An Overview of the Socio-Ecological System of Cays and Islets in the US Caribbean and Their Vulnerability to Climate Change

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Abstract

The offshore cays around the main islands of Puerto Rico, St. Thomas, St. John, and St. Croix are largely uninhabited and provide habitat for threatened, endangered, at-risk, and species of greatest conservation need including many resident and migratory species of seabirds, shorebirds, endemic reptiles, and plants. Management is limited by insufficient resources, capacity, and a mixture of ownership (federal, Commonwealth, Territorial, private NGO, and private), making regional planning a challenge. Invasive species are the dominant short- and long-term threats to these systems including invasive plants that alter habitat conditions and invasive mammals (e.g., mice, rats, goats) that kill native fauna and degrade habitats. Recreational and commercial uses by humans, as well as marine debris and accumulations from harmful algal blooms, pose a significant threat to crucial habitats and key conservation species, especially in the coastal zone. In the longer term, the cays ecosystems and fauna are expected to show high exposure and sensitivity with limited adaptive capacity, depending on the type of island, to the impacts of climate change. Current projections highlight substantially altered rainfall patterns and extensive drought, as well as extreme sea level rise (beyond 3 m by 2100 under the worst scenarios) and more frequent or intense hurricanes. The impacts of sea level and precipitation in particular were used to develop future scenarios to compare and contrast effects on focal species and coastal habitats. The scenarios and impacts were then used to suggest potential adaptation strategies.

Introduction

There are over 750 offshore islands within the U.S. Caribbean surrounding the main islands of Puerto Rico and U.S. Virgin Islands (USVI) of St. Thomas, St. Croix, and St. John (Fig. 1A and B). The diversity of these islands is influenced by geology, location (windward, leeward), adjacent ocean bathymetry, proximity to a larger land mass, elevation/topography, size, accessibility, and historical use. The terms island (*isla*), islet (*islote*), cay (*cayo*), and rock (*roca*, *peñón*, *piedra*) often prefix island names interchangeably but there appears to be no exact criteria for their use. An islet can refer to any small island, whereas interestingly, the word cay (or

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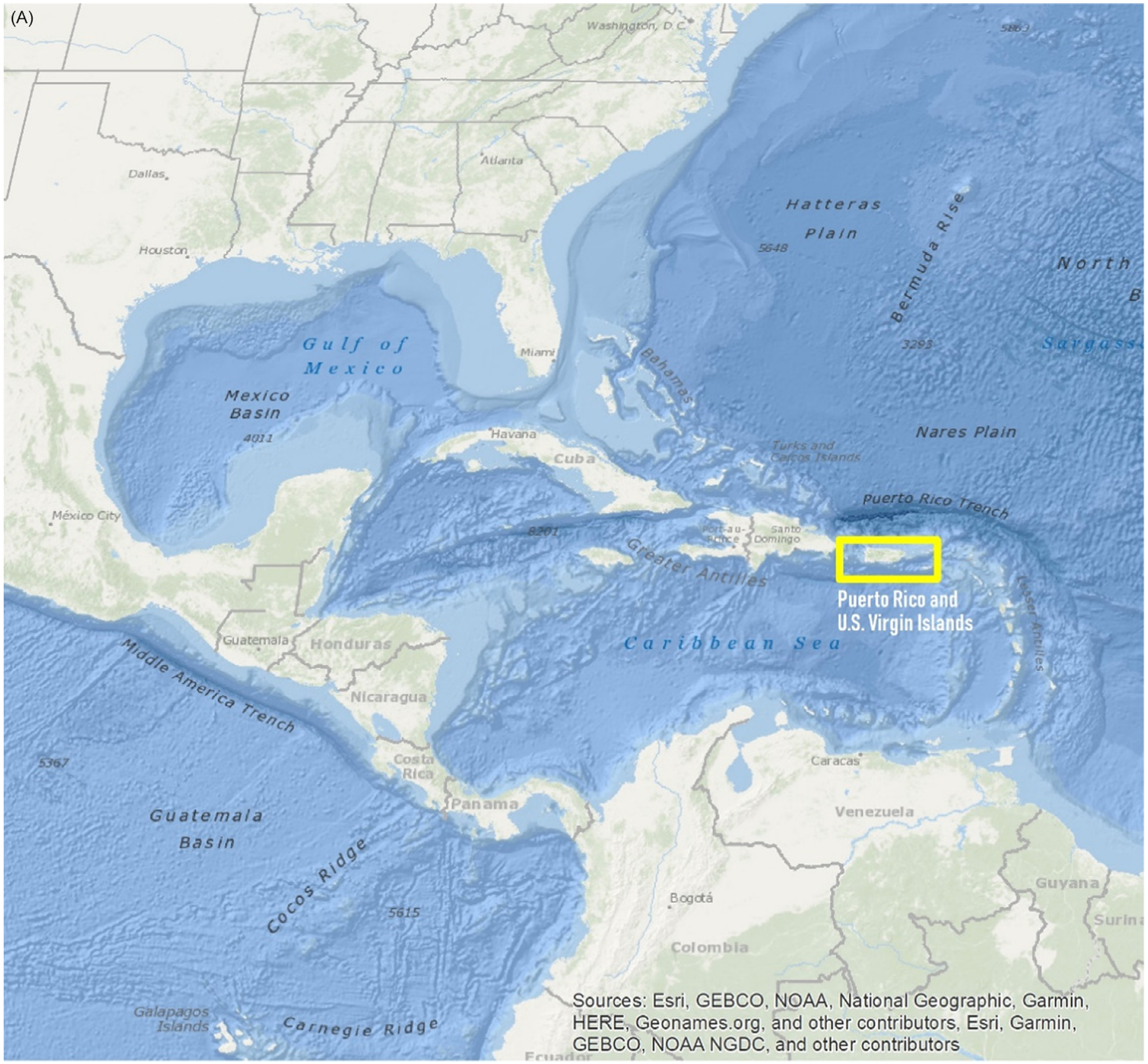

Fig. 1 (A) Regional map of the Caribbean framed by southern North American, Central America, and northern South America to provide reference for the location of the U.S. Caribbean, i.e., Puerto Rico and the U.S. Virgin Islands.

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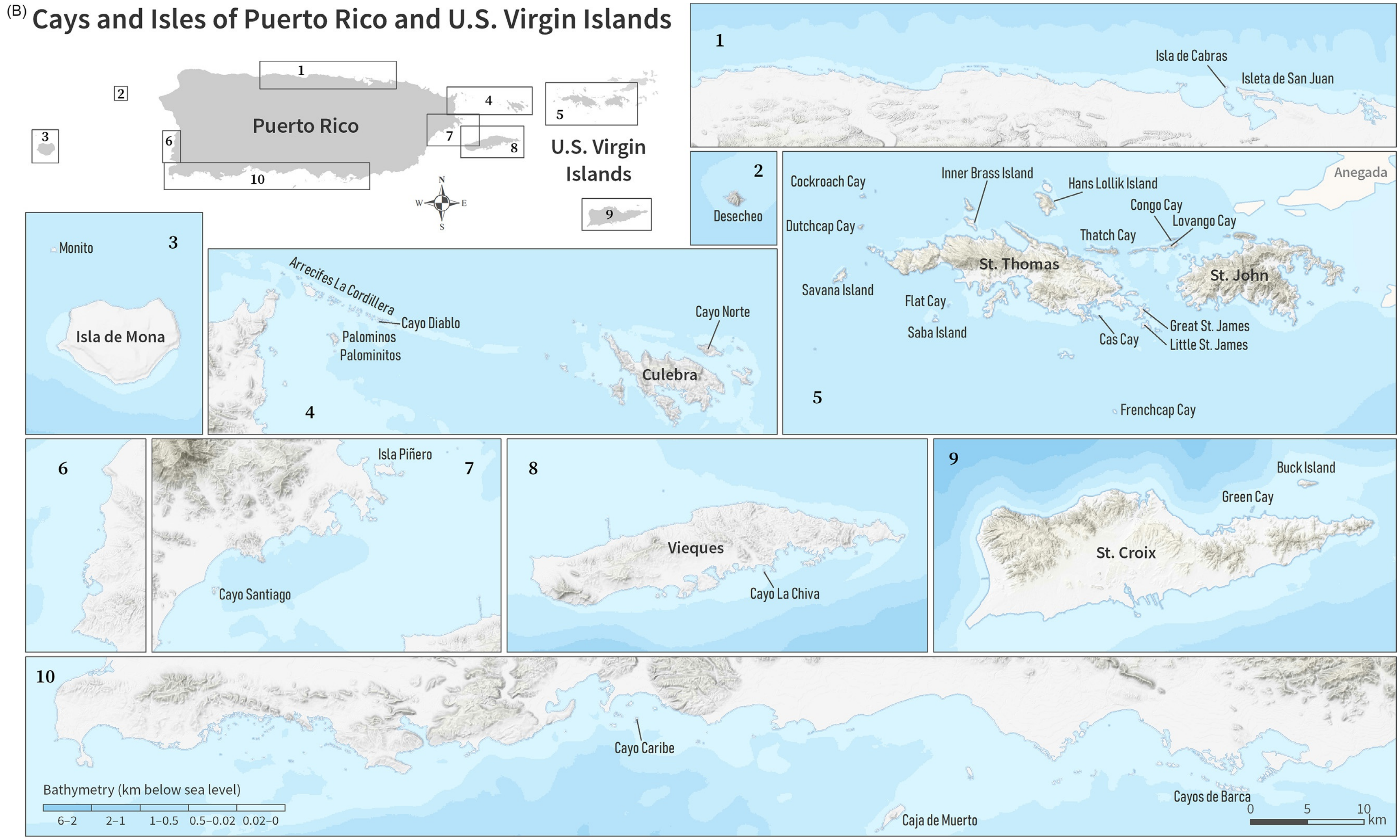

Cartography, Maya Quiñones, USDA Forest Service, International Institute of Tropical Forestry, Río Piedras, PR.

Fig. 1, Cont'd (B) Map of the primary cays of the U.S. Caribbean mentioned in the text.

cayo in Spanish) in Puerto Rico often refers to a small, low island or bank composed of sand and coral fragments, whereas in the USVI cays more commonly refer to the larger higher vegetated islands. Islands within the U.S. Caribbean can be classified into four types based on their formation or composition: (1) sand and coral cays; (2) mangrove cays; (3) volcanic and volcaniclastic; and (4) limestone. Each type is described in detail below.

Although some cays have been developed for human use, the majority are largely uninhabited and support many species, including some that are threatened, endangered, or endemic. In addition to providing wildlife refugia, the offshore islands are also important to society. Humans use the terrestrial and aquatic areas surrounding the islands for tourism, recreation, the extraction of resources (mining, fishing and forestry) and to market their scenic value. The excessive uses over time and high demand for the limited space on these islands has resulted in far reaching impacts such as invasive species (especially mammals such as rats, mice, mongoose, deer, feral cats, pigs, and goats, but also reptiles such as common iguanas, as well as non-native invasive plants) and anthropogenic disturbances due to direct use or plastic pollution reaching the cays.

There has been an extensive, and highly controversial, history of U.S. military use or lease for bombing practices from 1939 to 1975 within the Culebra Island archipelago and Desecheo Island (García-Muñiz, 1991, CINWRC-PR, 2011) and Monito Island. Additionally, the eastern end of Vieques Island, and many of the adjacent cays were used for various military practices (including bombing) from the 1940s to 2003.

Potential impacts stemming from the effects of the current climate crisis include sea level rise, projected increases in the intensity and duration of droughts, warming air and water temperatures, intense coral bleaching and disease, ocean acidification, saltwater intrusion, and increased intensity and frequency of tropical storms and hurricanes (Gould et al., 2018). The species and habitats that sustain island ecosystems are highly vulnerable to the combined effects of these impacts.

Effective conservation and adaptation of these island systems will require a regional approach. However, the ownership, legal status, and use of cays and islets in the U.S. Caribbean is highly complex making regional planning challenging. Most of the larger islands are located within marine managed areas (MMAs) (Schärer-Umpierre et al., 2014). These are designated as Natural Reserves or Wildlife Sanctuaries administered by Puerto Rico Department of Natural and Environmental Resources (PR-DNER) (e.g., Mona, Monito, Caja de Muertos, Fig. 1) and the U.S. Virgin Islands Department of Planning and Natural Resources (USVI-DPNR), National Wildlife Refuges (NWR) administered by the U.S. Fish and Wildlife Service (USFWS) (e.g., Desecheo, in Puerto Rico, Navassa between Haiti and Jamaica, and Green Cay and Buck Island in the USVI), national parks administered by the U.S. National Park Service (NPS) (e.g., Buck Island Reef National Monument off St. Croix and several cays around St. John in the USVI), and one National Estuarine Research Reserve. In addition, several Natural Reserves (NR) and their marine extensions (e.g., Northeast Ecological Corridor, Arrecifes de la Cordillera; La Parguera; Mona and Monito Islands and Jobos Bay), and the Culebra NWR incorporate multiple islets and cays. While not formally protected, several Critical Wildlife Areas also incorporate multiple islets including the Fajardo coastline and mangroves and adjacent cays within the Punta Petrona NR (Ventosa-Febles, 2005). In Puerto Rico some islands are privately owned including Cayo Norte off Culebra and Isla Palominos and Palominitos in Arrecifes de la Cordillera NR. Private islands are more common in the USVI, with approximately a quarter of the territory's islands in private ownership. Of 57 identified cays, 29 belong to the Virgin Islands government, 14 are wholly private, three are partially private, co-owned with an NGO or Federal entity, eight are US government owned, and three are uncertain. Notable privately-owned islands in USVI include Hans Lollik, Thatch, Great and Little St. James, and Lovango, the latter two being relatively very developed. Interestingly, there is a man-made island of fascinating origin and evolution and Box 1 provides more detail on this interesting situation. Overall, the mixture of ownership creates political and logistical challenges in developing regional management plans for species that cross political boundaries and similarly adds complexity to climate adaptation planning.

Island Type Descriptions

Sand and coral cays: Many of the small cays along the south coast of Puerto Rico have developed over surfacing coral reefs (Fig. 2). The emergent portions are created by the effects of high wave energy accumulating fragments of coral skeletons, principally Elkhorn coral (*Acropora palmata*), (Glynn et al.,1964). These emergent parts of the cays are called ramparts (Hernandez-Avila et al., 1977; Williams et al., 1999). Lower energy sites have cays composed mostly of sand, vegetation, and detritus in addition to the Elkhorn ramparts. Over time, the sediment may stabilize as beach-rock forms (cemented at water level by precipitated calcium carbonate), and the cay becomes vegetated. These islands are dynamic systems, and their shape changes considerably due to accretion and erosion during storms. Many cays are associated with a variety of fringing, patch, bank, and shelf-edge coral reefs. Cays on fringing reefs are the most common and are found throughout the northeast, east, and southern shelf of Puerto Rico. One of the best examples is Arrecifes de la Cordillera Natural Reserve (ACNR), a chain of small, low-elevation cays, rocky islets, and coral reefs stretching between Fajardo and Culebra along a shallow, submarine ridge approximately 29 km long. Some of these cays comprise oolitic (sedimentary rock formed from ooids, spherical grains of concentric layers) eolianite (rock formed by compaction and cementing of particles that have been deposited by the wind) deposits similar to those found in the Bahamas (Kaye, 1959). The rocky islets are the top of ancient dunes that were cemented by calcite. Vegetation associations on these cays include evergreen littoral forest, dry evergreen brush, rocky shores, mangroves, and sandy beach. Sand/coral cays are rare in the USVI.

Mangrove cays: Many cays along the south coast of Puerto Rico are associated predominantly with mangroves (Pittman et al., 2010). These form through a successional process originating with red mangroves (*Rhizophora mangle*) colonizing seagrass beds dominated by turtle grass (*Thalassia testudinum*) on submerged marine sands and may go through a coral reef stage. Vegetation

Box 1 Ruth Cay, USVI: Industrial destruction turns into endangered species habitat.

Ruth Island is a low-lying man-made cay off the south central coast of St. Croix, U.S Virgin Islands (Fig. B1.1). The 13 hectare island was created in 1965 through deposition of dredge spoil from construction of a shipping channel through Krause Lagoon, a large mangrove system that was effectively destroyed by this action and associated industrialization. Yet the tiny island has grown in ecological value over the decades to become a critical resource for declining species.

Fig. B1.1 Ruth Island. Credit: Google Earth https://earth.google.com/web/, accessed June 2019.

The island is comprised of shell and coral rubble and sand with patches of woodland, coastal scrub, and bare rubble habitats (Fig. B1.2). A salt pond has developed on the southeastern corner, surrounded by mangroves planted during mitigation efforts in the 1970s to compensate for the loss of Krause Lagoon (Lewis and Haines, 1980). Habitats on the islands are continuously undergoing vegetation succession, allowing shrublands to become dense. The wetland and woody habitats are used by a number of birds, including White-cheeked Pintails (*Anas bahamensis*) and White-crowned Pigeons (*Patagioenas leucocephala*, (Fig. B1.3) that nest in high numbers on this island (55–95 pairs; McNair, 2008). Due to historical hunting pressure combined with habitat loss and non-native mammalian predators, both of these species have been designated as territorial Species of Greatest Conservation Need.

Fig. B1.2 Ruth Island St Croix. Credit: R. Platenberg.

(*Continued*)

Box 1 (Continued)

In 1990, 10 federally listed St. Croix Ground Lizards (*Pholidoscelis polops*, Fig. B1.3) were released on the island in a bid to expand the distribution of this critically endangered species (McNair and Mackay, 2005). Subsequent population estimates indicated an increase in individuals to 60 in 2003, and a 10-fold increase between 2003 and 2008 (McNair and Mackay, 2005; Geographic Consulting, 2011). This tiny population represents an important species refugia, being one of only four extant populations of this species.

Fig. B1.3 White crowned pigeon and St Croix Ground Lizard. Credit: R. Platenberg.

Fig. 2 Cayo San Cristobal south of Puerto Rico is an example of a sand and coral cay. Credit: HJR Reefscaping.

diversity, structure, and biomass of these cays are influenced by differences in soil salinity, frequency of tidal over-wash, wave intensity, and nutrient input. Two notable mangrove cay clusters in Puerto Rico occur in La Parguera Natural Reserve (LPNR) in the southwest and at Jobos Bay National Estuarine Research Reserve (JBNERR) in the southeast (e.g., Cayos Caribe, Cayos de Barca, see Fig. 3) in Puerto Rico. The mangrove islands in LPNR have formed along fringing reefs, some of which lie up to four km from the

Fig. 3 Cayo Caribe south of Puerto Rico is an example of a mangrove cay. Credit: HJR Reefscaping.

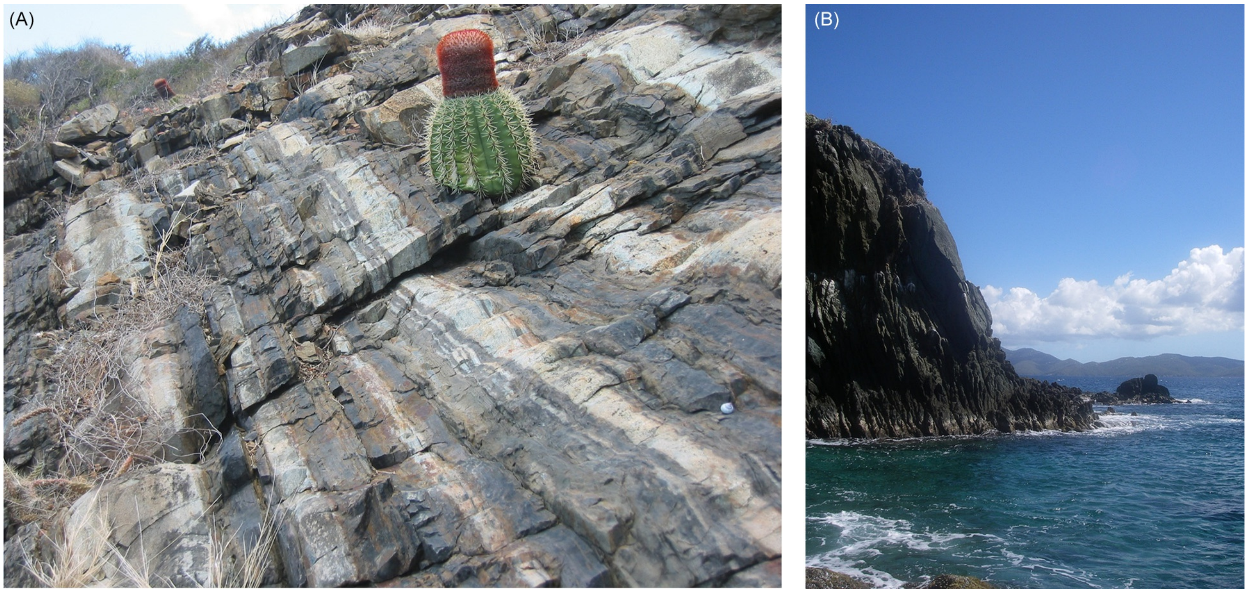

Fig. 4 (A) Geological interestingness associated with volcanic origin of most of the islands east of Puerto Rico, Grass Cay, St Thomas, USVI. (B) Many volcanic cays rise sharply from the sea providing safe nesting habitat for seabirds but restricting access for monitoring. Cockroach Cay, St. Thomas, USVI. (A) Credit: R. Platenberg and (B) Credit: R. Platenberg.

Puerto Rico shoreline. The cays in JBNERR stretch more than five km along fringing reefs, separated by deep drainage channels (Morelock et al., 1977). Most are covered by mangroves, but some larger cays contain small areas of evergreen littoral woodland and/or secondary vegetation and hypersaline lagoons. In the USVI mangrove cays are uncommon with only a single named cay (Cas Cay) and a few islets within the Mangrove Lagoon on the southeastern side St. Thomas.

Volcanic islands: The volcanic islands are represented by Desecheo Island to the west and Culebra Island to the east of Puerto Rico and most of the islands within the northern USVI (St. Thomas and St. John, Fig. 4). The Puerto Rican Bank archipelago comprises

Fig. 5 Coastal shrub and woodland, (A) Dog, (B) Flanagan, and (C) Dutchcap Cays, St. Thomas. Credit: R. Platenberg.

the large islands and over 100 smaller satellite islands, separated from each other in the late Holocene era by eustatic (due to glacial melting) sea level rise (5.3–2.5 million years before present). The islands are dominantly andesite lava, lava breccia, and tuffs (Banks, 1962; Veve and Taggart, 1996). The largest of the cays contain small patches of deciduous, semi-evergreen forest, while the smaller cays are largely steep-walled rocky platforms covered by grasses and shrubs or bare rock (Figs. 4B and 5A–C). Desecheo Island is primarily fragmented volcanic rocks of early Tertiary origin (Seiders et al., 1972) that is dominated by sub-tropical dry forest and is fringed by some of the healthiest coral reefs in the region (García-Sais et al., 2003).

Limestone islands: Situated in the Mona passage to the west of Puerto Rico are Mona (5500 ha) and Monito (14.5 ha) Islands and exemplify limestone islands (Fig. 6A and B); although Anegada Island in the British Virgin Islands, far to the east, is another important and very old limestone island. Mona Island is the largest offshore island in Puerto Rican waters (Fig. 1B). Both Mona and Monito have been separated from the main island of Puerto Rico far longer than the Culebra islands have been. Mona is a Mio-Pliocene tectonically uplifted carbonate limestone plateau (meseta) (Morelock et al., 2002; Renken et al., 2002; Frank et al. 1998; Seiders et al., 1972). This isolation has led to several endemic species, including an orchid, amphibians and reptiles such as the Mona Iguana (*Cyclura stejnegeri*) (Fig. 6C). Mona Island is dominated by sub-tropical dry forest and is fringed by well-developed coral reefs (García-Sais et al., 2003).

Ecological Value of Cays

Because of their isolation, offshore islands provide valuable refuges for flora and fauna where threats from human persecution, habitat degradation, and climate change are either lacking or evident but with the chance of being more manageable than on the mainland. For example, the largest hawksbill (*Eretmochelys imbricata*) and green (*Chelonia mydas*) sea turtle rookeries in Puerto Rico are on Mona Island and Vieques Island respectively, and leatherbacks (*Dermochelys coriacea*) nest on several of the cays off St. Thomas. Endemic species occur on the larger, more isolated islands (Mona Fig. 6A and B; Monito, Desecheo) and many of these

Fig. 6 (A) Aerial view of Mona Island, its steep cliffs rising out of the ocean and seemingly flat surface belies a rugged environment home to many endemic species. (B) Limestone cliffs, caves, white sand beach, and dry scrub habitat of Mona Island. (C) The endemic Mona Iguana (*Cyclura cornuta stejnegeri*). (A) Credit: M. García-Bermúdez, (B), Credit: B. Murry and (C) Credit: Molly Ramsey.

species are also designated as threatened under the US Endangered Species Act or local regulations. Other species such as white-crowned pigeon (*Patagioenas leucocephala*; see Box 1), brown pelican (*Pelecanus occidentalis*), other seabirds, and various shorebirds regularly nest or roost on offshore islets and cays. Coastal wetlands on cays provide habitat for a variety of migratory shorebirds and water birds, along with a variety of invertebrates. Several larger cays off the north shore of St. Thomas have cliff caves and fissures that are occupied by the Antillean Fruit-eating Bat (*Brachyphylla cavernarum*), while Mona and Monito Islands were mined for bat guano during the 19th century (Frank, 1998). Many reptile species that have been extirpated from human-inhabited islands maintain remnant population on these cays, such as the Puerto Rican racer *Borikenophis portoricensis*, the federally endangered St. Croix Ground Lizard (*Pholidoscelis polops*, see Box 1), and the endemic skinks *Spondylurus* spp. Amphibians and many land birds are also absent from most of these islands due to reduced habitat complexity. In a few cases, species threatened on the mainland have been translocated to offshore islets to safeguard populations (e.g., Virgin Islands boa, see Box 2).

Seabirds are an important component of marine biodiversity as they play significant regulatory roles and enhance primary productivity in local marine, intertidal, and terrestrial environments. Cays and islets are critical breeding sites for seabirds because of the reduced predation pressure and ease of access to foraging grounds. Eighteen species of seabirds breed on at least 37 offshore islands or island clusters in Puerto Rican waters (Fig. 7A). The major seabird nesting areas in the USVI are found on about 25 of the most remote or rugged cays off St. Thomas and St. John, where their eggs and offspring are less vulnerable to predators than on the major islands (Pierce, 1996; Fig. 4B). The species composition of breeding seabirds varies among the cays depending upon the availability of nest sites. For example, Flat Cay and Saba Island harbor active rookeries of gulls and terns, Cockroach Cay (Fig. 4B) and Dutchcap Cay host colonies of boobies (Fig. 7B and C) and tropicbirds, and Congo Cay, Dutchcap Cay, Buck Island (St. Croix), and Green Cay (St. Croix) support nesting pelicans. Many species exhibit high site fidelity and can be found in the same sites year after year, while some species, such as the federally protected Roseate Tern (*Sterna dougallii*) utilize a complex of islands by selecting different sites on an annual basis. Except for some terns, most seabirds nest at the same colony year after year, and rarely form new colonies. These patterns in the multiple uses of islands by key species have significant management and adaptation implications as

Box 2 Case Study: Virgin Islands Tree Boa

The Puerto Rican Bank is found within the Caribbean Region, which is considered a biodiversity hotspot (Cincotta and Engelman, 2000; Helmer et al., 2002; Myers et al., 2000). This geological area encompasses the island of Puerto Rico (excluding Mona Island) and its offshore cays, the U. S. Virgin Islands (but not Saint Croix), the British Virgin Islands, and more than 180 associated small islets and cays (Heatwole and MacKenzie, 1967; Thomas, 1999), islands harbor a high percentage of endemic species and have suffered a high percentage of extinctions (Island Conservation, 2014). This unfortunate condition has promoted the implementation of diverse single species conservation initiatives aimed mainly at vertebrate species.

The endangered Virgin Islands tree boa (Fig. B2.1; Federal Register, 1970, 35:16047), *Chilabothrus granti* (Rodríguez-Robles et al., 2015), presents a disjunct distribution on the islands of the Puerto Rican Bank (Nellis et al. 1983; Mayer, 2012). Its patchiness in occupancy has been explained by pre-historical (eustatic) changes in sea level and more recently by anthropogenic disturbances (deforestation, invasive species) that have caused the population's extirpation within the species' original range (Nellis et al., 1983; Tolson, 1996). Due to its risk of extinction, a recovery project started in the mid 1980s to release captive bred offspring of founders from wild populations in Puerto Rico (Cayo Diablo) and St. Thomas and to reintroduce them to two cays near each respective locality, After twenty years, it was classified as "highly successful" due to the establishment of the two new and sustainable wild populations on protected lands (Tolson et al., 2008). To accomplish this milestone, several phases had to be completed:

Fig. B2.1 The Endangered Virgin Islands tree boa is an example of one of many threatened and endangered species that find refuge on the largely uninhabited cays of the Puerto Rican Bank, but are vulnerable to sea level rise in the long-term, invasive species and development in the short-term. Credit: M. García-Bermúdez.

1. Pre-evaluation and selection of cays according to habitat condition, presence of invasive cats, rats, and abundance of boa prey
2. Eradication of rats
3. Capture of wild boas to establish an ex situ captive breeding program
4. Release of captive born individuals in the wild
5. Long-term monitoring of released individuals for survivability and population growth

It was assumed that the translocation of Virgin Island tree boas to cays after eradicating the invasive species in Puerto Rico and the USVI, respectively, had safeguarded its recovery. However, the threats related to climate change, particularly sea level rise turned all these efforts into a stopgap action because the recipient cays are relatively low in relation to current sea level and will be impacted negatively by the projected increments in sea level and catastrophic events—hurricanes and droughts (PRCCC, 2013). Furthermore, during a recent post Hurricane Maria survey, no boas were found, and rats have recolonized the Puerto Rican cay (Island Conservation, 2018). These threats acting individually or in synergy will exacerbate the risk of extinction of the species and other components of the Caribbean biota. Therefore, a landscape approach to the recovery of these species addressing common threats (i.e., invasive species and sea level rise) to protect them is timely and urgent.

new methods may be needed to facilitate colony formation on islands with greater resilience to sea level rise, drought, and other stressors.

Offshore islands also provide valuable stopover sites and wintering grounds for Nearctic and Neotropical birds migrating along the Atlantic Flyway. They are likely to be the first landfall site that migrants encounter (Wallace et al., 1996), and function as refuges for migrants during tropical storms and hurricanes. Larger islands such as Mona can support over-wintering migrants. As the spread of invasive species and frequency of weather disruptions increases, offshore islands may become increasingly important to migratory species.

Fig. 7 (A) Nesting habitat of seabirds at Media Luna Cay, La Parguera, Puerto Rico. Birds include least tern and brown noddy. (B) Masked booby nest on a St. Thomas cay. (C) Brown booby pair on nest, Kalkun Cay, St Thomas. (A) Credit: J. Vargas, (B) Credit: R. Platenberg, and (C) Credit: R. Platenberg.

Social Value of Cays

In addition to the ecological importance of supporting high levels of unique biodiversity, the islands surrounding Puerto Rico and USVI also have social, economic, and cultural value. Their position on the coast can dissipate wave and storm energy reducing impacts to coastal communities on nearby islands. The ecosystems associated with cays and islands also provide nursery habitats for commercially important fish and invertebrates that support local artisanal and recreational fisheries. Danylchuk (2015) used acoustic tracking to define preferred shoals for bonefish and the associated recreational catch-and-release fishery around Culebra, Puerto Rico. The study shows how this depth-associated recreational fishery, of commercial importance for fishing guides and associated businesses, could be affected by sea level rise. Changes in the ecological value of these small islands, shoals, and cays can impact tourism, recreational fisheries, and the economies of coastal communities.

Historically there was extensive mining of guano, agriculture, and forestry practices on many of the region's islands. An interesting use of cays can be found at Santiago Cay off the east coast of Puerto Rico where primate research spanning over 70 years has been ongoing by the Caribbean Primate Research Center of the University of Puerto Rico. Islands also provide extensive recreational opportunities such as second homes, boating, fishing, snorkeling and scuba diving, surfing, and simply gathering to relax and barbeque (Fig. 8). Significant tourism has been developed in some of the nearshore cays with high visitation rates, local fishing charters and dive operators generating income to multiple sectors of the local economy. However, recreational use of cays can also be highly damaging to the ecological integrity of the cays and surrounding marine habitats (e.g., coral reefs and seagrass beds), representing a clear and present conflict of use.

In response, the PR-DNER administered a program of installation and maintenance of mooring buoys since 2004. The objective of the program is to reduce anchor damage on seagrass meadows and coral reefs. High-use and high-risk areas were assessed via aerial surveys to increase the effectiveness of placement of the mooring buoys (Fig. 8). The program successfully installed over 300 buoys (Rodríguez-Robles et al., 2015). Over time, patterns of boater use of different anchoring areas and degree of acceptance of the mooring buoys by the boaters as an alternative to anchoring can be detected through the photos.

Recreational boat use tends to peak during holidays and the most popular and high-risk locations tend to be nearby long-term docking facilities and on islands with sandy beaches. All the high use areas are associated with damages and diminished habitat quality to local corals and seagrasses and the intensity of use makes it logistically impossible to supply enough moorings (Rodríguez-Robles et al., 2015). Further, there has been a recent shift in use (2005–12 compared to 1998–2004) toward cays closer to the coast and docking areas (e.g., yacht clubs) that appears to be driven by rising fuel costs (Rodríguez-Robles et al., 2015). Thus, until economics and behaviors change, cays nearer the main island and their surrounding marine habitats are especially vulnerable to anthropogenic damage.

Fig. 8 Recreational boat use of Cayo de Barca, Jobos Bay National Estuarine Research Reserve, Puerto Rico. Credit: E. Rodriguez.

A similar mooring installation program was also initiated in the USVI, although the social usage patterns are different. USVI cays do not experience the high-level congregation on weekends and holidays that PR cays do; USVI cays are more exposed to ocean current, have smaller beaches or none at all, and many require technical skills to access. Rather, visitation is focused on fishing and diving activities. Historically the seabird colonies were plundered for egg collection and in response VI-DPNR installed "no entry" signage and a requirement for visitation permits for access beyond the beach and this activity has largely ended. Some locals still access the cays to hunt non-native goats that were placed decades or centuries ago as an emergency food resource. Goats and rats have been removed from the cays with important seabird nesting colonies, but goats and rats still remain on many privately-owned cays.

The accumulation of plastics carried by currents and winds towards mangrove and coastal zones of small islands is significant. These plastics are associated with the habitat degradation and direct risk of entanglement with sea turtles and seabirds that come to shore. Ingestion of the plastics that float near the islands by chicks increases their mortality, although the extent of this impact has not been assessed. Recent accumulations of large quantities of sargassum algae have been impacting the nearshore and coastal communities of islands in the US Caribbean. The weight of the algae can overcome the sea turtles that inhabit nearshore areas drowning them. Hatchling sea turtles are also affected by the sargassum accumulations off sea turtle nesting beaches increasing their mortality as they try to reach the sea. Marine organisms also perish due to the anoxic conditions that are created when the seaweed decompose, and bacteria consume most of the dissolved oxygen.

Beyond recreational use, the US military utilized many of the islands off the eastern coast of Puerto Rico (between Puerto Rico and St. Thomas), including Vieques and Culebra with sizable human populations (and very popular tourist destinations), for target shooting and bombing practice. This practice, which ended in 1975 in Culebra, and in 2003 in Vieques, due largely to public anger and objections, has left a legacy of habitat damage, pollution, and potentially live munitions within the terrestrial and shallow nearshore aquatic zones (McCaffrey, 2018). The majority of the lands were subsequently transferred from US military possession to the U.S. Fish and Wildlife Service National Refuge System. To protect human safety many areas are closed to access, although Cayo La Chiva in Vieques will be opened to public access following completion of the cleanup. Although environmental clean-up has been on-going and slow, social discontentment remains strong. Cleaning-up potentially live munitions requires acre by acre forest removal. To date, reforestation has been lacking, such that "cleaned" areas tend to be quickly colonized by invasive plant and vertebrate species. Management of vertebrate invasive species has also been largely lacking. Thus, although from a conservation perspective these lands are under protected status with reduced human access (due to safety risks), the ecological value of these lands is compromised due to the impacts of invasive species. Military activity on Monito and Desecheo Islands off the west coast devastated seabird colonies; these islands remain off limits to humans due to the risks associated with unexploded ordnance.

Climate Change Effects

Cays are at risk from climate change due to drought, rising sea levels, more intense and frequent storms, and potential natural and anthropogenic limits to inward (upslope) migration (Powell et al. 2017; Costanza et al., 2016). The resources on cays are sensitive to these influences because of the relatively small area and typically unique species assemblages. The most recent downscaled climate projections (Bowden et al. 2018; Gould et al., 2018) suggest changes in regional precipitation patterns and specifically longer and more intense droughts by mid-century (see also Murry et al., 2019 for coastal wetlands). Many organisms are adapted for xeric conditions, however extended drought, combined with increasing sea levels, storm surges, saltwater intrusion, and increased sea spray readily impacts native vegetation, paving the way for robust invasive species or loss of vegetation, with subsequent habitat-related impacts to native fauna.

Cays within the US Caribbean are not static features in time and space but change in shape, habitat, and ecological value in response to sea level, waves, currents, hurricanes, sediment inputs, and invasive species. Bush et al. (2014) provided an evaluation of historical shoreline change for a few of the cays around Puerto Rico. It is important to understand both global sea level trends, as well as local trends. Local tide gauges provide better estimates of sea level rise, and thus better insights into the long-term vulnerability of cays in response to local conditions, that we use to analyze low profile cays and their respective biological systems or habitats. Regardless, the vulnerability of cays is dependent on the ability of their elevation and habitats to keep pace with rates of sea level rise. For example, cays located in regions of tectonic uplift or subsidence can potentially minimize or exacerbate the impacts of long-term global sea level rise. Local, or relative, sea level rise rates do not necessarily match those of eustatic global dynamics.

Physical damage to the structure and transport of the loose or cemented coral carbonate skeletons is likely to increase due to stronger or more frequent hurricanes coupled with low rates of coral growth due to coral mortality and the net eroding effect of increased ocean acidification. These erosion processes especially impact sand and coral cays. The physical action of the waves during high energy events such as hurricanes, storms, and swells increase substrates for coral re-colonization and coral fragmentation and redistribute coral rubble to low-lying areas creating space for islands to grow. These extreme events can also cause a high transport of sediments causing burial of benthic substrates and transporting material from shallow to deeper areas or vice versa. It has been suggested that reefs periodically disturbed by storms of intermediate intensity will increase growth rates and long-term calcification (Highsmith et al., 1980). However, it is certain that the ocean acidification caused by anthropogenic activities will increase in accord with atmospheric CO_2 emissions. Ocean acidification decreases the availability of the carbonate ion, CO_3^{2-} (the principal building block of most marine skeletal material), adversely affecting calcification and increasing dissolution processes. This leads to slow growth rates and malformed and less dense carbonate shells and skeletons (Cohen et al., 2009). As a result, species that undergo calcification may become displaced by species that do not. This will likely continue deteriorating reef conditions and cause ecological regime shifts from coral to algal reefs (Anthony et al., 2011). A decline in calcifying species (e.g., corals, crustose coralline algae, calcareous green algae) will affect the sediment budget available to island's shores, increase the potential for shore erosion, decrease the potential for carbonate island formation, and decrease beach and reef-based tourism and economic activity.

The combination of physical erosion, dissolution, and bioerosion processes in shallow reef habitats accelerate the loss of calcium carbonate sediments and decrease the stability of the reef skeletal framework (Eyre et al., 2014), potentially leading to a collapse of reef structures (Hoegh-Guldberg et al., 2007). Future acidification effects will not act independently from other global and local environmental pressures such as sedimentation. Such effects could compromise reef resiliency and increase vulnerability of certain types of islands in the face of other acute threats, such as thermal-stress, outbreak diseases, and rising sea level (Silverman et al., 2009).

It is estimated that coral reefs reduce the wave energy by an average of 97% (Ferrario et al., 2014) with most of the energy being absorbed at the shallower point (reef crest). In order for coral reefs to continue to provide coastal protection to low lying keys, corals will need to grow upward rapidly enough to keep pace with the rising sea level (Sheppard et al. 2005). If upward growth and reef complexity decrease due to ocean acidification, the reef will slowly "sink" as water depth increases and the wave energy reaching the shores behind those reefs will increase (Alvarez-Filip et al. 2009; Sheppard et al. 2005). In the case of the islands described herein, this will make coastal areas increasingly more vulnerable to the action of waves and storm surge with associated effects on the tourism sector, fisheries, and coastal infrastructure (Table 1).

Cay ramparts associated with high wave energy reefs are almost completely composed of Elkhorn coral as noted previously (Williams et al., 1999). If the live Elkhorn colonies that are the source of cay ramparts disappear, cays will be impacted in two ways: (1) they will receive more direct wave energy that is not dampened by the live corals, and (2) they may eventually erode away if no new pieces of coral skeletons are available to maintain accretion processes. Skeletons of Elkhorn coral form loose plate ramparts up to 4.5 m above sea level on cays exposed to high wave energy (Hernandez-Avila et al., 1977). This may protect the cays from wave-generated erosion and allow coral rubble and sand to accumulate on the cay. These ramparts also serve an ecologically important function as nesting habitat for many seabirds (e.g., least tern *Sternula antillarum*, brown noddy *Anous stolidus*).

Elkhorn coral once formed dense, high profile, monospecific stands in shallow depths (1–5 m) of the fore-reef zone and was abundant throughout the tropical Western Atlantic. In the 1970s and 1980s, Elkhorn coral experienced precipitous declines in abundance throughout its range, estimated at greater than 97% loss (NMFS 2014; Schärer et al., 2008). Data suggest that the decline in Elkhorn coral populations throughout Puerto Rico is primarily the result of disease and predation (Nemeth et al., 2014). Other threats to corals such as elevated seawater temperatures, overfishing, pollution, and ocean acidification are credible and potentially significant impediments to recovery of this species. In the past, storm damaged thickets have regenerated between major storms and thus produce the skeletal coral materials to replenish the cay ramparts during subsequent storms (Williams et al., 1999). The Elkhorn coral thickets also absorbed routine wave energy and protected the cays. Elkhorn coral abundance has significantly reduced the coral's ability to replenish cays and protect them from wave energy.

Table 1 Vulnerability of specific classes of biological targets to two specific drivers: sea level rise and extended droughts.

Climate driver	*Targets*	*Climate-related impacts and vulnerabilities*			*Non-climate stressors*	*Relative vulnerability*
		Exposure[a]	*Sensitivity*[b]	*Adaptive capacity*[c]		
Sea level rise	Sandy beaches and dunes	Extreme: at impact front	Extreme: change to aquatic habitat	Low: depending on island topography and accretion; habitat migration limited	Human recreation/ disturbance	High
	Coastal shrub	Extreme: at impact front	Moderate-extreme: reduction in suitable area and salt spray	Low-moderate: depending on island topography; habitat migration limited	Human recreation/ disturbance; invasive species (e.g., goats)	Moderate-high
	Rocky shores	Extreme: at impact front	Low-moderate: sand accretion could change to beach	Low-moderate: depending on island topography and accretion; habitat migration limited	Limited	Low-moderate
	Seabirds	Moderate-extreme: depending on specific microhabitat use	Moderate: depending on degree of habitat specificity	High: ability to alter habitat use (e.g., move upslope) or change islands	Invasive species; human recreation/disturbance; open ocean conditions (prey abundance, plastics)	Moderate
	Endemic lizards	Moderate-extreme: many islands are low-lying	High: reduction in habitat space	Low: inability to colonize new islands without human intervention		High
	Endemic plants	Moderate-extreme: depending on specific microhabitat use	Moderate-extreme: reduction in habitat space and salt spray	Low-moderate: depending on mode of seed dispersal and degree of habitat specificity		Moderate-High
Extended droughts	Sandy beaches and dunes	Low	Low: dune plant desiccation	High: limited impacts	Human recreation/ disturbance	Low
	Coastal shrub	Moderate	Moderate: shrub zone plant desiccation	Moderate: seed banking, selection toward drought resistance	Human recreation/ disturbance; invasive species (e.g., goats)	Moderate
	Rocky shores	Low	None	High: limited impacts	Limited	Low
	Seabirds	Low-moderate: may experience some habitat changes	Low-moderate: not dependent on rain and moisture, but may experience habitat changes	Moderate: flexible nesting behavior; ability to move to more suitable islands, but drought likely to be regional	Invasive species; human recreation/disturbance; open ocean conditions (prey abundance, plastics)	Low-moderate
	Endemic lizards	Moderate: may experience some habitat changes	Low-moderate: dry adapted, but may experience changes in habitat and prey availability	Low-moderate: Behavioral responses to dryness, habitat, and prey changes		Moderate
	Endemic plants	High: water dependent to varying degrees	Low (cactus) to high: will depend on physiology	Low-moderate: depending physiology and seed dispersal and dormancy		Low-high

This is not intended to be exhaustive nor overtly specific, but to serve as an example of the thought processes involved in assessing climate vulnerabilities. More precise vulnerabilities can be identified when considering specific species. Consideration is also paid to non-climate stressors that may have additive or synergistic effects.

[a]Exposure is defined by Stein et al. (2014) as the amount of change in climate and associated impacts the target species or system is likely to experience.

[b]Sensitivity is related to the affect or response of a species or target system to specific changes in climate variables or secondary effects.

[c]Adaptive capacity refers to a species or system's ability to accommodate or cope with climate-associated changes.

Modeled after materials derived from: Stein, B.A., Glick, P., Edelson, N., and Staudt, A. (eds.). (2014). *Climate-smart conservation: Putting adaptation principles into practice*. National Wildlife Federation, Washington, D.C.

Climate Change Vulnerability

Climate change impacts, such as sea-level rise, storm surges, and drought could lead to a reduction in the size and number of low-lying islands while others that are morphologically resilient are expected to persist. Because the main islands of the US Virgin Islands

Box 3 Case Study: Habitat Vulnerability Assesment of Small Oceanic Cays of Puerto Rico and U.S. Virgin Islands

Previous research conducted by Bush et al. (2014) between 2010 and 2013 focused on the assessment of coastal vulnerability and forecasted shoreline changes and land loss by application of three methods: (1) the simple slope/retreat model based on existing estimates of rates of sea-level rise; (2) historical shoreline change using t-sheets, aerial photographs, LiDAR, and satellite imagery, and extrapolation of those changes into the future; and (3) a coastal vulnerability index (CVI). The first approach presumes that the dominant control on coastal regression is the offshore/onshore long profile of the area of interest and the second approach presupposes that the shoreline change trends of the recent past will continue. Based on Bush et al. (2014), reliable data is available for both approaches; however, a more broad-based prediction can be made by applying a CVI. The CVI approach has been highly used in the United States and Canada but was applied in Puerto Rico and USVI for the first time to small islands in 2010. Bush et al. (2014) also employed the recently developed AMBUR (Analyzing Moving Boundaries Using R) software with the hazard-vulnerability assessment tool (AMBUR-HVA) to assess shoreline vulnerability for cays using geologic/geomorphologic data (Bush et al.2014; Jackson et al., 2012) (Fig. B3.1).

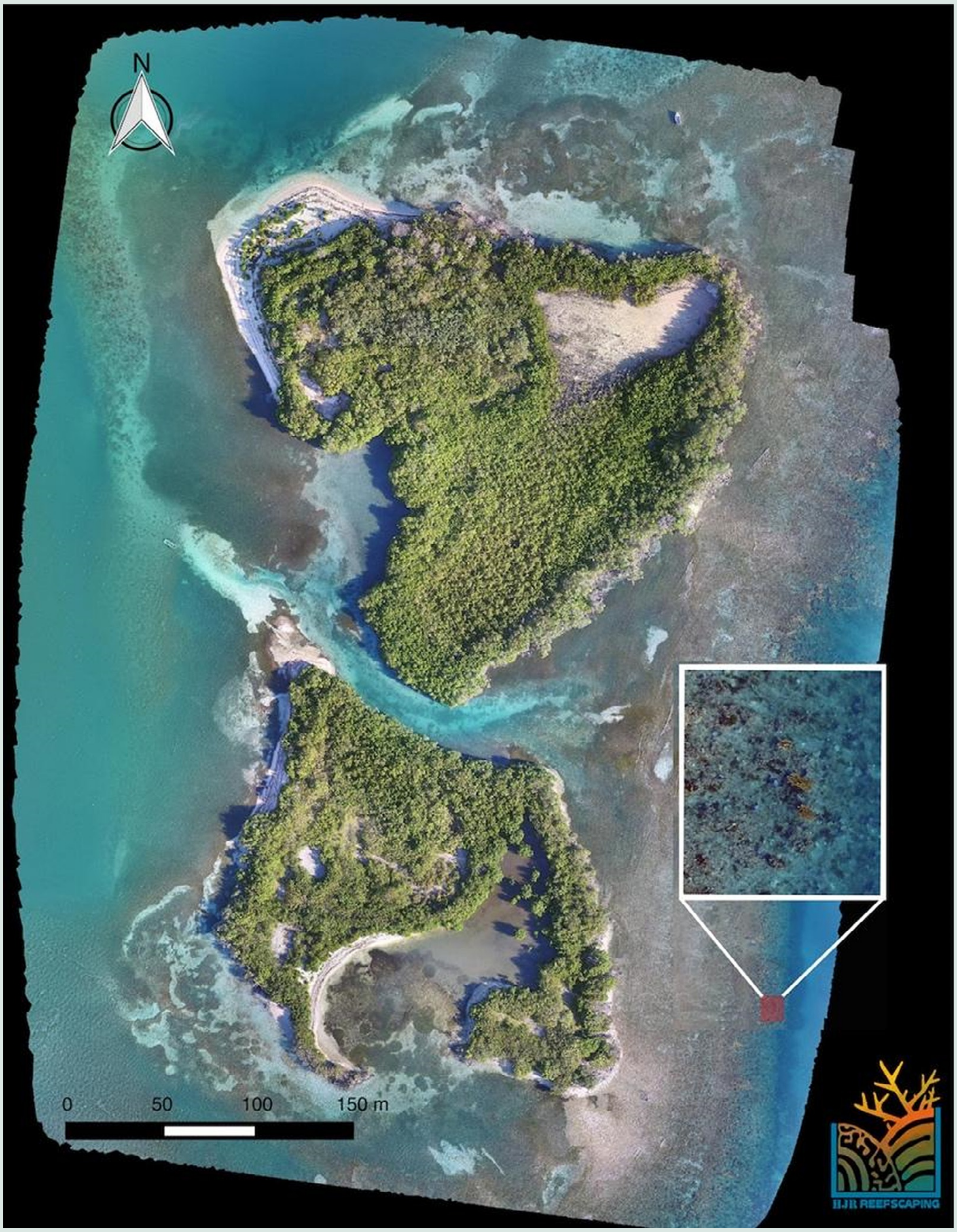

Fig. B3.1 High resolution UAV imagery of Caribe Cay, Peñuelas, Puerto Rico and inset showing submerged colonies of the threatened Elkhorn coral *Acropora palmata* in the forereef area. Credit: HJR Reefscaping.

(*Continued*)

Box 3 (Continued)

Since 2014, the USFWS Coastal Program has supported the collection of ecological information at landscape and seascape scales for cays around Puerto Rico and the USVI. The purpose is to determine population and/or habitat metrics that are more effective in assessing the sustainability of species and their habitats and to develop species/habitat vulnerability models that may be linked to existing and widely used geophysical models. This information will be used to assess species' vulnerability to coastal hazards (erosion, inundation, and coastal exposure), climate change effects, as well as the need for habitat restoration and/or enhancement, and to identify and implement best management strategies. This initiative will be providing managers critical information: potential habitat loss in the context of spatial (i.e., sea, shoreline, cays and/or inland), temporal (e.g., 1 year, 10 years, 50 years, 100 years), and severity (i.e., low, medium, high risk) of these hazards. When complete this project is expected to provide the basis for developing assessment methods that would potentially be widely applicable to many coastal settings in the Southeastern U.S. and the Caribbean.

A multi-agency effort was initiated to establish a baseline for determining the vulnerability to climate change of small oceanic cays in the U.S. Caribbean. In 2013, local and federal natural resources agencies in collaboration with academic, private, and non-governmental organizations defined a series of research questions and management concerns that should be addressed in priority areas of interest. These concerns refer mainly to the potential loss of important habitats and the impacts upon the biodiversity and threatened or endangered species, particularly in areas where the marine and terrestrial environments interact in dynamic ways. The multidisciplinary team identified criteria to rank study areas and chose 16 cays for this study spanning waters of Puerto Rico and the US Virgin Islands.

An ecosystem-based approach was devised to collect data on the marine, coastal, and terrestrial environments, allowing for the compilation of detailed data on habitat characteristics and species' composition on each cay. This information will be analyzed to determine habitat connectivity, patterns of habitat use (nesting, breeding, feeding, etc.), the location of critical habitats, incidence of habitat loss, and potential impacts to species' distributions. Detailed aerial ortho-photo mosaics, visual censuses, and underwater surveys near the shorelines are being conducted to evaluate the vulnerability of cays to climate change (Fig. 6). Preliminary results revealed the distribution of critical habitats for several threatened and endangered species such as the Virgin Island tree boa, St. Croix ground lizard, elkhorn and staghorn coral, and mountainous star coral on and around the cays. Data suggest that in some areas (1) inundation, (2) erosion, and (3) changes in vegetation are impacting the habitat quality and stability of cays and that preliminary model output (AMBUR-HVA-Cays, http://ambur.r-forge.r-project.org/) suggests fetch or coastal openness to wind/wave exposure is also a major factor influencing vulnerability.

have an extensive human footprint, they have relatively low conservation value; as such, the surrounding, largely uninhabited cays have been a focus of conservation efforts for decades. In contrast, until recently, the evaluation of small cays around Puerto Rico, their description, and ecologic importance have not received the attention that they deserve. Except for coral reefs, cays developed on coral rubble, sand shoals, and mangrove patches have received less attention. However, it is recognized that sea level rise and associated impacts are expected to negatively impact the ecological, societal, and economic benefits cays provide. Therefore, assessing the response of cays' shorelines to these stressors is critical for developing sound coastal management and land use planning guidelines for small islands (Bush et al., 2014; see Box 3).

Understanding the vulnerability of coastal areas is critical as this is the area where multiple stressors have the greatest opportunity to converge and where the greatest vulnerabilities lie (Gould et al., 2018). Toward that end, members of our writing team participated in a Climate Adaptation workshop to begin conceiving a long-term regional cays management plan in recognition that the species of greatest conservation interest span many jurisdictional management boundaries and occupy cays that individually range from low to very high vulnerability (based mainly on elevation). For this exercise two primary drivers were considered in scenarios that were deemed independent and potentially synergistic, sea level rise and drought (Table 1). Specific habitat and species targets were identified, and we assessed their respective (and specific) exposure, sensitivity, and adaptive potential to the climate-related drivers (defined in Table 1). Importantly, we also considered non-climate stressors that will inevitably affect the vulnerability of the targets. Invasive species represented the greatest current and future threat and will likely be exacerbated by climate related impacts. We found that habitats tended to be more vulnerable to sea level rise than to droughts and sandy beaches and dunes more vulnerable than rocky shorelines (Table 1). Target species (seabirds, nesting sea turtles, lizards, and native plants) tended to also show greater vulnerability to sea level rise (through loss of habitat and habitat changes) than to drought.

A key step in developing a climate-smart adaptation plan is visualizing and defining a suite of potential future scenarios (Stein et al., 2014). Comparing and contrasting two climate change related impacts, namely sea level rise and drought, postulates four potential future scenarios (Fig. 9); ranging from minor impacts from minimal sea level and minor increases in drought (lower left) to large increases in sea level rise and extended severe droughts (upper right).

The scenarios allow managers to prepare for a range of future conditions and prioritize actions to facilitate system adaptation (Table 2). All of the scenarios are nested within warmer ocean and air temperatures and continuing threats from invasive species and the impacts of human uses. Under the scenario of lowest impacts (lower left) managers can anticipate minor coastal erosion and instead focus attention on human disturbance and invasive species, whereas at the opposite extreme (upper right) where droughts and sea level rise are both high, managers will need to face increased threats of fire, loss of habitat space, potentially loss of low-lying islands, and severe habitat modification. Each scenario demands a separate suite of management actions to maximize resource

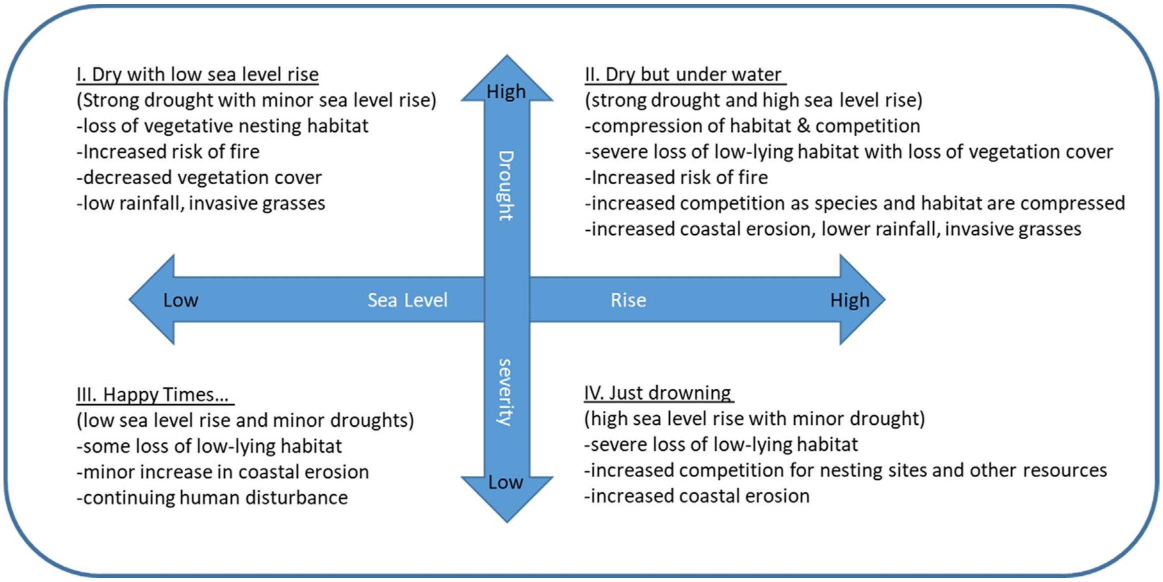

Fig. 9 Four potential future scenarios based on low to high sea level rise and small to large increase in drought.

Table 2 Potential management actions toward climate resilience on Caribbean cays

Conservation goal: Maintain or increase the population of endemic and native species and their associated habitats in the offshore islands of the Puerto Rican Bank and St. Croix through the end of the century

Key vulnerabilities: Sea level rise and droughts

Proposed action	Linkage of action to climate change
Coastal zone restoration: sand dunes, forests, implement living shorelines, facilitate habitat migration	Habitat loss from rising sea levels and drought
Artificial/engineered structures: e.g., breeding platforms, islands, shading breeding areas, oyster bars, desalinization and irrigation	Addresses negative impacts of drought and habitat loss
Captive propagation and breeding programs: for population supplementation plus genetic diversity	Supports evolutionary potential and mortality associated with extreme events
Move populations: Translocations of vulnerable species populations to less vulnerable islands (higher and bigger), use of enclosures and supplemental feeding/care to improve success, improve seabird attraction techniques	Response to sea level rise and loss of islands and habitat loss from drought
Invasive species elimination and prevention: continue to improve and implement biosecurity measures and eradications	Reduction of non-climate stressors and exotics that may benefit from climate change
Improve seabird foraging success: fish aggregation devices (FADs) to congregate prey fish and protective fisheries regulations, e.g., nursery areas, no-take zones	Reduction of non-climate stressors
Restore degraded habitats: e.g., bombed islands, by using drought tolerant species	Non-climate stressors and drought response
Human dimensions: "adopt a skink" or "adopt an island" program, visitor centers and education with sacrificial populations for public interaction	Non-climate stressors
Restricted human use areas: controlled access beached, target priority areas; conservation easements and other incentives	Non-climate stressors and avoid climate-driven habitat loss

allocation on the most likely threats. In the worst-case scenario this may include translocation of rare species from low-lying cays to higher elevation cays, facilitating habitat migration, and reducing non-climate stressors and threats (Table 2).

In conclusion, we continue to gather data on species and habitat distributions as well as climate, human, and ecological threats. The main goal must remain the implementation of conservation initiatives aimed at higher elevation habitats and species resilience to safeguard the long-term existence of these globally unique ecosystems.

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