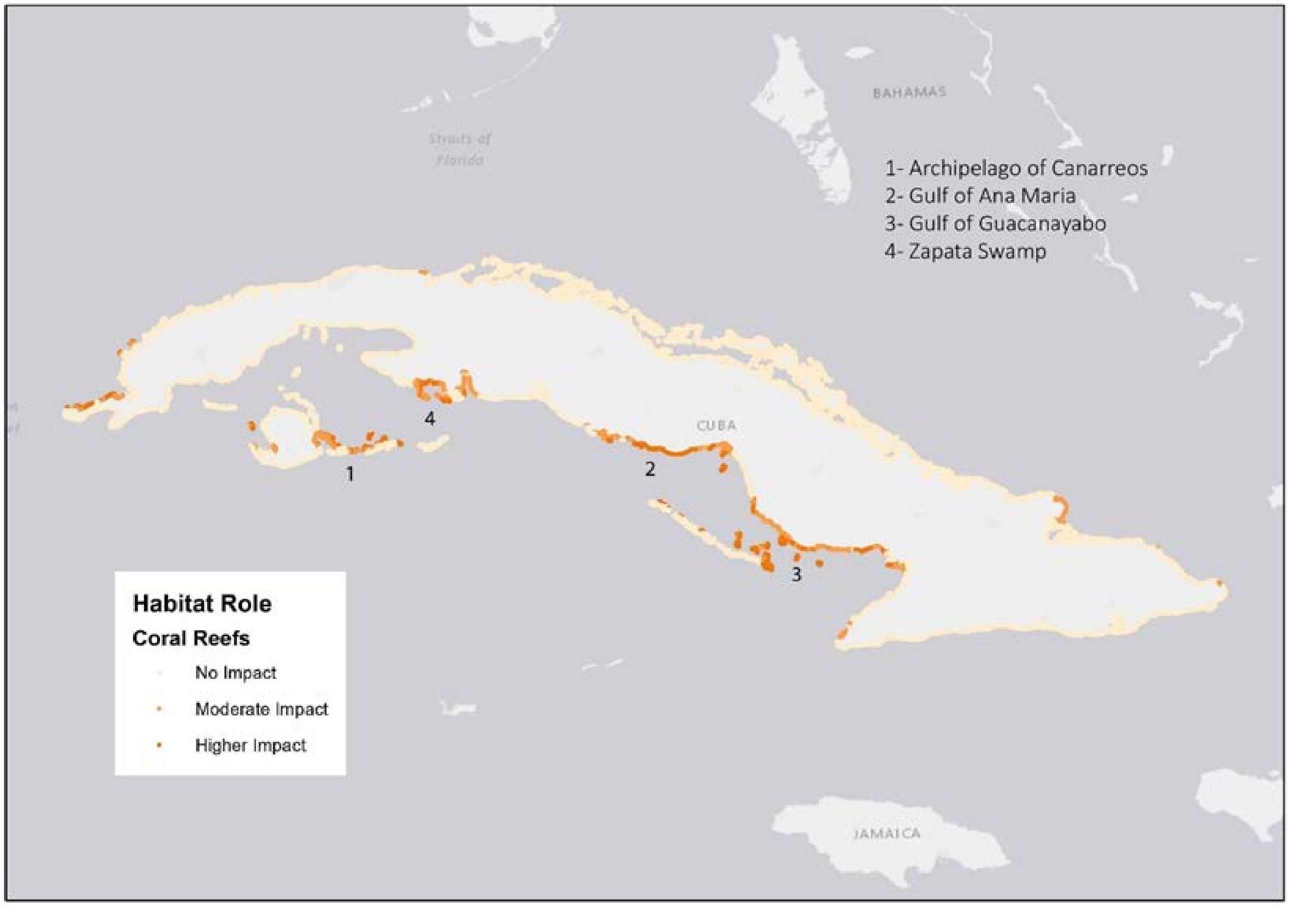
MAP 4 - Exposure index along the coast of Cuba when mangroves are coral reefs are present (habitat present). Exposure Index ranges from extreme to low.



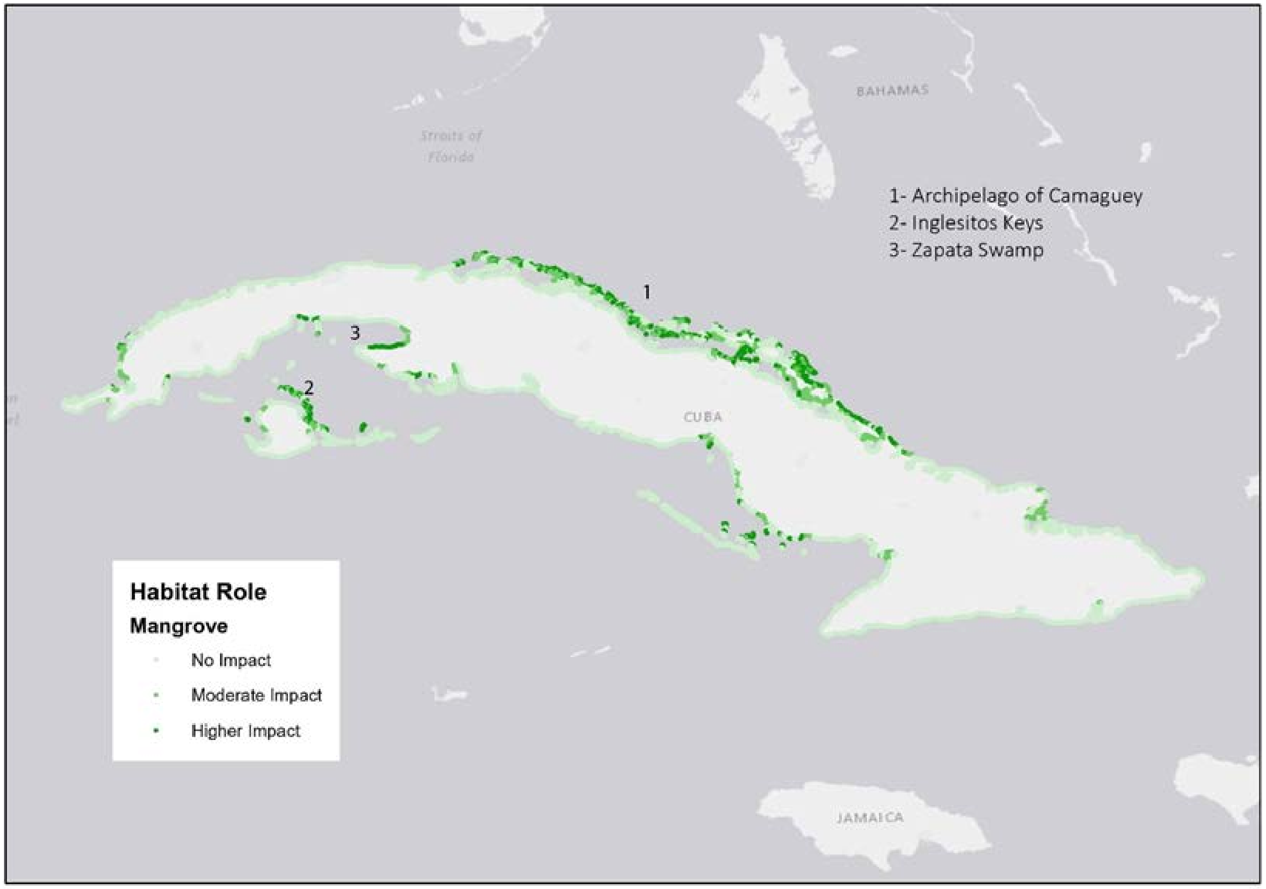
MAP 5- Exposure index along the coast of Cuba when mangroves and coral reefs are absent (habitat absent). Exposure ranges from extreme to low.



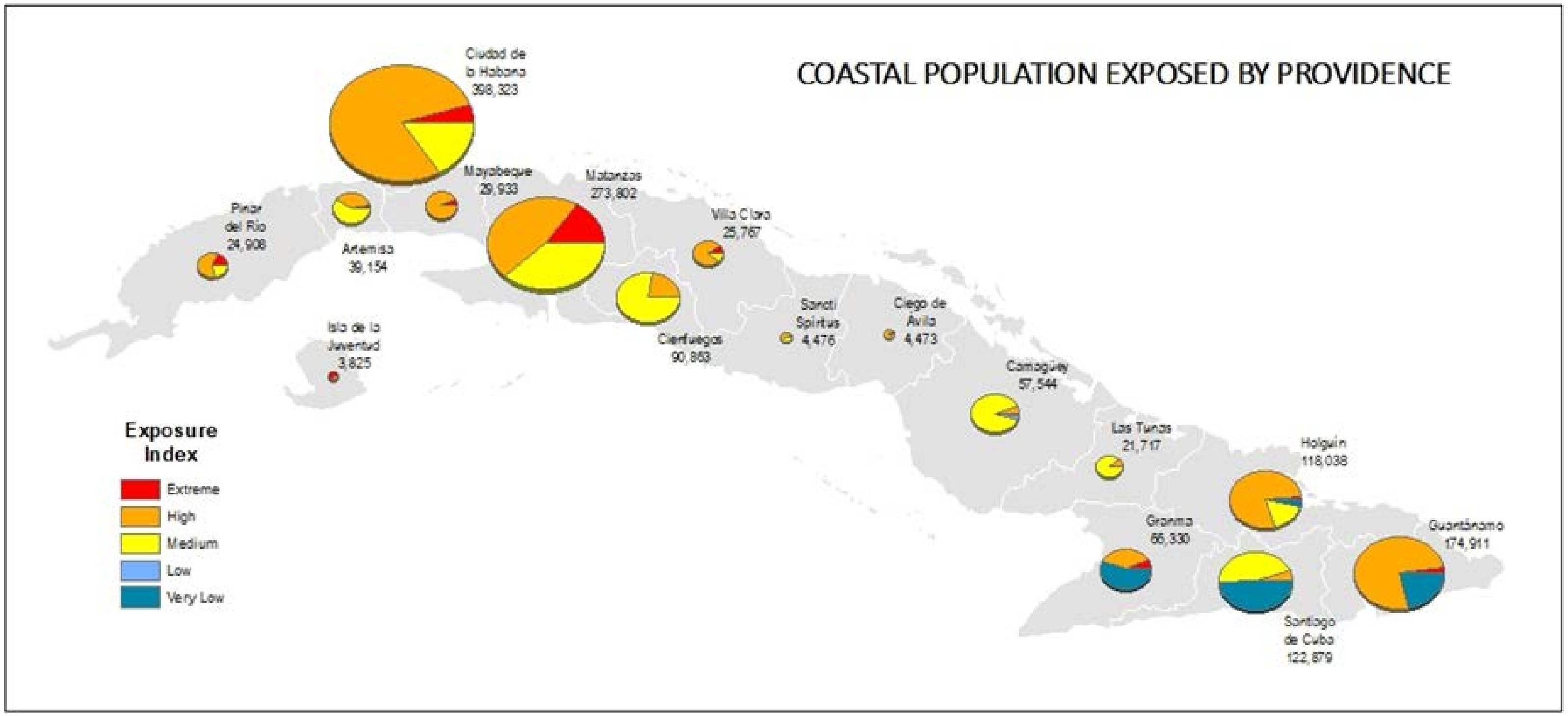
MAP 6 – Habitat role when coral reef and mangrove are present (habitat present). Ranges from no impact to high impact.



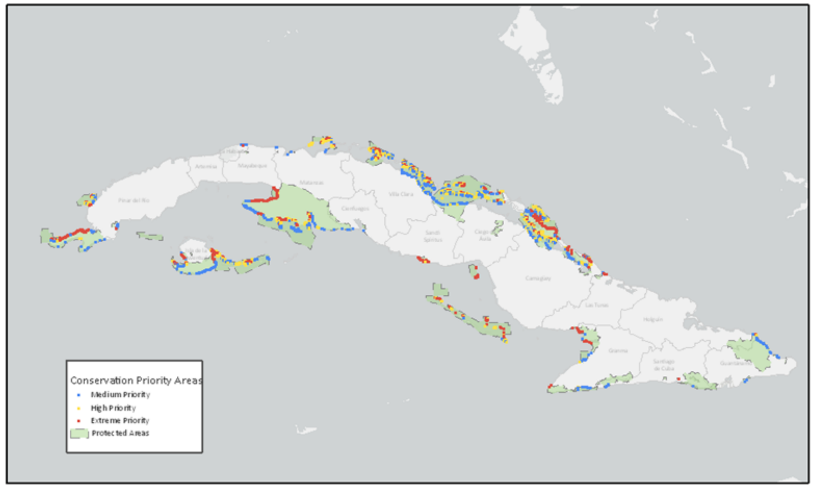
MAP 7 – Habitat role when only coral reefs are present (habitat present). Ranges from no impact to high impact. Indicating important coastal marine areas where coral reefs have higher protective impact.

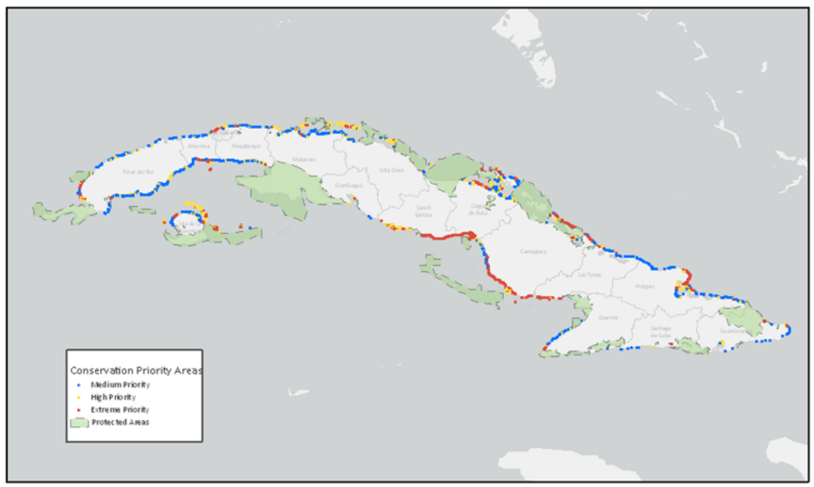


MAP 8 – Habitat role when only mangroves are present (habitat present). Ranges from no impact to high impact, indicating important coastal marine areas where mangroves have higher protective impact.

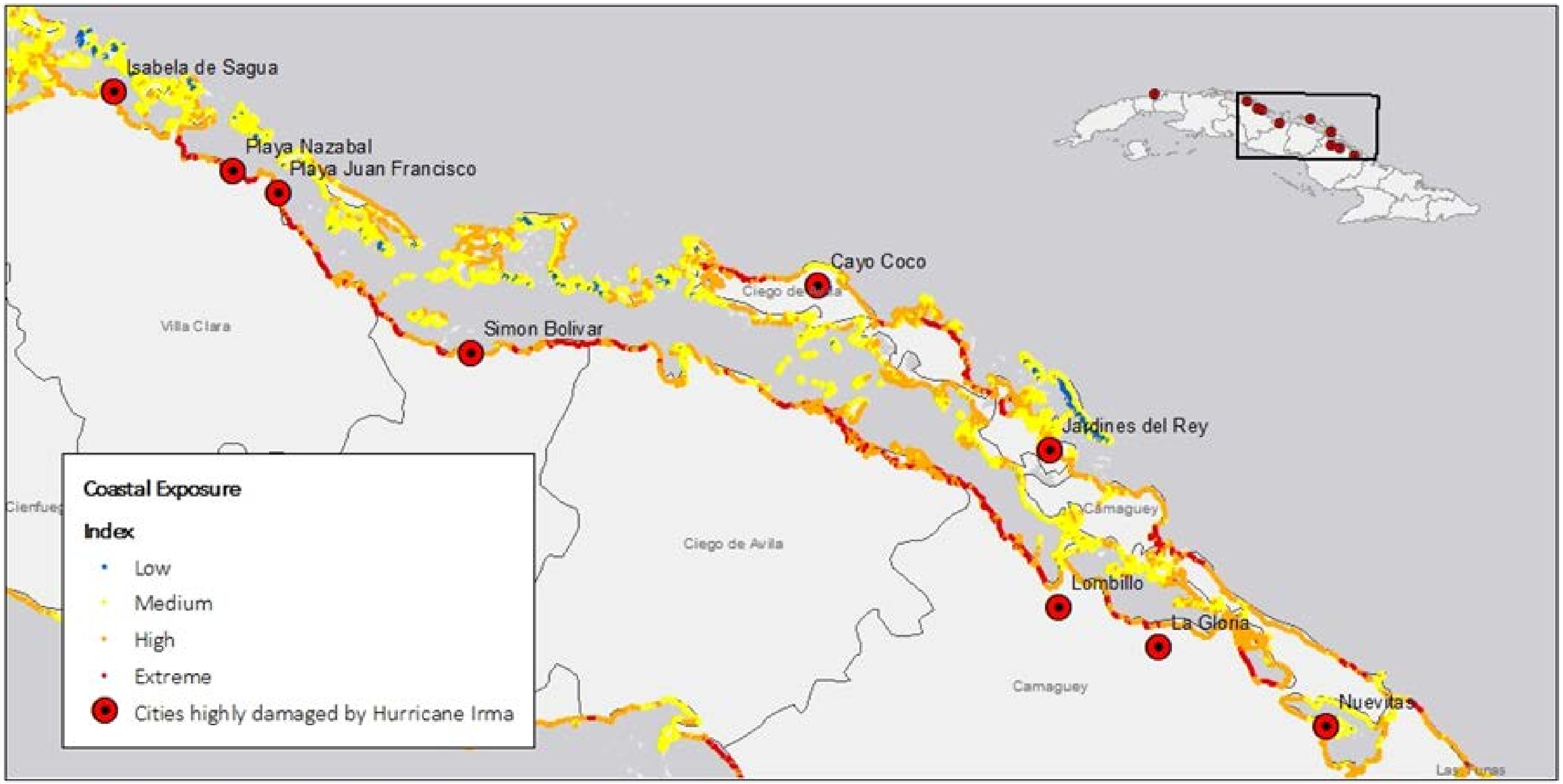


MAP 9 – Exposure index for coastal population by providence. The pie charts in each geographic location of each providence indicate different exposure index values for the population living in that providence. Population numbers indicated by numbers next to each pie chart. Exposure index varies from extreme to very low.





MAP 10 – Areas of conservation priority based on the calculated index based on index of exposure, habitat role and population. Conservation priority index ranges from medium to extreme priority and it is indicated in areas within the current protected area network.



MAP 11 – Cities affected by hurricane Irma (September, 2017) compared to coastal exposure indices obtained from the coastal vulnerability model. Exposure index ranges from low to extreme.

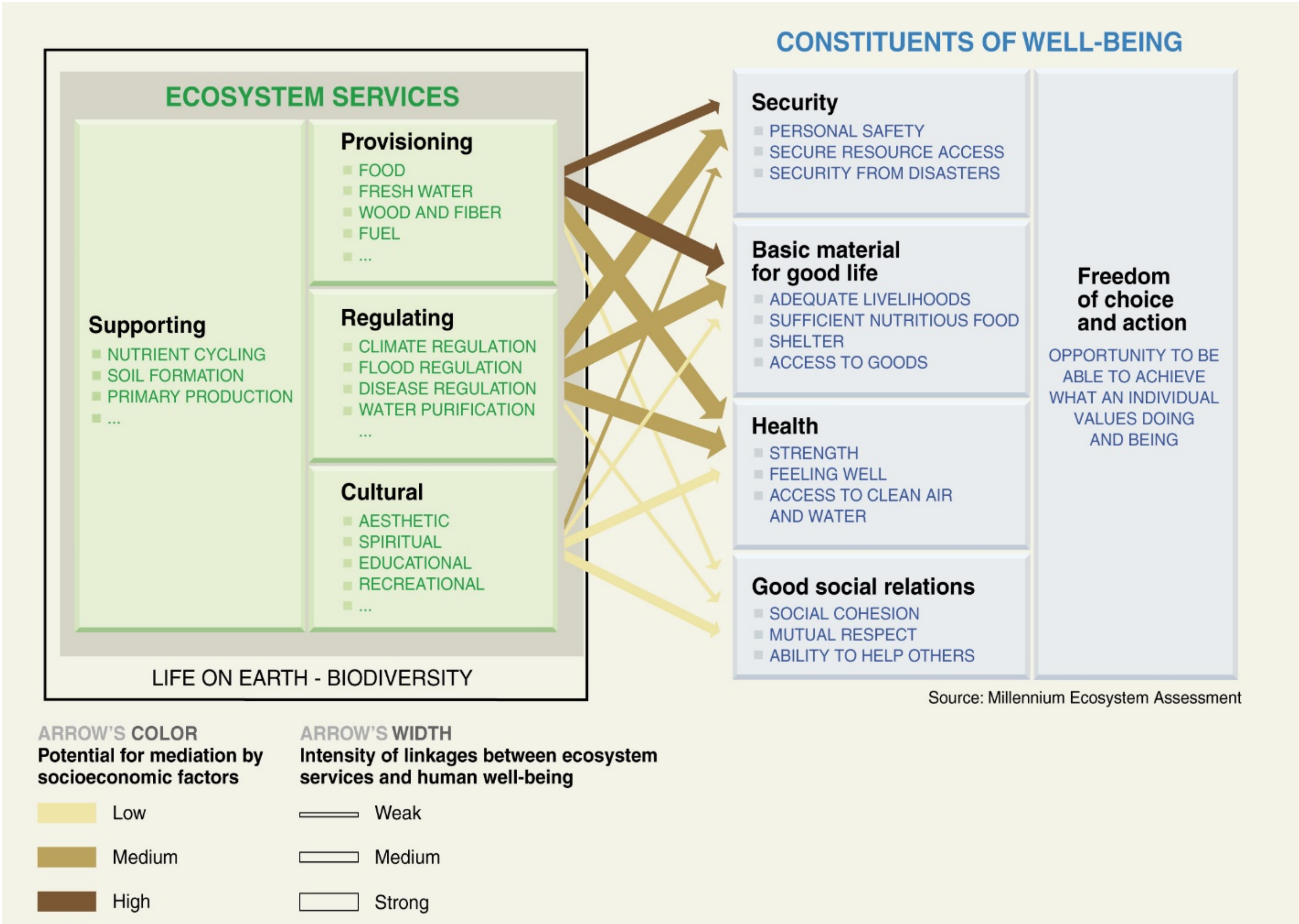


FIGURE 1 - The Millennium Ecosystem Assessment's framework on ecosystem services and human wellbeing (Board 2005).

ECOSYSTEM GOODS AND SERVICES	CORAL REEFS	MANGROVES	BEACHES	SEAGRASSES
Provisioning services				
Food (e.g., fisheries)	X	X	X	X
Raw materials	X	X	X	X
Medicinal resources	X	X		X
Genetic resources	X	X		X
Regulating services				
Flood/storm/erosion regulation	X	X	X	X
Climate regulation	X	X	X	X
Cultural services				
Tourism and recreation	X	X	X	
History, culture, traditions	X	X	X	X
Science, knowledge, education	X	X	X	X
Supporting services				
Primary production	X	X	X	X
Nutrient cycling	X	X		X
Species/ecosystem protection	X	X	X	X

Sources: Adapted from Schuhmann 2012a, UNEP 2006, Barbier et al. 2011, Costanza et al. 2006.

FIGURE 2 – Examples of coastal ecosystem goods and services (Waite, Burke et al. 2014).

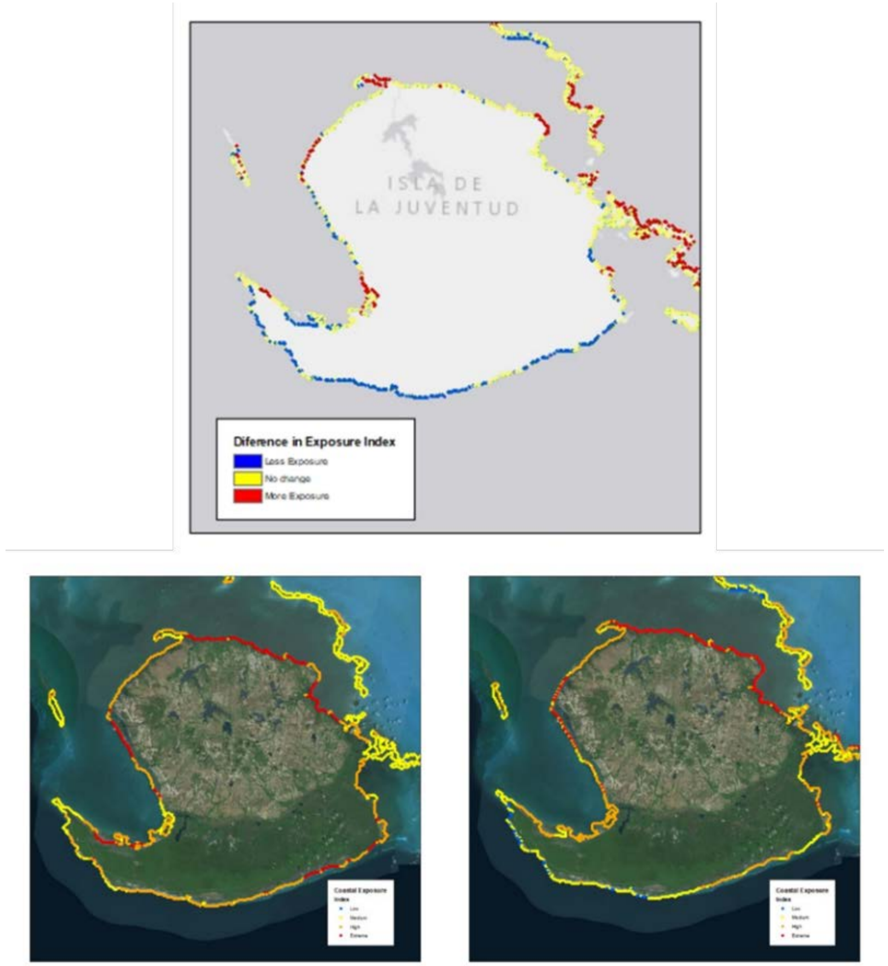


FIGURE 3 – Top map: Difference in exposure index between model results using global data vs refined local data. Bottom left map: Exposure index – Global data. Bottom right map: Exposure index – Refined data. Exposure index ranges from extreme to low.

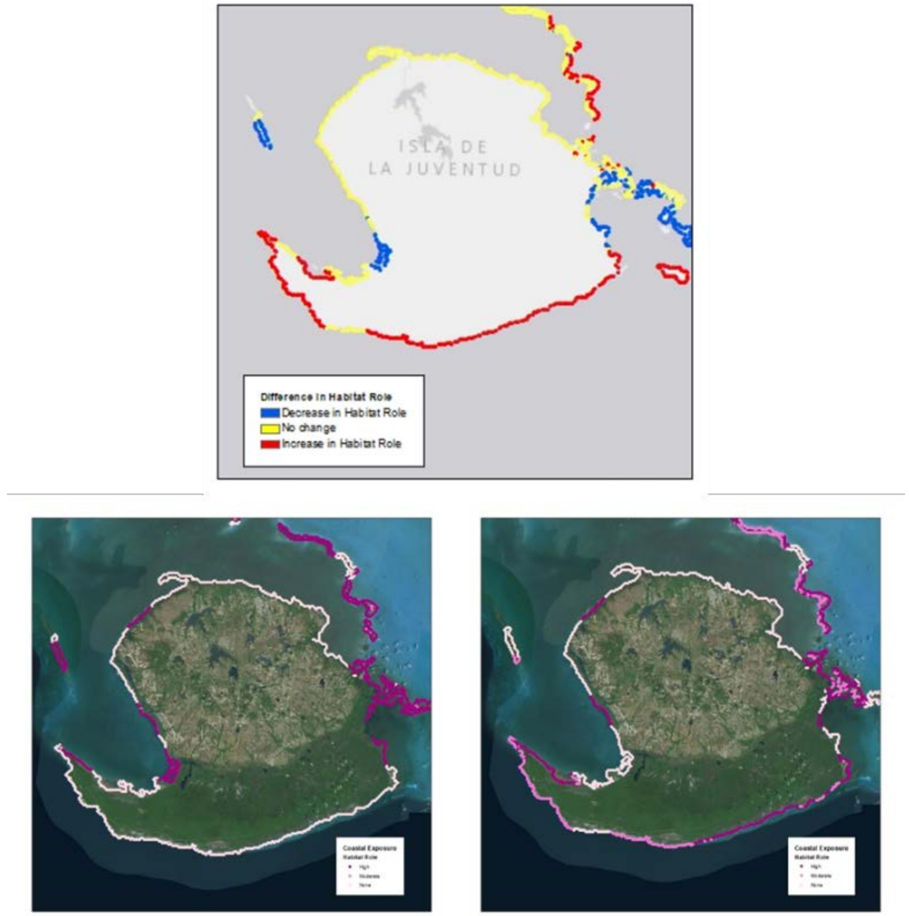


FIGURE 4 - Top map: Difference in habitat role between model results using global data vs refined local data. Bottom left map: Habitat role – Global data. Bottom right map: Habitat role – Refined data. Habitat role ranges from high to none.

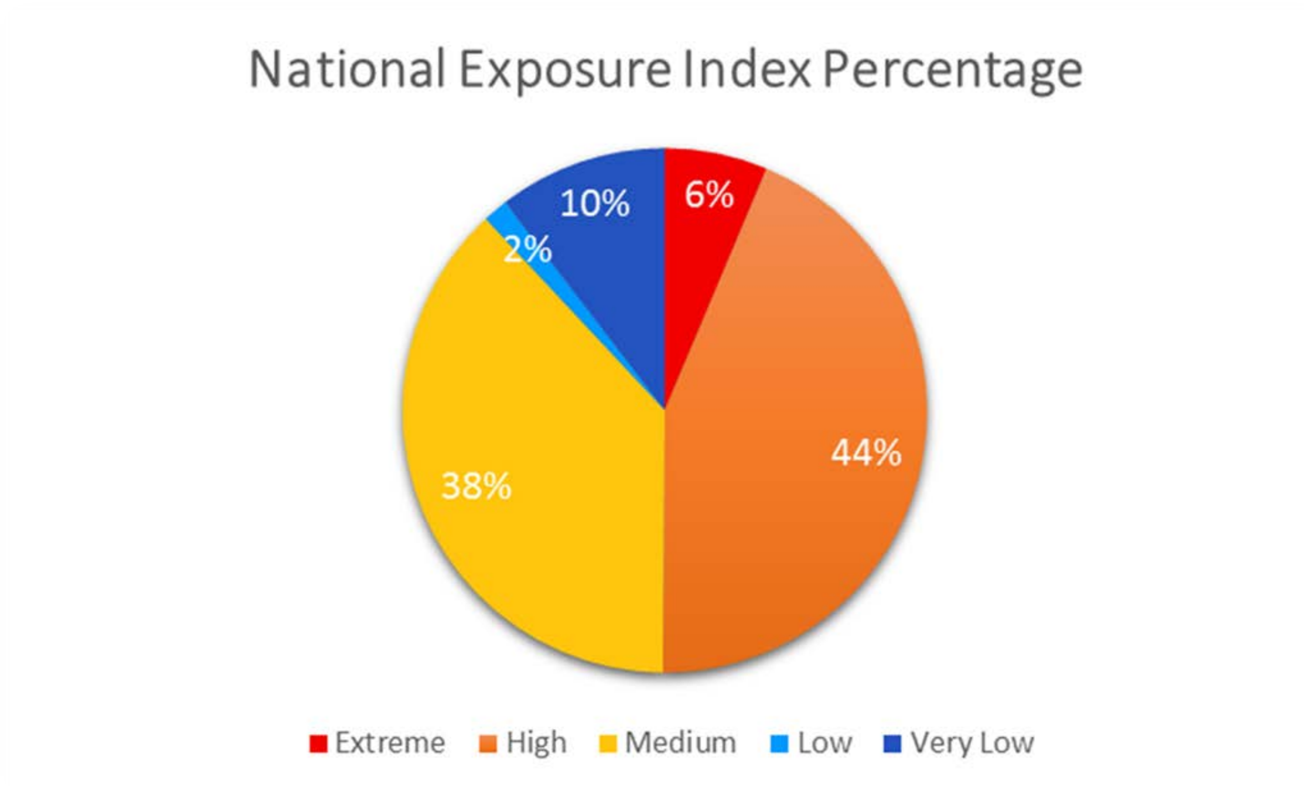


FIGURE 5 – National Exposure Index Percentage for the entire country ranging from extreme to very low.

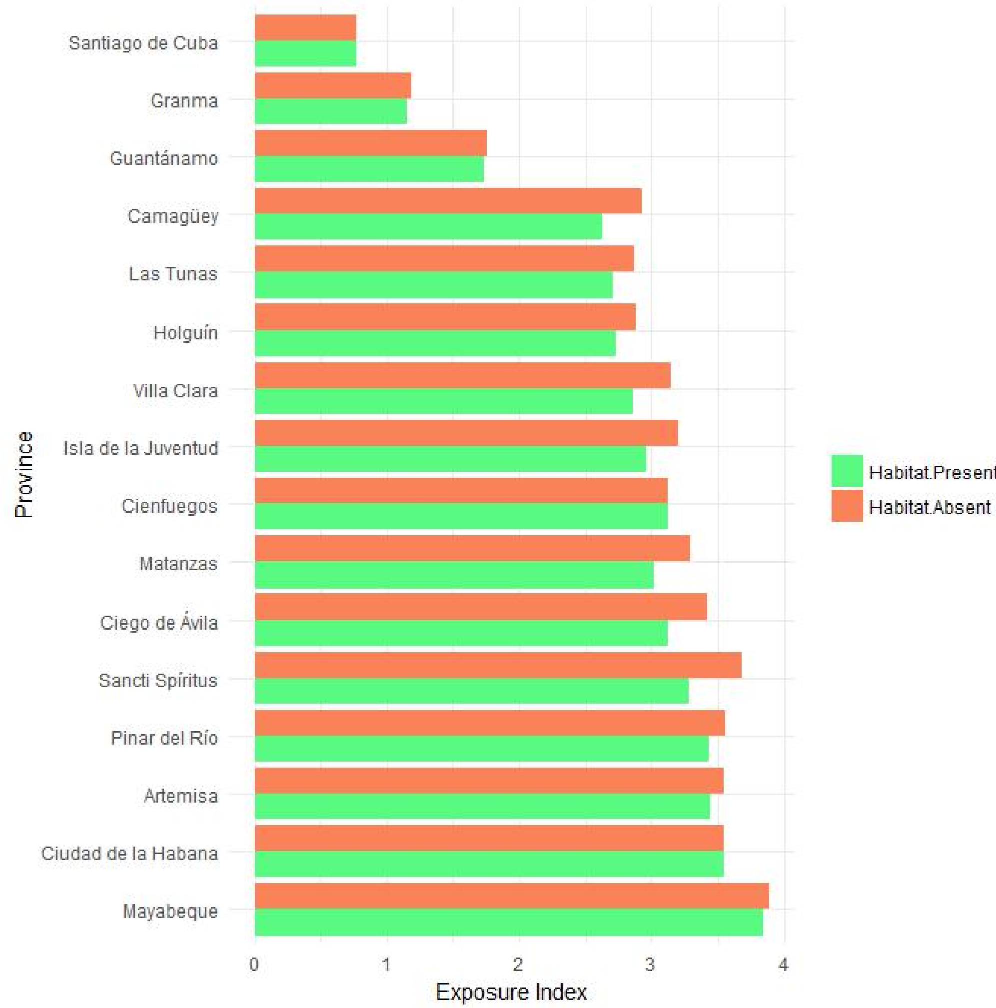


FIGURE 6 – Exposure index difference between habitat present in green and habitat absent in orange scenarios for all 16 provinces in Cuba. Only the presence of coral reefs and mangroves were considered as habitat in these scenarios.

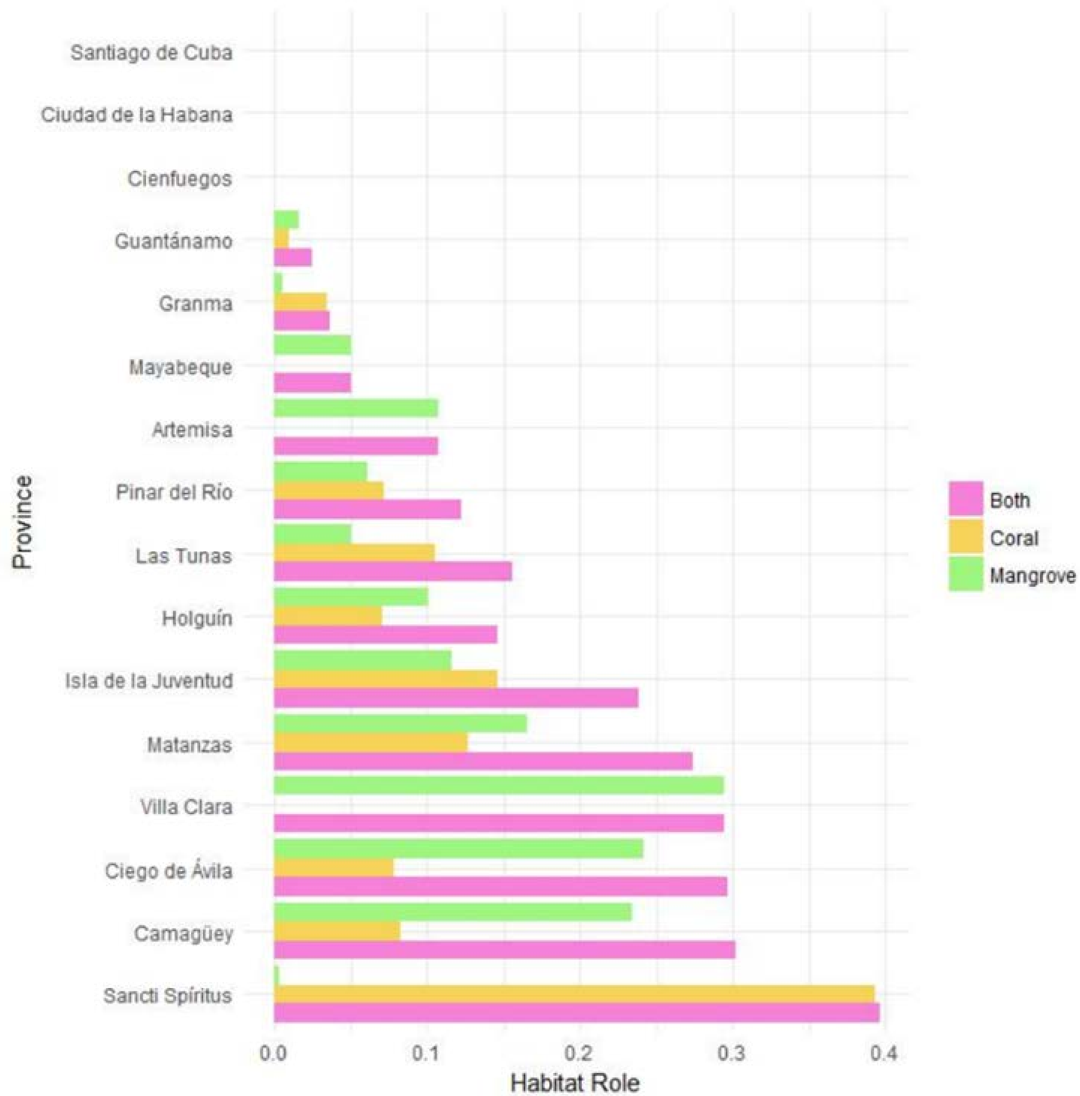


FIGURE 7 – Habitat role (mangroves and coral reefs) per providence (for all 16 provinces) under various scenarios. Pink – Mangroves and coral reefs present, Orange – Only coral reefs are present and Green – only mangroves are present. Habitat role ranges from 0 to 1.

TABLES

	Very Low	Low	Moderate	High	Very High
Rank - Variable	1	2	3	4	5
Geomorphology	Rocky; high cliffs; fjord; seawalls	Medium cliff; indented coast, bulkheads and small seawalls	Low cliff; glacial drift; alluvial plain, revetments, rip-rap walls	Cobble beach; estuary; lagoon; bluff	Barrier beach; sand beach; mud flat; delta
Relief	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Natural Habitats	Coral reef; mangrove; coastal forest	High dune; marsh	Low dune	Seagrass; kelp	No habitat
Sea Level Change	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Wave Exposure	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Surge Potential	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile

TABLE 1– The model computes the physical exposure index by combining the ranks of the seven biological and physical variables at each shoreline segment. Ranks vary from very low exposure (rank- 1), to very high exposure (rank- 5), based on a mixture of user and model defined criteria.

Municipality	Index of Exposure
Most exposed provinces	
Güines	4.38
Melena del Sur	4.32
Los Palacios	4.31
San Nicolás	4.29
Artemisa	4.22
Consolación del Sur	4.18
San Cristóbal	4.17
Candelaria	4.15
Quivicán	4.15
Camajuaní	4.13
San Luis	4.01
San Juan y Martínez	3.99
Bauta	3.96
Sierra de Cubitas	3.95
Florencia	3.93
Batabanó	3.91
Guane	3.91
Nueva Paz	3.91
Florida	3.86
Pinar del Río	3.86

Municipality	Index of Exposure
Least exposed provinces	
Regla	2.19
Guantánamo	2.15
Campechuela	2.11
Maisí	2.10
Amancio	2.10
Manzanillo	1.93
Frak País	1.86
Santa Cruz del Sur	1.71
Caimanera	1.68
Jobabo	1.52
Niquero	1.28
Pilón	1.24
San Antonio del Sur	1.09
Bartolomé Masó	1.08
Santiago de Cuba	1.00
Colombia	0.99
Guamá	0.96
Imías	0.89
Río Cauto	0.57
Yara	0.10

TABLE 2 – Municipalities with the highest and lowest exposure index. Ranges from 1- very low exposure to 5 – very high exposure.

	All Habitats	Coral	Mangrove
Venezuela	0.866	0.739	0.363
La Sierpe	0.779	0.779	0.000
Baraguá	0.683	0.598	0.247
Vertientes	0.671	0.548	0.213
Unión de Reyes	0.640	0.000	0.640
Sancti Spíritus	0.624	0.624	0.000
Guantánamo	0.533	0.000	0.533
Amancio	0.484	0.484	0.000
Antilla	0.466	0.106	0.429
Esmeralda	0.443	0.000	0.443
Jobabo	0.390	0.390	0.000
Nuevitas	0.372	0.000	0.372
Trinidad	0.371	0.371	0.000
Ciénaga de Zapata	0.355	0.229	0.160
Banes	0.350	0.287	0.147
Mantua	0.350	0.090	0.288
Caibarién	0.323	0.000	0.323
Nueva Paz	0.313	0.000	0.313
Corralillo	0.295	0.000	0.295
Morón	0.291	0.000	0.291

TABLE 3 – Municipalities with the highest habitat role index values, for both habitats (coral reef and mangroves, for only coral reefs and for only mangroves). Habitat role values ranging from 0 to 1.