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A climate change vulnerability framework for Corales del Rosario y San Bernardo National Natural Park, Colombia

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ABSTRACT: Assessing the vulnerability of resources to the potential impacts from climate change is critical in implementing management strategies aimed at resource conservation. A conceptual framework of climate change vulnerability was developed for Corales del Rosario y San Bernardo National Natural Park (PNNCRSB), Colombia, a park designated to protect coastal and marine ecosystems. Climate change vulnerability scores were developed based on resource-specific sensitivity, exposure, and adaptive capacity to climate change factors (sea surface and air temperature, precipitation, ocean acidification, and inundation from sea level rise and extreme events). Exposure scores were based on exceedances of thresholds, or when applicable, inundation. Scores were calculated for 10 m^2 grid cells every 5 yr between 2010 and 2100 under 'optimistic' and 'pessimistic' climate change scenarios. Sea turtle nesting beaches, coastal and interior lagoons, corals and bird habitat are the natural resources with the highest vulnerability scores. Among socioeconomic resources, recreational beaches and low-lying roads are among the most vulnerable. Based on the 2100 pessimistic scenario, adaptive capacity contributed the most to the vulnerability score (range: 34–55% contribution), followed by sensitivity (range: 27–41%) and exposure (range: 14–37%). Based on elevation alone, coastal and interior lagoons, mangroves and sea turtle nesting beaches in low-lying areas are among the most susceptible resources to inundation, which ranged from −0.7 to −172 m^2 yr^{-1} and from −3.7 to −473 m^2 yr^{-1} for the optimistic and pessimist scenarios, respectively. While this climate change vulnerability framework for PNNCRSB may aid in the prioritization of mitigation and conservation strategies within the park, an understanding of the approach, including its limitations and uncertainties, is recommended.

KEY WORDS: Colombia · National park · Vulnerability framework · Threshold exceedance · Inundation · Marine and coastal resources · Mitigation and conservation

1. INTRODUCTION

Climate change has the potential to disproportionally impact small islands, with low-lying coastal regions being particularly vulnerable to inundation, erosion and saline intrusion (e.g. Bijlsma et al. 1995, Mimura et al. 2007). Under all existing sea level rise scenarios, and particularly in the worst-case scenario, small islands are expected to lose at least a portion of their land. This will have negative effects on multiple natural terrestrial and aquatic resources, with consequences for economic resources such as tourism, fisheries, and associated infrastructure (see Doney et al. 2012, Nurse et al. 2014). In the greater Caribbean and Latin America, several efforts have been made (e.g. INVEMAR 2003, Cambers et al.

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2009, CEPAL 2012, BIOMARC-USAID 2013, USAID-BIOMARCC-GIZ 2013, Magrin et al. 2014; www.c3a.ihcantabria.com/[accessed 10 February 2015]) to understand the potential effects of climate change on natural and societal resources, and to provide the basis for realistic adaptation strategies. However, not all areas affected by climate change have the resources or technical capacity to quantify associated threats. To address this problem, international initiatives have been developed to help countries and communities prepare for and adapt to climate change, including the development of data and tools to identify climate change vulnerabilities (USAID 2012). Colombia is not immune to the ecological, social, and economic challenges that accompany climate change. Over the last decade, the Colombian government, through several institutions and in collaboration with international partners, has been actively engaged on issues related to climate change with a focus on identifying vulnerable areas within the national territory (IDEAM 2001, INVEMAR 2003, 2008, 2011, Vides 2008, CEPAL 2013). As with many other countries in the Americas, these efforts are important for implementing adaptation measures aimed at reducing and mitigating the impacts of climate change. Similarly, the agency in charge of the national natural parks of Colombia has established research priorities that specifically include assessments of vulnerability, adaptability, and mitigation of climate change impacts on all national parks, including effects on natural, societal, and cultural resources and associated ecosystem goods and services derived from these areas (PNNC 2011). These steps are important for setting conservation and protection strategies and priorities for the near future.

The national natural park system of Colombia is currently comprised of 59 protected areas. Eleven of these parks, which in total comprise 1.4 % of the national territory, are designated to protect coastal and marine ecosystems. One of the largest parks is the Corales del Rosario y San Bernardo National Natural Park (hereafter CRSB). The CRSB was originally created in 1977 to protect 178 km^2 of marine habitats; it was expanded in 1996 to 1200 km^2 to encompass reefs around the San Bernardo Islands (Zarza-González 2011). In addition to containing nearly 80 % of all coral reef coverage within the continental shelf of Colombia (excluding San Andrés y Providencia) (Díaz et al. 2000), this park also has a variety of coastal and marine ecosystems, and harbors extensive marine and coastal biodiversity. However, environmental degradation within CRSB and surrounding areas has been occurring for several years, resulting in a decline in seagrass, mangroves and coral coverage, an increase in coral bleaching and disease, and loss of biodiversity (Zarza-González 2011). This degradation is the result of numerous factors including accelerated coastal erosion, high sediment loading and freshwater inputs from the Magdalena River mainly through the Canal del Dique (an artificial channel connecting Cartagena Bay to the Magdalena River), lack of wastewater treatment, and other effects of anthropogenic activities within the protected area (e.g. localized deforestation, illegal resource harvesting, poor waste management, unsustainable fishing practices, etc.) (Díaz et al. 2000, Garzón-Ferreira et al. 2001, Cendales et al. 2002, Restrepo et al. 2006, 2012, INVEMAR 2011, Zarza-González 2011, INVEMAR-MADS 2012). As a result, conservation objectives have been formulated by the managing agency to protect marine and coastal ecosystems within the park, as well as dry tropical forests, endangered species, and species of artisanal or commercial importance.

As for many other protected areas in the Caribbean, climate change has been identified as one of the emerging issues of concern within the CRSB (INVEMAR 2011, INVEMAR-MADS 2012). In response to this concern, the primary goal of the present research is to develop a conceptual framework of climate change vulnerability for key coastal and marine habitats, and associated socioeconomic resources, within the CRSB. This site was chosen based on its high natural resource value and valuable socioeconomic resources, including those associated with both tourism and artisanal fishing. A first step towards developing a resource strategy to address climate change threats is an assessment of what geographic areas and resources are most at risk. Vulnerability to climate-based hazards is well documented within the literature, and numerous conceptual models and frameworks have been developed to describe it (Cutter 1996). Within the climate change framework, vulnerability assessments incorporate 3 important dimensions: exposure, sensitivity, and adaptive capacity (after Adger 2006). The current analysis builds on similar approaches, using site- and resource-specific information to inform all dimensions of the vulnerability framework, as well as site-specific climate change knowledge and trends for several climate factors of interest: sea surface and air temperature, precipitation, ocean acidification, and inundation from sea level rise and extreme events. The outcomes of this vulnerability framework are intended to serve as a starting point to outline and evaluate climate change mitigation and adaptive strategies within the CRSB.

2. METHODS

2.1. Resources within the Corales del Rosario y San Bernardo National Natural Park

The management plan of the CRSB divides the park into 3 zones (INVEMAR-MADS 2012) (Fig. 1). The first zone is an area of high conservation priority or largely untouched areas where human activities are restricted or prohibited; includes the islands of Rosario, Tesoro, Mangle and Maravilla, and their surrounding waters. The second zone is managed as an area of natural recovery, where activities associated with habitat degradation are reduced thereby enhancing the ability of habitats to recover via restoration activities and natural recovery processes; this area includes all coral reefs (0 to 5 m depth) and ecosystems surrounding Grande, Barú, and Tintipán Islands, and other smaller islands (i.e. Ceycén and Panda Islands). The third zone is open to recreational activities and tourism; it includes lagoons in Grande Island, marine ecosystems between 5 and 50 m depth, navigation channels, as well as most of Barú, Múcura and Tintipán Islands, and Santa Cruz Islet. All other emerged areas of Grande, Barú, Tintipán and Múcura Islands are not part of the CRSB, but any human activities within these areas are likely to impact the adjacent designated areas.

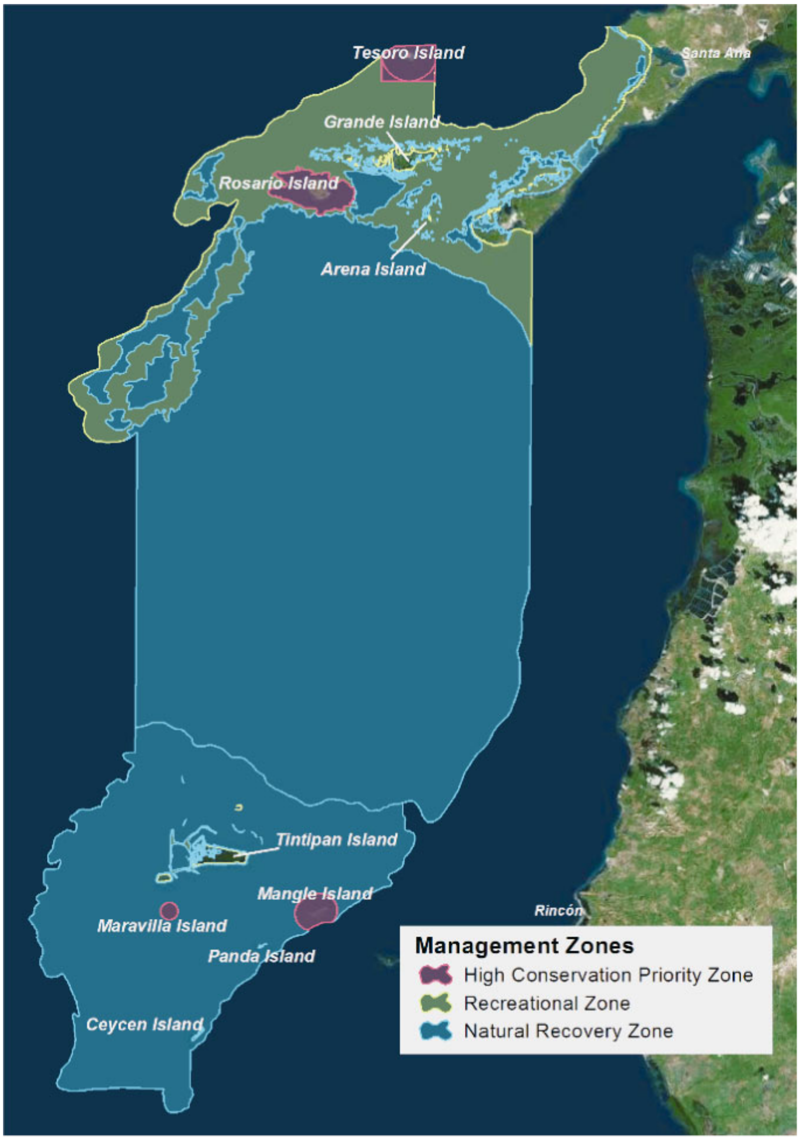


Fig. 1. Corales del Rosario y San Bernardo National Natural Park (CRSB), Colombia. The map shows the National Park boundary, principal islands, and the 3 management zones. Basemap Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Biological resources within the park (Fig. 2) include birds (terrestrial, seabirds, and migratory species), coral reefs (representative species: *Orbicella* spp., *Agaricia* spp., *Porites* spp.), sponges, sea grasses (i.e. *Thalassia testudinum*, *Syringodium filiforme*, *Halodule wrightii* and *H. decipiens*), marine algae (calcareous algae, micro and macroalgae), mangrove forests (dominant species: *Rhizophora mangle*, *Laguncularia racemosa*, and *Avicennia germinans*) and tropical dry forests, as well as rocky shores, sedimentary deposits, sandy shores, coastal and interior lagoons, and sea turtle nesting beaches. Sea turtles known to nest in the area include the critically endangered hawksbill turtle *Eretmochelys imbricata* (Mortimer & Donnelly 2008) and the endangered green turtle *Chelonia mydas* (Seminoff 2004). Within the context of this research, important species are evaluated within their respective habitats.

Socioeconomic resources include those that primarily support tourism and its infrastructure in areas designated for recreation and tourism (i.e. beaches, coastal and interior lagoons, and tropical dry forest), subsistence crops and pasture grasses, hotels, docks, shoreline protection projects, and pedestrian trails. Most of these resources fall outside the jurisdiction of the park, with exception of the CRSB

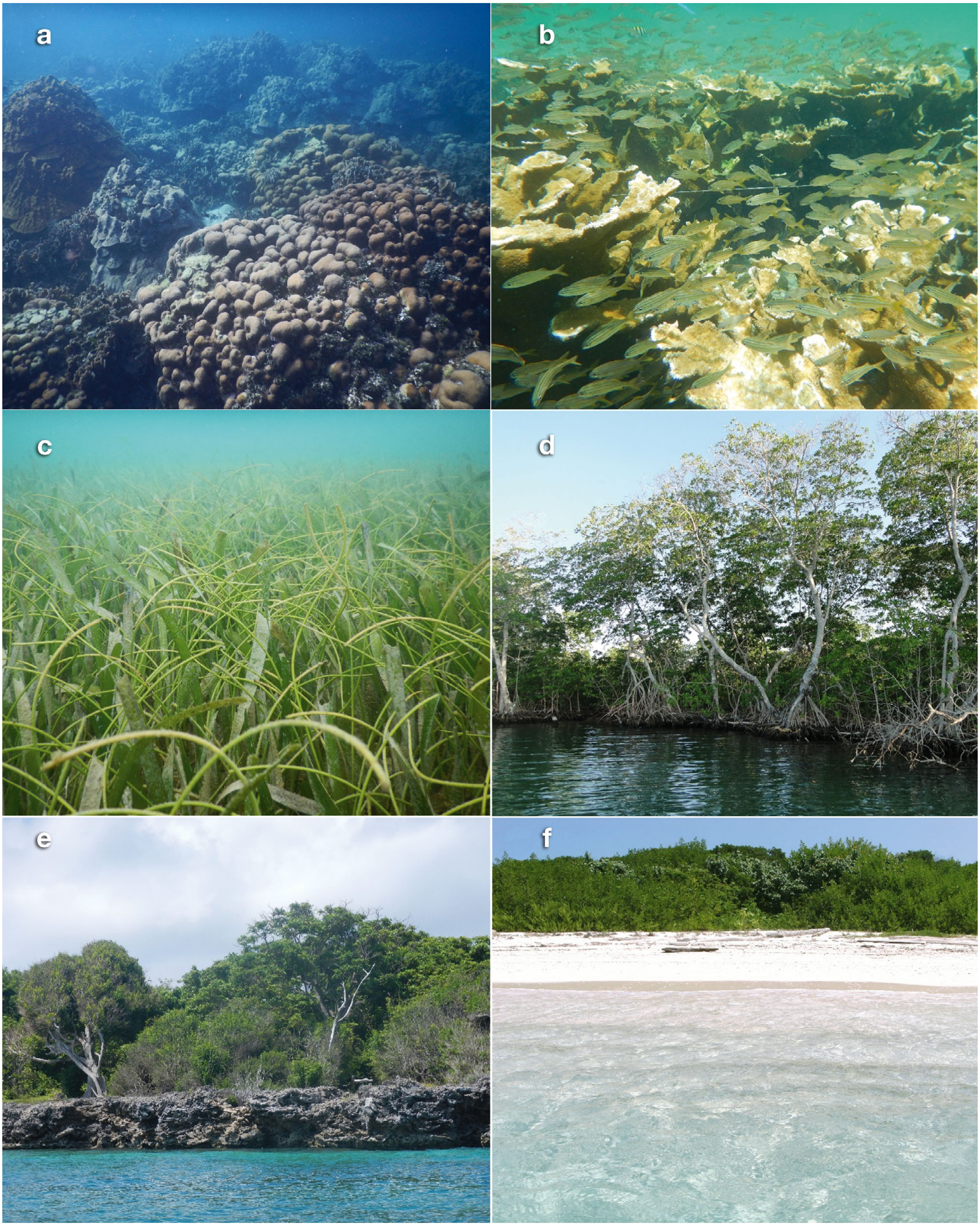


Fig. 2. Representative resources within CRSB: (a,b) coral reefs; (c) seagrasses; (d) mangrove forest at Ceycén Island; (e) tropical dry forests and rocky shores in Grande Island; (f) tropical dry forests and sandy shores in Tesoro Island. Photos: courtesy of E. Zarza-González, Parques Nacionales de Colombia (PNNC)

facilities, but these resources are included in this vulnerability framework as activities within these areas have the potential to affect the natural resources within the park.

2.2. The conceptual framework of climate change vulnerability

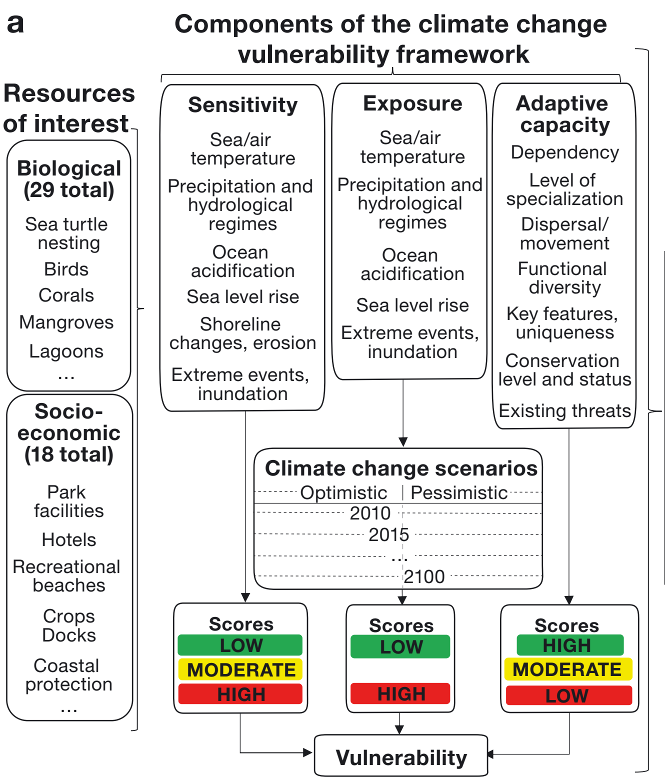
A comprehensive climate change vulnerability framework, which is qualitative in nature, was developed to identify protected resources at potential risk from climate change (Fig. 3). The purpose of this conceptual framework is to provide information needed to aid in the identification of future conservation, restoration, and mitigation strategies and other management policies that could be implemented in response to climate change. However a clear understanding of the assumptions supporting this conceptual framework, and their associated uncertainties, is a prerequisite for its use in informing management actions. For the development of the vulnerability framework for the CSRB, key definitions to quantify vulnerability were modified from existing definitions (Holling 1973, Burton 1993, Cutter 1996, Gunderson 2000, Walker et al. 2004, Adger 2006, Parry et al. 2007, Comer et al. 2012, Doney et al. 2012) and are as follows (for further details see Table S1 in the Supplement at www.int-res.com/articles/suppl/c070p001_supp.pdf):

Sensitivity: the extent to which a resource is susceptible or sensitive to changes induced by one or more climate change factors. This is a function of resource-specific thresholds and tolerances to specific climate change factors.

Exposure: the extent to which a resource is directly and physically affected by changes induced by one or more climate change factors. Exposure depends on the degree of exceedance of resource-specific thresholds, as well as to the degree of physical exposure experienced by the resource.

Adaptive capacity: the potential capacity of a resource to adapt, adjust or cope in response to changes induced by one or more climate change factor, thereby moderating, reducing or minimizing the magnitude of adverse direct effects. These include responses leading to restored essential function, identity, structure, and feedbacks. Adaptive capacity is greatly influenced by inherent resource-specific characteristics, which for the purpose of this research, include: dependency, level of specialization, dispersal/movement, functional diversity, key features and uniqueness; as well as external factors including conservation status and conservation priority, and existing threats. These, and possibly other non-climate change-related characteristics, may contribute to the ability of a resource to respond to climate change.

Vulnerability: the propensity or predisposition of a resource to be vulnerable or adversely impacted by climate change. Vulnerability is a function of sensitivity, exposure, and adaptive capacity.



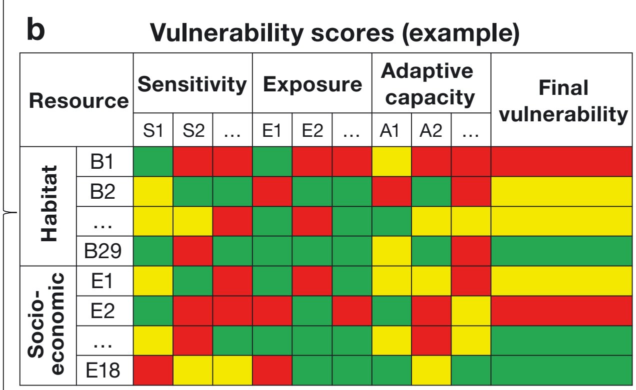


Fig. 3. (a) Climate change vulnerability framework for CRSB. Exposure scores were determined based on resource-specific thresholds and area-specific climate change scenarios. Sensitivity and adaptive capacity scores are informed by qualitative information and assumed to be static over time. (b) Hypothetical example of color coded scores associated with the final vulnerability score (for illustrative purposes only)

2.3. Development of the vulnerability scores

Relevant resource- and site-specific sources of information were evaluated to inform the sensitivity, exposure, and adaptive capacity of each resource of interest, and only quantitative data were used to inform exposure (Table S2 in the Supplement). Best professional judgment was used when these types of information were unavailable. In order to facilitate an understanding of the outcomes of this conceptual framework, theoretical background information associated with sensitivity, exposure, and adaptive capacity for each resource of interest were assigned a qualitative scalar value with an associated numerical value, which were then aggregated to generate a numeric 'score' of relative vulnerability. This type of approach has been traditionally used when assessing vulnerability (e.g. Adger 2006). Sensitivity and exposure scores were developed by accounting for climate change factors that were identified to be of concern within the park: sea surface and air temperature, precipitation, ocean acidification, and inundation from sea level rise and extreme events. Adaptive capacity scores were developed based on resource-specific inherent characteristics and external factors, giving a higher degree of importance to specific locations with habitats targeted for restoration or preservation by the CRSB, or resources that are known to be under localized threats. Sensitivity and adaptive capacity were given scores ranging from low to high with associated numerical values (low, moderate, and high: with numerical values of 1, 2 and 3, respectively, for sensitivity; and 3, 2 and 1, respectively, for adaptive capacity). These scores, which are informed by qualitative information, were assumed to be static over time.

Unlike sensitivity and adaptive capacity scores, exposure scores were given only 2 score levels (low and high, with numerical values of 1 and 3, respectively) as these were driven by whether or not area- or resource-specific thresholds were exceeded (see Section 3.2). Therefore these scores are semi-quantitative in nature. Exposure scores were in most cases based on area-specific historical and trend data (i.e. annual rates of change) associated with each of the climate change factors, and compared where appropriate to mean baseline values. While establishing these values was necessary to infer changes over time, it is also important to point out that there are many uncertainties associated with these trends, and therefore, the underlying assumptions used in these analyses would need to be reevaluated when more accurate information becomes available. Given limited historical information on trends for each factor, it was assumed that these rates of change would remain constant between 2010 and 2100. To estimate changes over time, and given the paucity of area-specific climate change trends, projections and forecasting, 2 climate change scenarios — optimistic and pessimistic — were develop to partially capture these uncertainties. The optimistic scenario was based upon moderate annual rates of change or values reported for each climate change factor, while the pessimistic scenario was based upon the most severe or extreme value associated with each climate change factor of interest. For each of these scenarios, comparisons of estimated changes of each factor at 5 yr intervals from 2010 to 2100 were made relative to resource-specific threshold criteria. These thresholds were based on local or resource-specific information. With the exception of inundation from sea level rise and extreme events, exposure scores were determined based on exceedances of resource-specific climate change factor thresholds. Given high uncertainty regarding the effect of changes in precipitation to resources within the CRSB, it was assumed that either a 5 or a 15% change relative to baseline may result in adverse effects depending on the resource. These criteria were only applied to resources known or suspected to be impacted by changes in precipitation. The 5% change criteria was applied to the assessment of vulnerability of sea turtle nesting beaches and coastal and interior lagoons, and the 15% change criteria was used for all other resources. There is also high uncertainty regarding the effects of changes in pH to all resources included in this study. Consequently, it was assumed that a change in 0.2 units relative to the mean baseline value may cause adverse effects. This criterion, which was driven by the impact of ocean acidification on the calcification processes of marine organisms, was applied to all resources suspected to be negatively affected by changes in pH. In cases where the predicted climate change factor at any given time step under each scenario exceeded the resource-specific threshold, exposure to that resource was scored as high.

For climate change factors that are area-specific and expected to change at a specific spatial scale (i.e. inundation from sea level rise and extreme events), exposure scores were determined based on the georeferenced location of the resource as a function of the physical exposure to each of these climate change factors (see Sections 2.4 & 3.2). For all resources in dry or tidally influenced areas, it was assumed that any inundation (i.e. permanent or temporary), would have adverse effects on these resources, with assessments based on their elevation relative to predicted changes in inundation over time from current seawater levels. All baseline data (air temperature: 28.9°C; sea surface temperature: 28.3°C; precipitation: 1,141 mm yr^{-1}; seawater: pH 8.2) were based on relatively limited information, and were taken from Zarza-González (2011). Most of this information was generated from monthly averages collected during the period 2008–2010 at 3 monitoring stations in the proximity of the CRSB.

For each resource, the combined sensitivity, exposure, and adaptive capacity scores comprised the final relative vulnerability score at each time step for each scenario. All climate change factors and vulnerability dimensions were given equal weights. Once these final vulnerability scores were calculated, a weight (multiplier) was used to account for the relative management 'value' of resources, based on their physical distribution in relation to the boundaries of the management areas within the CRSB. Resources within the high conservation priority zone had a higher weight (1.5) than those resources within the recreational zone (1), while resources within the area of natural recovery were given an intermediate score (1.25). A detailed example of a final vulnerability matrix for a specific time step is provided in Table S3 in the Supplement. Based on this conceptual framework, final relative vulnerability scores are higher for the most vulnerable resources (e.g. high exposure, high sensitivity and low adaptive capacity), and lower for the least vulnerable resources.

2.4. Permanent and temporary inundation

Effects of sea level rise and extreme events, hereafter referred to as inundation, required analyses based on elevation. Because elevation data were not available for the CRSB, digital elevation model (DEM) data (3 arc-second resolution) from NASA's Shuttle Radar Topographic Mission (SRTM) (USGS 2014) were used as the baseline elevation. These data have an absolute horizontal and vertical accuracy of 20 m and 16 m (at 90% confidence), respectively (USGS 2014). However, DEM SRTM data were deemed too coarse to allow for estimates of changes in sea level rise at 5 yr intervals. To address this issue and to better represent the footprint of resources with small spatial coverages, SRTM DEM data were interpolated from 30 to 10 m resolution generating finer elevation values for the CRSB. All interpolations used shoreline vectors to constrain the interpolated DEM to the observed shoreline. The interpolation method uses a discretized thin plate-spline technique (Wahba 1990) optimized to maintain the computational efficiency of local interpolation methods, without losing the surface continuity of global interpolation methods. Furthermore, the uncertainty introduced by DEM interpolation is likely small when compared to that from SRTM.

To estimate permanent inundation caused by changes in sea level, a 'bathtub' model corrected for local subsidence (NOAA 2012) was used to estimate inundation levels for each future time step within each scenario. Permanent inundation is described as follows:

$$\text{Permanent inundation}_{T(i),\mathrm{S}} = \mathrm{SLR}_{T(i),\mathrm{S}} + \mathrm{TL} - \mathrm{LS}_{\mathrm{S}} \qquad (1)$$

where $T(i)$ is the time step, S is the scenario (optimistic or pessimistic), SLR is sea level rise, TL is the tide level equivalent to the zero-level contour of the interpolated DEM, which is assumed to represent the mean sea level (MSL), and LS is the local subsidence. LS for the optimistic and pessimistic scenarios was set at −3.6 and −7 mm yr^{-1}, respectively (Page 1983, Aubrey et al. 1988). To estimate temporary inundation caused by extreme events (e.g. storm surge and swell waves) (Lerma et al. 2008, Andrade et al. 2013), the resulting permanent inundation for each time step and scenario were added to a stationary storm surge of 20 and 50 cm for the optimistic and pessimistic scenarios, respectively (Lerma et al. 2008, Andrade et al. 2013). For each time step and scenario, grid cells with elevations within 0 cm or below the estimated permanent or temporary inundation levels were assigned a high exposure score (numerical value of 3), as they are most likely to be flooded from permanent or extreme event changes in sea levels.

2.5. Geospatial data management

Several key data processing steps were used to develop the CRSB climate change spatial tool (Fig. S1 in the Supplement). Georeferenced information for all resources of interest was obtained through the Colombian National Park System, and data manipulations were only made to sea turtle nesting data. The georeferenced position of nesting sites were corrected in cases where the data did not line up with the most current shoreline. In cases where nesting sites occurred in areas designated as water, dry forest, or mangroves, coordinates were adjusted to the nearest beach. In addition, relative nesting densities were created from point data to better represent within these analyses all potential nesting habitat.

Table 1. Percent of total area covered by each resource within each of the 3 management zones of CRSB. As a reference, the total area of the CRSB is approximately 1200 km^2. 'Other' resources include marine algae, rocky shores, and sedimentary deposits. The latter comprises 97% of all resources within this resource group. The area of sea turtle nesting beaches was estimated based on historical nest distributions (2000–2011). Socioeconomic resources include all infrastructure and tourism facilities

Resource	Total area (km^2)	Management zone (% of total area) High conservation priority	Natural recovery	Recreational zone
Bird habitat	0.008	32	57	11
Corals	180	3	24	73
Dry forest	1.47	45	9	46
Coastal/interior lagoons	1.41	8	7	86
Mangroves	2.93	8	10	82
Other	981	1	14	86
Seagrasses	68	7	13	80
Sea turtle nesting beaches	0.98	39	0	61
Socioeconomic	0.70	1	53	46

To consistently apply numerical calculations to multiple data sources, all georeferenced information was rasterized to 10 m^2 grid cells, matching the grid cells of the interpolated DEM. To facilitate interpretation of these relative vulnerability scores, all resources were assigned to one of the following resource categories: bird habitat, corals (including all coral species, octocorals, and octocoral-sponge assemblages), dry forest, coastal and interior lagoons, mangroves, 'other' (including marine algae, rocky shores, sedimentary deposits), seagrasses, sea turtle nesting beaches, and socioeconomic resources (all combined). All calculations of final relative vulnerability scores for all resources, and for each scenario and time step with and without weights by management area were performed in a geographic information system platform.

3. RESULTS

3.1. Resources and baseline conditions

Most of the total area of the CRSB (1200 km^2) comprises sedimentary deposits (77%), followed by corals (15%) and seagrasses (6%) (Table 1). Most of the CRSB is designated as an area of natural recovery (83%), while a small fraction is designated as an area of high conservation priority (2%). The remainder of the CRSB is designated as a recreational area (16%).

For each scenario and time step, there are over 12 million 10 m^2 grid cells containing final relative vulnerability scores with and without weights by management area. Calculation of vulnerability of resources within the CRSB to climate change factors, and in particular exposure scores, required information on mean baseline values, as well as annual rates of change (Table 2). Historical trends of sea level rise along the Caribbean coast of Colombia range between 2.88 mm yr^{-1}

Table 2. Baseline conditions (based on Zarza-González 2011) and annual rates of change of climate change factors in the CRSB under optimistic and pessimistic scenarios, and the levels of uncertainty associated with forecasts. These rates of change were assumed to remain constant over time. Equations mentioned are from the appropriate cited sources

Factor	Mean baseline conditions	Annual rate of change by scenario: Optimistic	Pessimistic	Source(s) of scenario values: Optimistic	Pessimistic	Level of uncertainty
Sea level rise (mm yr^{-1})	Tide level[a]	2.883	5.64	www.c3a.ihcantabria.com	Restrepo et al. (2011, 2012)	High
Air temperature (°C yr^{-1})	28.9°C	0.03	0.05	Girvetz et al. (2009)	Girvetz et al. (2009)	Moderate
Sea surface temperature (°C yr^{-1})	28.3°C	0.01	0.03	www.c3a.ihcantabria.com	INVEMAR (2015)	Moderate
pH (ΔpH)	8.2	Based on equation	Based on equation	Joos et al. (2011)	Feely et al. (2009)	High
Precipitation (mm yr^{-1})	1141	−0.11	−0.66	Girvetz et al. (2009)	Girvetz et al. (2009)	High

[a]Equivalent to the zero-level contour of the interpolated digital elevation model (DEM); assumed to be an estimate of mean sea level

(www.c3a.ihcantabria.com) and 5.64 mm yr^{-1} (Restrepo et al. 2011, 2012); these values were used to bracket the 2 scenarios. Field measurements of air and sea surface temperature are limited for the area, but several sources of information were available to define the annual rate of change for both the optimistic and pessimistic scenarios (Girvetz et al. 2009, INVEMAR 2015; www.c3a.ihcantabria.com). Given the paucity of field measurements within the CRSB related to ocean acidification (using pH as a proxy), it was assumed that trends would follow those established elsewhere (Feely et al. 2009, Joos et al. 2011). Data on precipitation were not readily available; this required the use of alternate sources, which showed generallydecreasing trends (Girvetz et al. 2009). Given limited long-term data on trends and field measurements of all climate change factors, in particular for pH and precipitation, predictions over time were assumed to be moderately to highly uncertain. As acknowledged previously, all underlying assumptions used in these analyses could be refined upon the collection of long-term monitoring data.

3.2. Final vulnerability scores

Threshold criteria for climate change factors were based on local or resource-specific information (Table 3). Threshold exceedances of each climate change factor, and consequently changes in final relative vulnerability scores, occurred at different time steps during the 2010–2100 simulation period. For example, under the optimistic scenario, exceedances of the established thresholds for pH would occur for some resources in 2050 (e.g. corals), while under the pessimistic scenario exceedances would occur 10 yr earlier. Similarly, while under the optimistic scenario changes in air and sea surface temperature and precipitation are not expected to exceed the established thresholds, under the pessimistic scenario, exceedances of air and sea surface temperatures and precipitation thresholds would occur for some resources in 2070, 2080 and 2095, respectively. Impacts of inundation would occur at different time periods as these are based on the relative elevation of resources on tidally influenced or dry land. For all other resources and factors, the established thresholds are not exceeded.

As described previously, the final relative vulnerability scores generated through this conceptual framework are based on assignments of qualitative scalar values with an associated numerical value. Thus, these scores are relative, and mostly qualitative in nature. Vulnerability scores without and with weights by management area range from 20 to 25, and from 20 to 67.50, respectively (Table S3 in the Supplement). In order to synthesize the vulnerability scores generated through this research, comparisons of the initial (2010) and future (2100) scores, without and with weights by management area and by sce-

Table 3. Resource-specific climate change thresholds and years in which these thresholds are exceeded in CRSB under optimistic and pessimistic scenarios. Only factors that negatively impact each resource are shown. ∅: threshold not exceeded; Δ: location specific and based on relative elevation. See Table 1 for descriptions of resources. Note that there is uncertainty in threshold values and assessments based on relative elevation

Resource	Factor (threshold above baseline)	Scenario Optimistic | Pessimistic
Bird habitat	Air temperature (≥3°C)	∅ | 2070
	pH (≥ 0.2)	2050 | 2040
	Precipitation (± 171 mm)	∅ | ∅
	Inundation[a]	Δ
Corals	Sea surface temperature (≥2°C)	∅ | 2080
	pH (≥ 0.2)	2050 | 2040
	Precipitation (± 171 mm)	∅ | ∅
Dry forest	Inundation	Δ
Coastal/interior lagoons	Precipitation (± 57 mm)	∅ | 2095
	Inundation	Δ
Mangroves	Air temperature (≥6°C)	∅ | ∅
	Sea surface temperature (≥6°C)	∅ | ∅
	Precipitation (± 171 mm)	∅ | ∅
	Inundation	Δ
Other	Air temperature (≥3°C)	∅ | 2070
	Sea surface temperature (≥6°C)	∅ | ∅
	pH	2050 | 2040
	Precipitation (± 171 mm)	∅ | ∅
	Inundation	Δ
Seagrasses	Sea surface temperature (≥6°C)	∅ | ∅
	Precipitation (± 171 mm)	∅ | ∅
Sea turtle nesting beaches	Air temperature (≥3°C)	∅ | 2070
	pH (≥ 0.2)	2050 | 2040
	Precipitation (± 57 mm)	∅ | 2095
	Inundation	Δ
Socioeconomic resources	Inundation	Δ

[a]Permanent inundation from sea level rise and temporary inundation from extreme events (e.g. storm surge)

nario, were made for resources within individual grids. These comparisons were further used to generate density distributions of vulnerability scores for individual resources within the CRSB as shown in Fig. 4. Note that, in Fig. 4 and subsequents figures, vulnerability scores are indicated by the colored *y*-axis scale bars to facilitate interpretation. Changes in vulnerability scores to climate change factors for the resource with the highest score per grid were anticipated between the beginning (2010) and the end (2100) of the simulation period, but in some cases the scores remained unchanged. Based on vulnerability scores, and regardless of the scenario, the least vulnerable resources are sea grasses (range: 22–31 without weights, 30–45 with weights) and those within the 'other' resource category, most of which are sedimentary deposits (range: 20–33 without weights, 20–46.5 with weights). When all areas are weighted equally (Fig. 4a,b) sea turtle nesting beaches followed by coastal and interior lagoons, corals and bird habitat, are the resources with the highest vulnerability scores (range: 40–45, 35–40, 33–39, and 33–36, respectively). The same is true when weights by management area are used (Fig. 4c,d), although the scores for sea turtle nesting beaches, coastal and interior lagoons, corals and bird habitat cover a wider range of values (range: 40–67.5, 34.5–60, 33–55.5, and 34–54, respectively). In the case of sea turtle nesting beaches, most of this habitat is located within the area designated for recreation. Socioeconomic resources cover a wide range of vulnerability scores, with recreational beaches and low-lying roads being among the most vulnerable resources (range: 36–43, and 34–37, respectively). In contrast, mangroves and dry forest fall within the middle of the vulnerability scale (range: 32–35 for both habitats). When comparisons were made between scenarios, the pessimistic scenario (Fig. 4b,d) was only marginally different from the optimistic scenario (Fig. 4a,c) for several resources, but this is likely due to the additive scoring system used in these analyses. Vulnerability scores were higher under the pessimistic scenario for corals, coastal and interior lagoons, and sea turtle habitat. Exposure thresholds under both scenarios were not exceeded for resources in some grid cells, where there was no change in vulnerability scores between 2010 and 2100 (e.g. grid cells of dry forest not influenced by inundation).

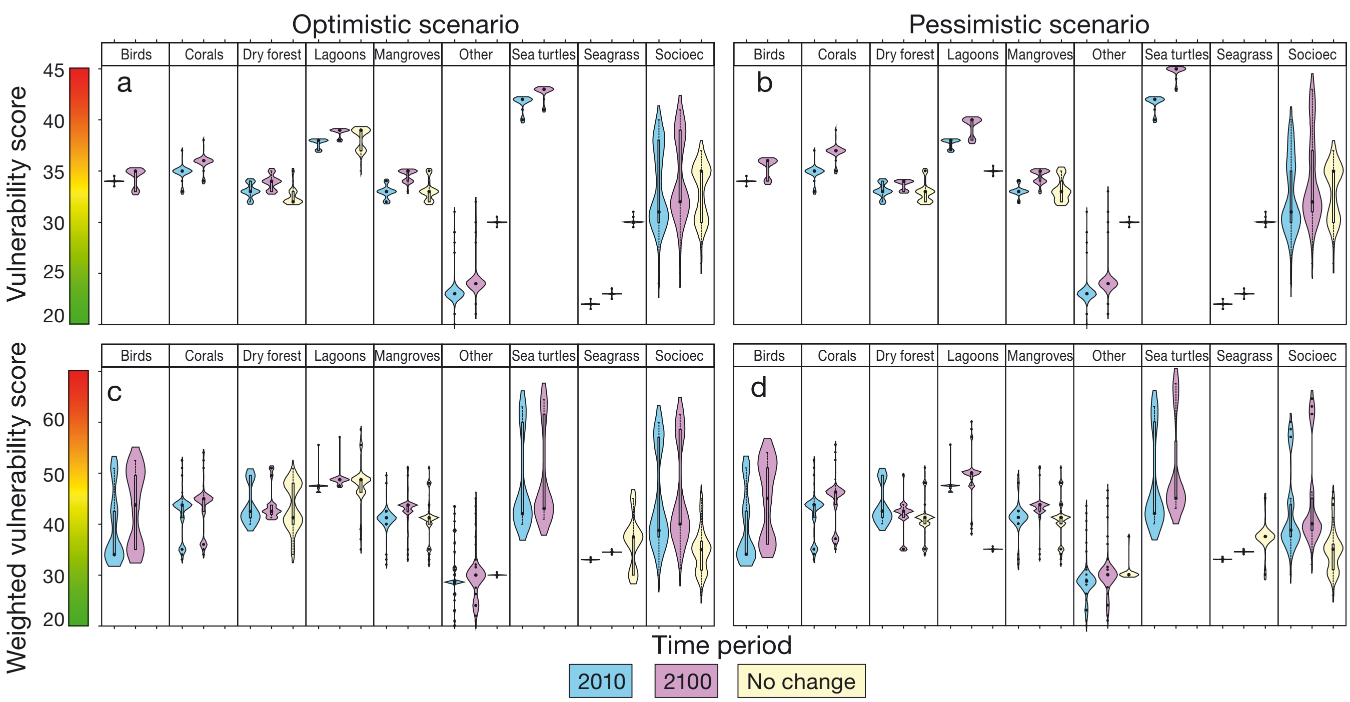


Fig. 4. (a,b) Weighted and (c,d) unweighted density distribution of resource-specific vulnerability scores for resource categories within the CRSB, under (a,c) optimistic and (b,d) pessimistic scenarios at the beginning (2010) and end (2100) of the analyzed time period. 'No change' indicates identical vulnerability scores between 2010 and 2100 in areas not influenced by inundation. Top and bottom of embedded boxes: first and third quartile; whiskers: minimum and maximum. Color density plot — length: smoothed minimum and maximum; width: frequency distribution. Larger central dot: median; smaller dots: outliers. The colored *y*-axis scale bars represent the relative vulnerability from least (dark green) to most vulnerable (dark red)

3.3. Relative contributions and differences in final vulnerability scores

Resources within the CRSB are not all equally sensitive to climate change; they do not all have the same thresholds to climate change factors, or the same characteristics that influence their adaptive capacity. Consequently, the final relative vulnerability scores are unique for each resource. Based on results for the 2100 pessimistic scenario (Fig. 5), adaptive capacity was the dimension of the conceptual framework that contributed most to the final vulnerability scores (range: 34–55 %), followed by sensitivity (range: 27–41 %) and exposure (range: 14–37 %). In the case of some of the most vulnerable resources within the CRSB (e.g. corals, coastal and interior lagoons, sea turtle nesting beaches and beaches within the 'other' category), their vulnerability is based on their relatively high sensitivity to climate change factors (e.g. coral sensitivity to changes in sea surface temperature and pH), as well as their relatively limited adaptive capacity. In addition, the most vulnerable resources, except for corals, are exposed to inundation (permanent and/or temporary), which contributes to their higher vulnerability. Most changes in scores within the same resource are driven by exposure and adaptive capacity. For example, all mangroves have the same sensitivity (score: 12). In contrast, their adaptive capacity varies (score: 15 or 16) depending on their conservation priority within the CRSB, while their exposure varies depending on their relative elevation (score: 5 when not affected by sea level rise or inundation, 7 when affected by sea level rise only, and 9 when affected by sea level rise and inundation). As a result, the relative contribution of each vulnerability dimension and the final vulnerability score varies depending on resource-specific characteristics.

3.4. Final vulnerability scores across islands within the CRSB

Within the high priority management area of the CRSB, resource-specific final relative vulnerability scores for the pessimistic scenario show similarities among islands and their surrounding waters (Fig. 6). The area within and around Mangle Island (Fig. 6a) comprises 6 resource types: birds, corals, mangroves, seagrasses, other habitats, and socioeconomic resources. Vulnerability scores for these resources ranged from 23 to 43, with scores for all but 2 resources (i.e. most mangrove and all seagrass grid cells) changing by at least 2 units between 2010 and 2100. Similar results were obtained for the area within and around Maravilla Island (Fig. 6b), which comprises 5 resource types: birds, corals, mangroves, seagrasses, and other habitats. Vulnera-

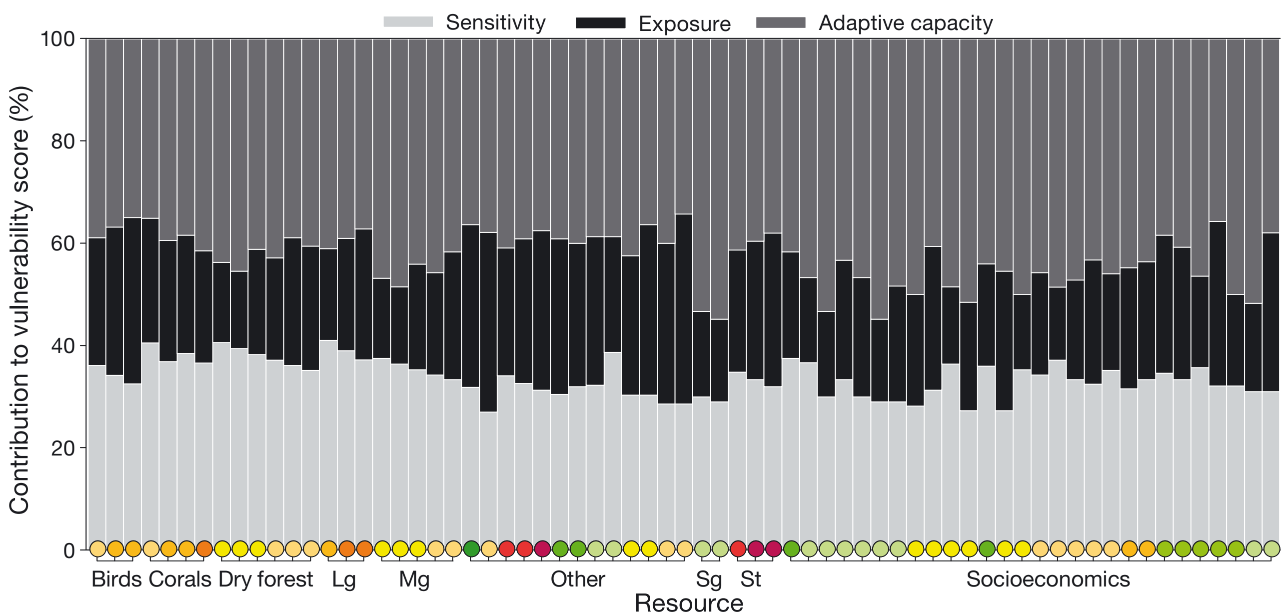


Fig. 5. Relative contribution of each dimension of the vulnerability framework (bars) to the final vulnerability score by resource category, using as an example the final scores for the 2100 pessimistic scenario. The color of filled circles depicts the value of the final vulnerability score (dark green: least vulnerable; dark red: most vulnerable). Lg: = coastal and interior lagoons; Mg: mangroves, Sg: seagrasses, St: sea turtle nesting beaches

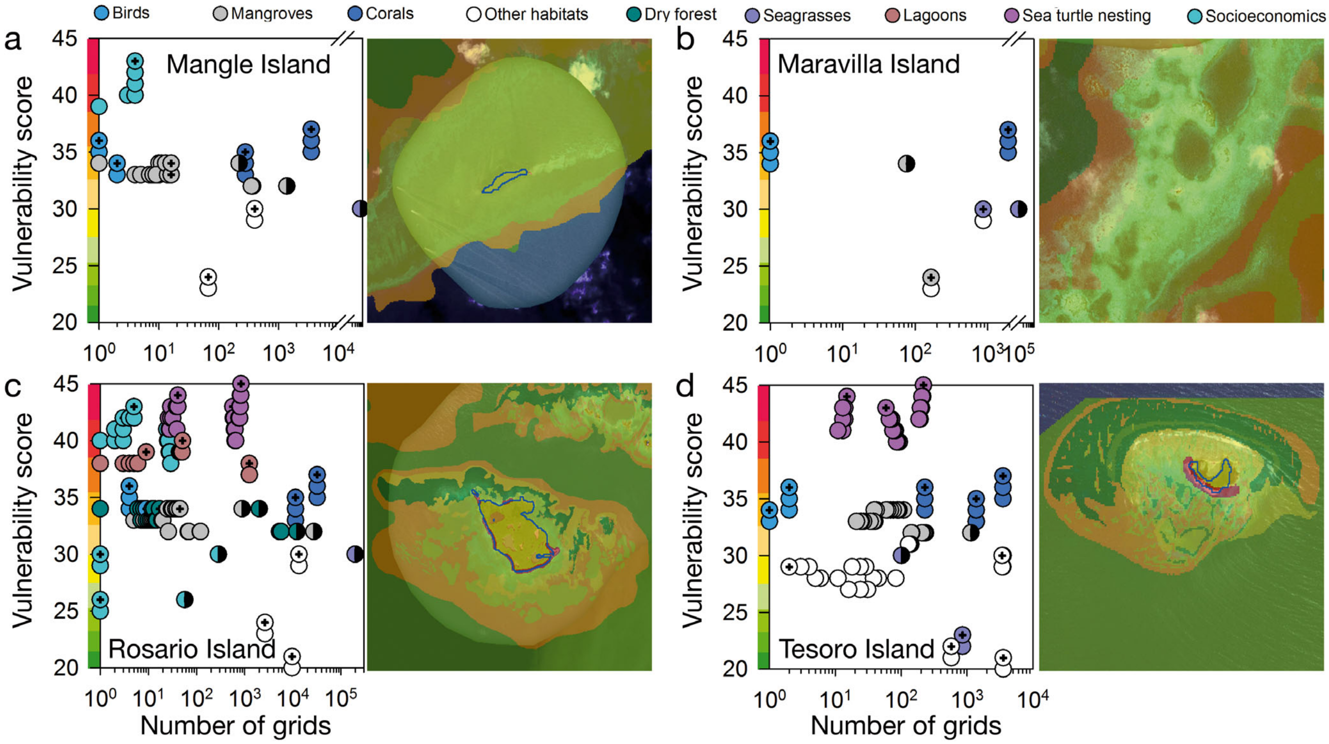


Fig. 6. Resource-specific final vulnerability scores under the pessimistic scenario over time (2010 to 2100) for islands within the high priority management area of CRSB and their surrounding waters: (a) Mangle, (b) Maravilla, (c) Rosario and (d) Tesoro Islands. Half black symbols indicate no change between 2010–2100; crossed symbols indicate the 2100 score, and filled symbols indicate the highest score for intermediate time steps. The colored *y*-axis scale bars represent the relative vulnerability from least (dark green) to most vulnerable (dark red). Map panels: spatial visualization of the 2100 vulnerability for each area, with shorelines indicated by blue lines

bility scores for these resources ranged from 23 to 37, with scores for all but 2 resources (i.e. all mangrove and seagrass grid cells) changing by at least 2 units between 2010 and 2100. Unlike Mangle and Maravilla Islands, the area within and around Rosario Island (Fig. 6c) contains all 9 resource types included in these analyses. Vulnerability scores for these resources ranged from 20 to 45, with scores for all but 4 resources (i.e. some mangrove, dry forest and socioeconomic resources grid cells, and all seagrass grid cells) changing by at least 2 units between 2010 and 2100. Tesoro Island and surrounding waters (Fig. 6d) comprises 6 resource types: birds, corals, mangroves, seagrasses, sea turtle nesting beaches, and other habitats. Vulnerability scores for these resources ranged from 20 to 45, with scores for all but 2 resources (i.e. most mangrove and all seagrass grid cells) changing by at least 2 units between 2010 and 2100. In most cases, changes in vulnerability scores resulted in shifts of color scheme categories. Corals and socioeconomic resources in Mangle and Maravilla Islands, sea turtle nesting beaches, corals and socioeconomic resources in Rosario Island, and sea turtle nesting beaches, bird habitat and corals in Tesoro Island experienced larger changes in vulnerability scores. However, by 2100 there are a larger number of grid cells with higher scores compared to 2010 in mangroves (Mangle, Rosario and Tesoro Islands), sea turtle nesting beaches (Rosario and Tesoro Islands), lagoons and socioeconomic resources (Rosario Island), and habitats within the 'other' habitat category (sedimentary deposits; Tesoro Island).

3.5. Relative elevation and impacts from inundation

Many of the changes in vulnerability scores of resources within tidally influenced or dry land described above are directly linked to resources influenced by inundation, specifically bird habitat, dry forests, coastal and interior lagoons, mangroves, sea turtle nesting beaches, and socioeconomic resources. However, not all of these resources are equally affected by inundation. For example, bird habitat (Fig. 7a) covers a wide range of elevations within the CRSB. By contrast, 90% of all grid cells in lagoons, mangroves, and sea turtle nesting beaches (Fig. 7c–e) are concentrated within a narrow elevation range, mostly <7 m elevation; 50% of those grid cells are at <3 m elevation. Furthermore, 90% of all grid cells in dry forest or associated with socioeconomic resources (Fig. 7b,f), are found within a 14.5 m elevation range; 50% of those grid cells are at <7 m elevation. Based on elevation alone, lagoons, mangroves, and sea turtle nesting beaches in low-lying areas are among the most susceptible coastal resources to inundation.

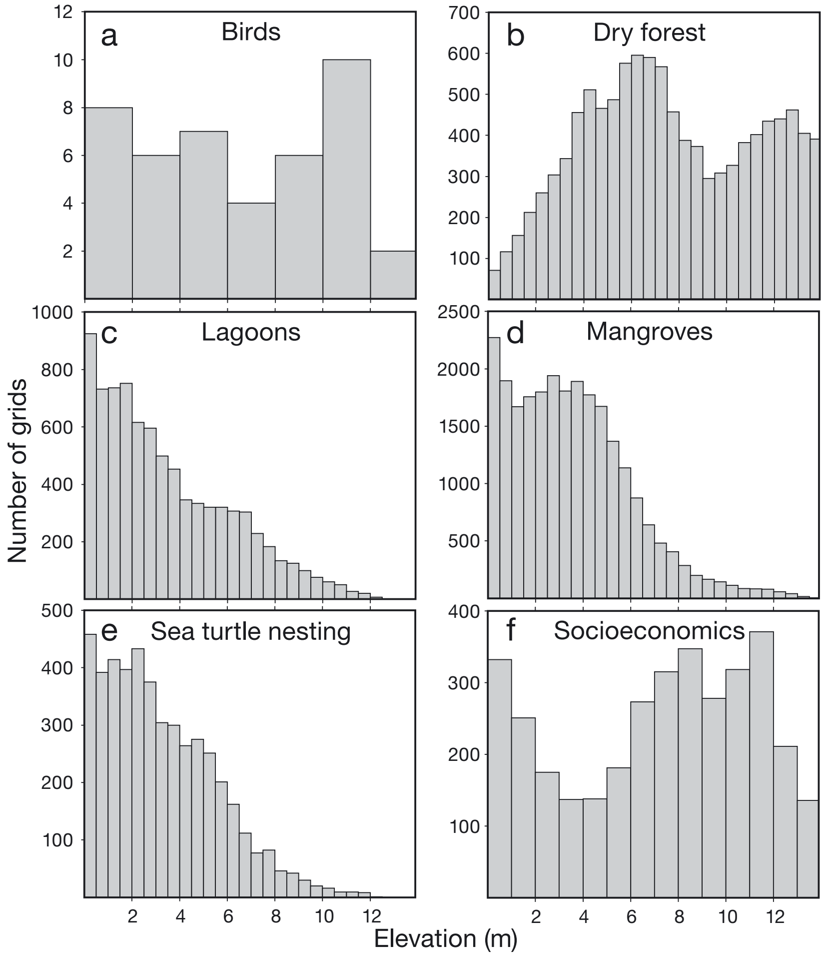


Fig. 7. Number of grid cells for each coastal habitat versus their relative elevation (m) in 2010 within the CRSB, based on an interpolated digital elevation model (DEM)

Because of differences in relative elevation across islands within CRSB, there are also differences in the potential impacts to resources from inundation (see Videos S1–S9 in the Supplement at www.int-res.com/articles/suppl/c070p001_supp/). Between 2010 and 2100 under the optimistic scenario, estimated annual inundation rates ranged from −0.7 to −172 m^2 yr^{-1}, while under the pessimistic scenario, inundation rates ranged from −3.7 to −473 m^2 yr^{-1} (Fig. 8). The scale of potential impacts from inundation varies across islands, with Tintipán Island (Fig. 8d) being the area most affected by inundation, followed by Ceycén, Rosario, Tesoro, Panda, and Mangle Islands (Fig. 8 a–c,e,f). However, when comparisons of inundated area by 2100 are made relative to the estimated non-inundated land in 2010, some of the smaller islands (i.e. Tesoro, Panda, and Ceycén) are at greater risk of impacts from inundation particularly under the pessimistic scenario. Across islands, mangroves are the resource at greatest risk from inundation, except in Rosario Island, where sea turtle nesting beaches are at greater risk. Consistently, most resources susceptible to impacts from inundation have vulnerability scores by 2100 that fall within the middle to upper range of the vulnerability scale (e.g. mangroves: 33–35 without weights, 33–51 with weights; lagoons: 38–40 without weights, 38–60 with weights; sea turtle nesting beaches 42–45 without weights, 42–67.5 with weights).

4. DISCUSSION

The climate change vulnerability framework specifically developed for the CRSB integrated several sources of information including local expert knowledge, conservation priorities and needs, relevant peer review information on select resources, and available data on climate change factors. During the development of this framework, there were limitations in acquiring accurate and high quality data (e.g. historical trends and baseline information on climate factors, elevation data), increasing the uncertainty of vulnerability scores, and possibly constraining the use of this framework within the CRSB. As a result, and in order to support meaningful management actions, the use of this vulnerability framework requires an understanding of the underlying assumptions, limitations and uncertainties.

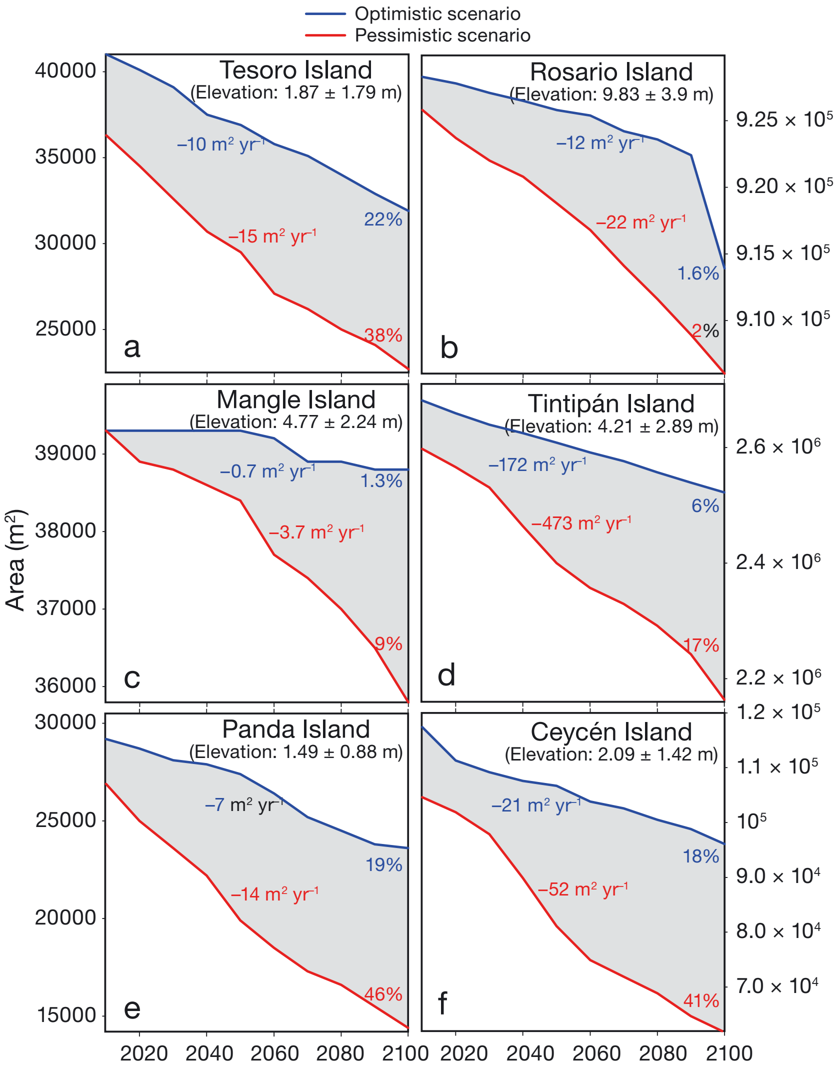


Fig. 8. Effects of inundation on the dry land area (left and right y-axes) of selected islands in the CRSB as a function of time under the optimistic (blue lines) and pessimistic (red lines) scenarios with estimated annual inundation rates (m^2 yr^{-1}) and changes in inundated area by 2100 relative to the non-inundated area in 2010 (%). Gray section: potential range of inundated area as a function of time. Calculations are based on the relative elevation (m) of grid cells within the CRSB, based on the interpolated digital elevation model (DEM)

Despite limited monitoring data on climate change factors, the historical trends used in the development of the present vulnerability framework are comparable to trends in other parts of the Caribbean (e.g. sea surface temperature rise: 0.03–0.04°C yr^{-1}; sea level rise: 1.8–4.4 mm yr^{-1}) (USAID-BIOMARCC-GIZ 2013) as well as global predictions (Bindoff et al. 2007). Sea level rise in the Caribbean between 1950 and 2000 appears to be near the global mean (Church et al. 2004), and climate change predictions indicate increases in air temperature, sea level rise, and ocean acidification (1.8–4°C, 180–590 mm, 0.14–0.34 pH units, respectively) by the end of the century (IPCC 2007). As a comparison and based on the present research, by the year 2100 for the pessimistic scenario, air temperature, sea level rise, and ocean acidification within the CRSB are estimated to be 4.55°C, 507 mm and 0.31 pH units, respectively. One of the main assumptions used in the conceptual framework for CRSB was that rates of change of each climate change factor would remain constant between 2010 and 2100. However, it is well known that at least the rate of sea level rise accelerates over time (e.g. Church & White 2006), and therefore some of the results presented here may have actually underestimated resource vulnerabilities. This was one reason why the conceptual framework presented here was developed bracketing low (optimistic scenario) and high (pessimistic scenario) rates of change.

While the agency in charge of the National Natural Parks of Colombia has acknowledged their concerns about climate change impacts on CRSB resources, more immediate pressures on resources influence their adaptive capacity to climate change (Rangel-Buitrago 2011). Consistently, within this climate change conceptual framework, adaptive capacity was the factor that generally contributed the most to the vulnerability score, followed by sensitivity and exposure. Factors across resources that consistently ranked low in terms of adaptive capacity were dependencies on other resources or habitats, inability to relocate to other suitable habitat, ecological importance within the CRSB, conservation level or status, and current threats. Within the CRSB, known threats and sources of local disturbance include, inter-alia, unsustainable fishing and forestry practices, the widespread presence of tourist activities that cause habitat alterations, poor to nonexistent treatment of wastewater, high sediment loading during the rainy season, and elevated shoreline erosion rates (Zarza-González 2011). A combination of these factors added to the inherent susceptibility of some resources to climate change factors (e.g. sensitivity of sea turtle nesting areas to inundation, and of corals to ocean acidification) plus exposure to such factors, distinguish resources with relatively higher vulnerability to climate change within the CRSB. Based on this climate change vulnerability framework for the CRSB, when all management areas within the park are weighted equally, sea turtle nesting beaches, coastal and interior lagoons, corals and bird habitat, are the resources with the highest vulnerability scores, while within socioeconomic resources, recreational beaches and low-lying roads are among the most vulnerable. Among islands and their surrounding waters within the high priority management area of the CRSB, corals and socioeconomic resources in Mangle and Maravilla Islands, sea turtle nesting beaches, corals and socioeconomic resources in Rosario Island, and sea turtle nesting beaches, bird habitat and corals in Tesoro Island, showed relatively large changes in vulnerability scores between 2010 and 2100. The high vulnerability of these resources is consistent with similar assessments of coastal resources in other areas (Fish et al. 2005, Nicholls et al. 2007, Carpenter et al. 2008, Pandolfi et al. 2011).

Given limited data availability, one of the shortcomings of the climate change vulnerability framework for the CRSB was the fact that accelerated erosion rates resulting from both permanent inundation and driven by storm events (temporary inundation) were not accounted for. Nearly half of the low-lying coastlands along the Caribbean coast of Colombia are rapidly eroding due a low topographic gradient, movement of sediments and sand, changes in sediment supply, sea level rise, storm events, inappropriate building of coastal infrastructures, and human modification of habitats that provide natural shoreline protection (e.g. corals, mangrove forests) (INVEMAR 2008, Rangel-Buitrago et al. 2015). Within the CRSB, shoreline erosion processes over the last half a century have caused a substantial loss of land (Restrepo et al. 2011, 2012). Restrepo et al. (2012) found that between 1954 and 2007 the areas of Grande, Rosario, and Tesoro Islands declined by 6.7, 8.2, and 48.7%, respectively. Smaller islands such as Tesoro, have experienced annual shoreline erosion rates as high as 2.4 m, with greater erosion rates found along most of the shoreline directly exposed to wave action (Restrepo et al. 2011, 2012). Incorporation of erosion trends into the climate change conceptual framework developed for the CRSB would allow for improved assessments of vulnerabilities to those resources more severely impacted (e.g. sand beaches) by this factor.

Another key source of uncertainty in the current conceptual framework is associated with elevation data. High resolution elevation data for the area were not available; therefore, assessments were based on interpolated DEM data to a 10 m resolution. Based on these data, under the pessimistic scenario in 2100, inundation alone (permanent and temporary combined) would affect 25, 20 and 23% of all lagoons, mangroves and sea turtle nesting beaches within the CRSB, respectively. If, for example, higher resolution elevation data indicated a 20 cm elevation below the elevation near the tideline used in these analyses, and more accurate sea level rise predictions indicated a median sea level by the end of the century of 0.75 m for the highest climate change scenario (RCP8.5, range: 0.52–0.98 m; Church et al. 2013), these would result in impacts to 34, 27 and 31% of all lagoons, mangroves and sea turtle nesting beaches, respectively, within the CRSB from inundation alone. Despite these limitations, analyses based on estimates of total inundated areas showed that Tintipán Island may be the island most affected by inundation, but relative to their total area in 2010, some of the smaller islands (i.e. Tesoro, Panda, and Ceycén) are at greater risk. Based on inundation alone and under the pessimistic scenario, by the year 2100 Panda Island is predicted to split into 2 smaller islands, while large areas of Mangle, Tesoro, Panda, and Ceycén Islands are predicted to be affected and potentially sustain large land losses. As described by Andrade et al. (2013), coastal inundation caused by storm swells originating in the Gulf of Mexico is a common seasonal phenomenon in the area, potentially causing large scale damage even during weak events. As demonstrated in the present study and as stated by Andrade et al. (2013), the combined effect of sea level rise and swell wave inundation may cause stronger and more recurrent impacts in the area, which could also exacerbate localized erosion.

While it is clear that there are large uncertainties and limited empirical data related to climate change along the Caribbean coast of Colombia, and particularly within the CRSB, the conceptual framework developed here is flexible and could be readily modified to allow for future incorporation of new climate change predictions or additional monitoring data. Modifications could also be made to the scoring system, so that specific weights could be given to each climate change factor based on resource-specific sensitivities. In addition, in line with the specific objectives of this research, no attempts were made to examine or model future spatial and compositional changes of species distributions that may occur as a result of climate change. However, these analyses are of paramount importance as such changes are likely to have occurred in the past and will very likely occur in the future. Improvements of the conceptual framework presented here would also benefit from future and targeted monitoring efforts. For example, given that nearly 80% of the coral coverage in the continental shelf Colombia is found within the CRSB (Díaz et al. 2000), monitoring aimed at establishing baseline data on aragonite saturation and carbonate chemistry, taking account of spatial and temporal variability, would allow for improved assessment of the effects ocean acidification. In addition, a systematic collection of environmental data linked to indicators of climate change would also be of great value in future assessments, particularly if emphasis were placed on identifying data sources aimed at informing enhanced adaptation capacity and climate change mitigation.

As discussed here, high data quality and high resolution spatial data are important in allowing characterizations of climate change impacts on coastal and marine resources. Despite data limitations, quantifying the vulnerability of resources within the CRSB is an essential first step in prioritizing management actions and identifying areas of greatest concern. While this assessment provides useful insights on the relative vulnerability to climate change of resources within CRSB, the implications of the vulnerability scores themselves may be difficult to interpret and may not be particularly helpful in informing specific management actions. However, with the development of this conceptual framework, CRSB resource managers may be able to explore changes in adaptive capacity (e.g. reduced localized threats) that, in combination with habitat restoration strategies aimed at reducing or mitigating shoreline loss (i.e. reducing exposure), may lead to reduced localized vulnerabilities. Similarly, the final vulnerability scores and the associated coloring scheme could be used to help inform the prioritization of conservation strategies, to make relative comparisons across the most vulnerable resources, and to communicate potential climate change impacts to stakeholders and partners. However, because of the uncertainties highlighted previously, management decisions should not rely solely on this vulnerability framework, but be based on localized experience. The climate change conceptual framework presented in the present study could be implemented in other marine and coastal national parks, as well as in other areas around the globe. However, further refinements would require the collection of additional data, in order to accurately characterize resource-specific vulnerabilities to climate change.

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