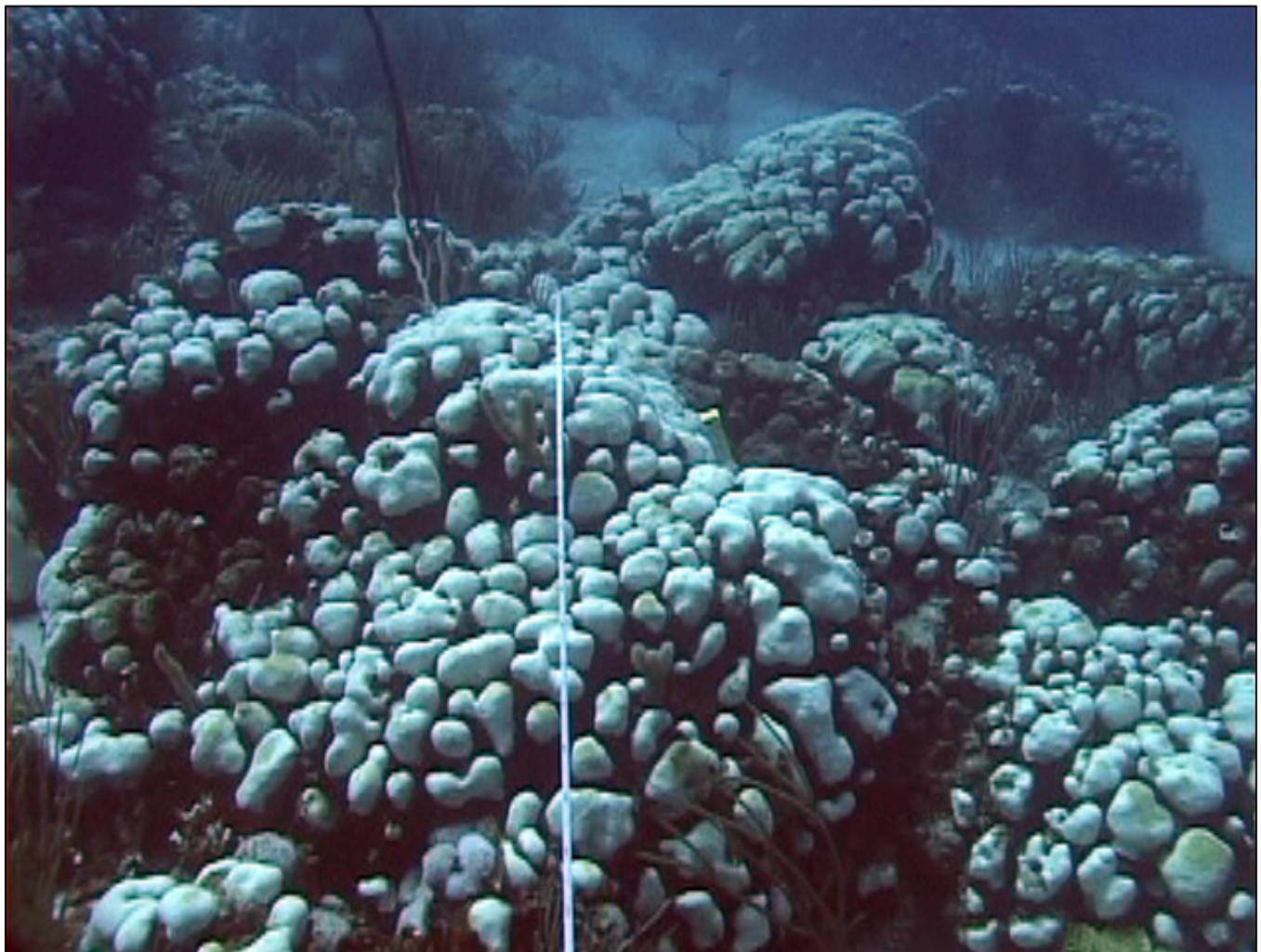


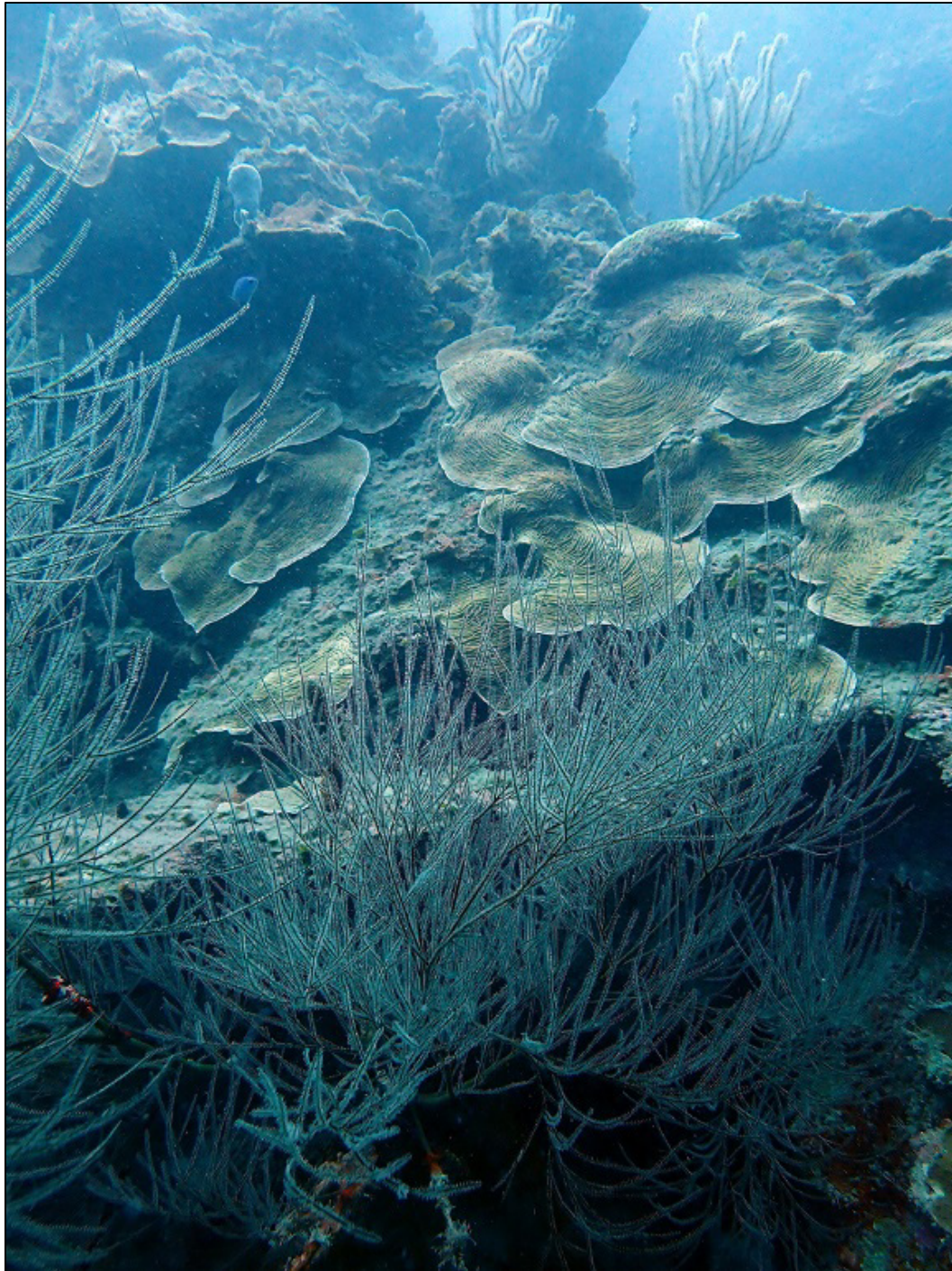


A Synthesis of Coral Reef Research at Buck Island Reef National Monument and Salt River Bay National Historical Park and Ecological Preserve, St. Croix, U.S. Virgin Islands

1961 to 2022

Natural Resource Report NPS/BUIS/NRR—2022/2447





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Monitoring site at Salt River Bay National Historical Park and Ecological Preserve
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September 2022

U.S. Department of the Interior
National Park Service
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Executive Summary

This synthesis focuses on the history of research on coral reefs within two U.S. National Park Service units in St. Croix, U.S. Virgin Islands: Buck Island Reef National Monument (from 1961 to 2022) and Salt River Bay National Historical Park and Ecological Preserve (from 1980 to 2022). Buck Island Reef National Monument (BUIR) is off the north shore of the island of St. Croix, in the U.S. Virgin Islands. Established in 1961 and expanded in 2001, it is under the jurisdiction of the National Park Service (NPS). Long-term monitoring programs maintained by the NPS and jointly by the University of the Virgin Islands (UVI) and the Virgin Islands Department of Planning and Natural Resources (VIDPNR) provide data on trends in living coral cover and specific coral species from 2000 and 2001, respectively. Disease, thermal stress (indicated by coral bleaching), and hurricanes reduced total coral cover periodically, but cover remained relatively stable from 2007 through the end of 2020.

Salt River Bay National Historical Park and Ecological Preserve (SARI) is a national park on the north shore of the island of St. Croix, in the U.S. Virgin Islands. Established in 1992, it is co-managed by the NPS and the Government of the Virgin Islands. Long-term monitoring programs maintained by the NPS and by the UVI with the VIDPNR provide data on trends in living coral cover and individual coral species from 2011 and 2001, respectively. In spite of thermal stress (indicated by coral bleaching), disease, and hurricanes, total coral cover remained relatively stable through the end of 2020.

This document also includes results from extensive investigations by the National Oceanic and Atmospheric Administration (NOAA) and from many individual projects including those based out of the underwater saturation habitats Hydrolab and Aquarius from 1977 to 1989, as well as studies from researchers at Fairleigh Dickinson University's West Indies Laboratory. While not possible to review all of these in detail, this report highlights information considered useful to managers, and scientists planning future research.

In 2021, a particularly virulent disease called stony coral tissue loss disease (SCTLD), first noted in 2014 in Florida, and then in 2019 in the U.S. Virgin Islands, started killing corals in BUIR and SARI with the different species showing a gradient of susceptibility. An exact cause or link between this disease and human actions has not been discovered to date. The losses associated with this disease have now exceeded those from any other stressors in these national parks.

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Dedication

This report is dedicated with admiration and gratitude to Zandy Hillis-Starr, who worked tirelessly for over 30 years to protect the sea turtles and reefs of Buck Island and Salt River Bay National Historical Park and Ecological Preserve.

Introduction

This synthesis focuses on research on corals and coral reefs within Buck Island Reef National Monument (BUIS) from about 1961 to 2022 and Salt River Bay National Historical Park and Ecological Preserve (SARI) from about 1980 to 2022. It is based on detailed data summaries from many agencies working independently and collaboratively including the National Park Service (NPS) South Florida/Caribbean Inventory & Monitoring Network program, and the U. S. Virgin Islands Territorial Coral Reef Monitoring Program (TCRMP) conducted jointly by the University of the Virgin Islands (UVI) and the Virgin Islands Department of Planning and Natural Resources (VIDPNR). It is also based on information about the ecology of coral reefs in the U.S. Virgin Islands presented in a comprehensive book chapter in 2008 that included a history of research, mapping, and results of monitoring fish and benthic assemblages and on a comprehensive spatial inventory by the National Oceanic and Atmospheric Administration (NOAA) of key habitats evaluated using aerial images from 2000. Additional information for SARI came from earlier published and unpublished reports from projects supported by the underwater saturation diving program under the National Undersea Research Program (NOAA), first from the Hydrolab and then Aquarius habitats, from 1977 through 1989. The synthesis also draws on peer review publications and NPS BUIS and SARI Investigator Annual Reports (IARs) by researchers from agencies and universities including many from the former Fairleigh Dickinson University's West Indies Laboratory (1971 to 1989), and a Natural Resource Assessment prepared by . Information came from NPS archives, the NPS online portal "IRMA", peer review literature, online searches, and requests of individual researchers.

This synthesis is divided into two major sections, the first on BUIS and the second on SARI.

Ecological Context and Background

In the U.S. Virgin Islands reef-building corals are found from the surface to a depth of about 50 m. They form coral reefs and occur in communities widely dispersed on hard bottom and granitic boulders around the islands. True coral reefs can be defined as rigid, topographically complex structures developed from carbonate accretion by corals and other cementing and calcifying organisms and the product of biological and geological processes (see Buddemeier and Hopley 1988, Hubbard 1997, Hubbard et al. 1998, Kleypas et al. 2001, Rogers and Miller 2016). About 40 scleractinian coral species are found within U.S. Virgin Islands waters, but the *Orbicella* species, *Acropora palmata*, and several brain corals in the genera *Pseudodiploria*, *Diploria*, and *Colpophyllia* are the major contributors to reef frameworks. Most reefs are dominated by species in the genus *Orbicella*.

Maps showing the location of reefs and hardbottom around the three major islands, St. Croix, St. Thomas and St. John, are available from the National Oceanographic and Atmospheric Administration (NOAA) Biogeography program (Costa et al. 2012). In general, the most developed reefs are found off the eastern, windward ends of the islands. Scientists do not agree on which “hardbottom” habitats constitute coral reefs. Some would include communities with corals growing on boulders or other non-carbonate pavement, as well as low-relief habitats dominated by gorgonians as reefs, while others would not. Hubbard noted (1986): “A coral reef is the result of the complex interaction of constructive processes that build solid framework, and destructive processes that alter and remove that material. Of primary importance in understanding the overall forces that shape the reef, is a quantification of the individual contributions made by the carbonate producing organisms that live in and on it. Primary among these in present-day reefs are the scleractinian corals.”

A variety of reef types are present, including fringing, patch, bank, spur and groove, mesophotic reefs, and a submarine canyon. The reefs and coral communities within the National Park Service (NPS) units are often near mangroves, seagrass beds and algal plains that contribute to the overall mosaic of marine habitats and support a high biodiversity of fish, sea turtles, and other marine organisms (Bak 1983).

Corals are found growing on boulders or hard pavement around most of the island shorelines. A unique habitat is found within Hurricane Hole, inside Virgin Islands Coral Reef National Monument (VICR), where corals and other reef organisms grow on the prop roots of Red Mangrove trees. Other unusual features include the submarine canyon in SARI with steep walls colonized by large plating Agaricid corals and the “haystacks” at BUIS, conical structures of *A. palmata* that extend from the bottom at a depth of about 10 m to the surface.

The corals and reefs within BUIS, SARI and Virgin Islands National Park (VIIS) have been the center of a remarkable number of fundamental and cutting-edge biological and geological studies, largely because of commitments by scientists associated with the NPS, West Indies Laboratory (from 1971 to 1989), NOAA, University of the Virgin Islands, U.S. Geological Survey (USGS), Mote Marine Laboratory and others (see Rogers et al. 2008).

Our knowledge of general Caribbean reef ecology and geology increased with information gained from numerous studies at Buck Island and within VIIS, including those on effects of diseases (Gladfelter 1982, Mayor et al. 2006); hurricanes (Rogers et al. 1982, Bythell et al. 1989, Hubbard et al. 1991); coral growth rates, skeletal development and metabolism (Gladfelter et al. 1978, Gladfelter et al. 1983a, b, Gladfelter 1984); fishes (Tobias et al. 1988, Gladfelter et al. 1991a, Smith-Vaniz et al. 2006); bleaching (Lundgren and Hillis-Starr 2008); and geological development (Hubbard 1991). Studies of the effects of powerful Hurricane Hugo (1989) shed light on the formation of the reef complex within BUIS (Hubbard et al. 1991). Much of the available historical information comes from Beets et al. (1986), Bythell et al. (1989), Gladfelter et al. (1991), and Rogers et al. (2008). A detailed history of research in the U.S. Virgin Islands can be found in Rogers et al. (2008) with more recent information on trends in coral cover in resource summaries from the South Florida/Caribbean Inventory & Monitoring Network (SFCN 2022a,b,c), Ennis et al. (2019, 2020), and Ogarcuk et al. (2022).

Most notably, commitments by the NPS and the USGS to support long-term monitoring in the U.S. Virgin Islands have resulted in insights into trends in benthic cover (including corals and algae) and changes in the population of *A. palmata* and the *Orbicella* complex arguably the most significant framework-building species. As a result, some of the longest continuous records of anywhere in the Caribbean on coral reefs, reef fishes and water quality are available for the U.S. Virgin Islands. Other major contributions to the overall understanding of the reefs under NPS jurisdiction come from the TCRMP and NOAA's Coral Reef Monitoring Program (NCRMP). In addition, BUIS is significant as foraging and nesting habitat for Hawksbill Sea Turtles, the subject of a long term (over 30 years) project by NPS.

The Virgin Islands Resource Management Cooperative (VIRMC), established in 1983 with support primarily from the NPS and under the direction of Island Resources Foundation, produced a series of reports that established baseline data for the U.S. Virgin Islands and British Virgin Islands (see Rogers and Teytaud 1988). These included descriptions and maps of bays and fish habitats within Virgin Islands National Park (VIIS) and BUIS (Anderson et al. 1986, Beets et al. 1986, Boulon 1986a, b), assessment of fish and shellfish stocks in the VIIS and BUIS (Dammann 1986, Tobias et al. 1988), early fish and reef monitoring efforts (Boulon et al. 1986a,b; Rogers and Zullo 1987), and observations of white band disease on Elkhorn Coral at BUIS and several locations in the British Virgin Islands (Davis et al. 1986). As part of the VIRMC studies, maps of St. John and Buck Island were produced from visual interpretation of aerial photos by Beets et al. (1986), Boulon et al. (1986a,b), and Anderson et al. (1986). A map of Buck Island from 1977 appears in Gladfelter et al. (1977).

The reefs in BUIS, SARI and VIIS have in general lost significant coral cover over the last several decades (SFCN 2022 a, b, c). They have been affected by most of the global, regional and local stressors that have altered reefs elsewhere in the Caribbean, including coral diseases, hurricanes, thermal stress, and vessel groundings. However, sewage and sediment runoff, two of the most deleterious local factors that degrade coral reefs, are not major problems within BUIS as the island is

uninhabited and has no perennial streams or other freshwater input (Rogers and Ramos-Scharrón 2022).

Several major hurricanes have significantly affected the overall reef structure and coral cover on many reefs within the U.S. Virgin Islands national park units, including Hurricane David (1979), Hugo (1989), and Irma and Maria (2017).

All of the significant coral diseases reported for the Caribbean (Sutherland et al. 2004, Weil et al. 2006, Weil and Rogers 2011) have been seen on the reefs in the U.S. Virgin Islands, including those within BUIS, VIIS, SARI and VICR. The dramatic demise of the *Acropora* spp. at Buck Island in the 1970s and 1980s can largely be attributed to white-band disease (WBD) which affected many Caribbean reefs during this time period (Gladfelter 1982, Rogers 1985, Bythell and Sheppard 1993, Aronson and Precht 2001). The disease left extensive stands of these corals intact but dead within BUIS and on some reefs around St. John (Anderson et al. 1986, Beets et al. 1986). No reefs in the U.S. Virgin Islands currently have densities of *A. palmata* as high as those recorded in the 1960s and 1970s, although in some locations this species has shown limited signs of recovery (Rogers and Muller 2012, Muller et al. 2014).

The devastating stony coral tissue loss disease (SCTLD) was first reported in St. John in December 2019, and then in BUIS and SARI in 2021 (Brandt et al 2021). This disease is affecting over half of the stony coral species, but not the acroporids (*A. palmata* and *A. cervicornis*). As of April 2021, it was documented at all of the NPS South Florida/Caribbean Inventory and Monitoring (SFCN) sites within BUIS. Until the recent appearance of SCTLD, white plague and white band were the most severe diseases; however, Caribbean yellow band disease has also been particularly damaging at BUIS.

In contrast to the effects of storms and WBD, which particularly affect acroporids (*A. palmata* and *A. cervicornis*) in shallow water, the bleaching episode in 2005 and subsequent outbreak of diseases (primarily white plague) in 2006 affected most of the coral species to depths of over 30 meters and resulted in an average loss of about 60% of the coral cover (Miller et al. 2009). The water temperatures in 2005 were the highest ever recorded in the Caribbean (Eakin et al. 2010). No other stressor has caused such substantial loss of coral cover as this disease, although SCTLD may well end up surpassing this and already has at some locations (Brandt et al. 2021).

Buck Island Reef National Monument

Buck Island is a small island (0.7 km²) 1.6 km north of St. Croix, the largest of the U.S. Virgin Islands. It is about 1 km long, 0.53 km wide, and 100 m at its highest point. A shallow, narrow lagoon separates the island from a coral reef off the eastern, northeastern and southern shores (Figure 1).

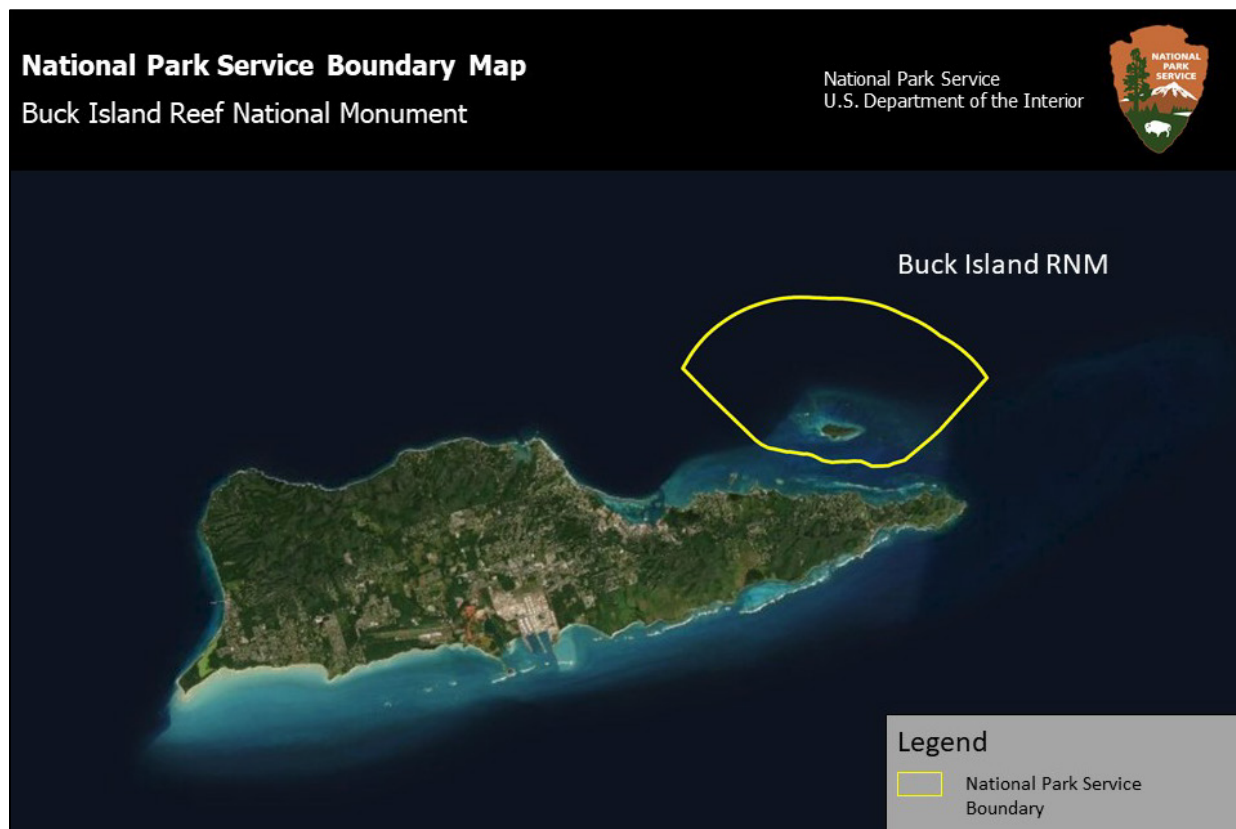


Figure 1. Location of Buck Island Reef National Monument, St. Croix. U.S. Virgin Islands. (Map created by K. Ewen, NPS).

Although the impressive, dense stands of living and dead *A. palmata* do constitute a physical barrier, and the word “barrier” appears in many official documents and scientific reports, the reef around Buck Island is best considered a fringing reef rather than a barrier reef (Dennis Hubbard, Oberlin, written communication, 2020). As with many other coral reefs, the classification schemes do not readily apply to this site.

The enthusiastic recommendation by the late Dr. John (Jack) E. Randall, a world-renowned ichthyologist, that the area be established as part of Virgin Islands National Park or as a national monument led to President John F. Kennedy’s Presidential Proclamation 3443 in 1961 designating the island and the surrounding seascape as Buck Island Reef National Monument. Along with Virgin Islands National Park (after the addition of submerged lands in 1962), Buck Island is one of the first Marine Protected Areas established in the United States.

In the Beginning

In 1961, Dr. Randall was doing marine biological surveys for the NPS on St. John when the Superintendent of Virgin Islands National Park, John Lewis, asked him to go to Buck Island and report back with his observations.

In his report to NPS Dr. Randall wrote:

“The barrier reef is undoubtedly the most magnificent coral reef in the possession of the United States and deserving of protection from the depredations of man. The broad beach at the west end and placid, clear lagoon have excellent recreational potentiality. Colonies of pelican and frigate birds and sea turtles are in need of protection.” (Randall 1961, Sale and Szmant 2012).

Further descriptions appear in Robert Schroeder’s book Something Rich and Strange (Schroeder 1965):

“We slipped through a narrow passage and snorkeled along the reef’s outer edge. The motivation for the Park Service’s interest became clear at once. Buck Island reef is a fantastic jungle of palmate coral, the like of which I had not seen in all my years of diving. The dominant growth is Acropora palmata, huge masses of it with beamlike branches two feet in diameter, lying in parallel tiers one above the other. This is truly a coral reef!” – *“The reef matrix comprises Acropora coral and very little else.”*

“Along the north shore the reef breaks up into a series of buttresses, with deep passages between. To seaward of the main reef are huge coral patches, vertical growths of palmate coral with massive girders and crossbraces rising vertically for fifty or sixty feet to the outflung, flattened tips of living coral at the surface.”

“The place is a fish heaven. Huge snappers and groupers peered at us from the coral grottos. Vast schools of parrotfish and surgeonfish were everywhere. That first day our decision was made; if the Park Service wanted an underwater park, this was the right place for it.”

“We dived among the mighty buttresses and deep grottos of the northeastern section of reef. –This was big league snorkeling where the ambitious diver could skin (?) down a vertical escarpment for fifty or sixty feet to find himself eye-to-eye with yard-long permit and Seriola, the great amberjack”.

Schroeder also referred to:

“the solid phalanx of palmata coral that is the southern reef.”

Dr. Randall also took photos and movies that helped make the case for Buck Island being a special place worthy of greater recognition and protection.

He wrote:

“The author has dived over a period of 10 years on reefs in the Atlantic in Florida, the Bahamas, Cuba, Jamaica, Haiti, Puerto Rico, and the Netherland Antilles and in the Pacific in Hawaii, Tahiti, Tuamotus, Marshalls, and Gilberts. He has seen no lovelier reef than the barrier reef of Buck Island. It is strongly recommended that every effort be made to include the small island and its marine environs in the Virgin Islands National Park” (Randall 1969).

Other scientists besides Jack Randall were also very enthusiastic. In a 1966 report, Frederick Bayer and C. Richard Robins wrote:

“The park site is a most attractive reef area. There is no comparable reef development at St. Croix or elsewhere in the U.S. Virgin Islands nor do we know of comparable areas at Puerto Rico. In short the reef is as good as any in U.S. Atlantic waters save for certain Florida reefs some of which are in an area now under consideration for a National Park” (Bayer and Robins 1966).

The initial proclamation created BUIS with 176 acres of land and 704 acres of water and refers to the intention of preserving “one of the finest marine gardens in the Caribbean Sea.” There was also reference to “the caliber and scientific importance of the coral reefs.” One small area off the south side of Buck Island, the Marine Garden, was designated a no-take marine reserve. In 1975, 30 more acres were added (Presidential Proclamation 4346). In 2001, on his last day in office, President William Clinton, in Presidential Proclamation 7392, used the Antiquities Act to expand the original boundaries to include a total of 7695 ha (19,015 acres). This expansion resulted in inclusion of habitats to a depth of about 915 m, the deepest protected areas in the NPS system. New regulations resulted in making the entire monument a “no-take” and “restricted anchoring” zone. The NPS implemented Interim Regulations (36 CFR Part 7.73) in 2003 and completed the General Management Plan in 2012.

Official NPS documents highlight the significance of the coral reefs within BUIS. For example, the Statement for Management reads: “The primary resource at Buck Island is the unique and fragile coral reefs that surround the island.” The draft General Management Plan also emphasizes the value of the monument’s coral reef ecosystem.

This report primarily summarizes and synthesizes the biological studies of corals and coral reefs that have taken place at BUIS, with an emphasis on studies of *Acropora palmata* and trends in total coral cover. The reef at Buck Island has about 40 species of scleractinian corals (as in VIIS and SARI) (Appendix A). The most abundant in terms of the amount of living cover on the reef are species within the genus *Orbicella*. The Buck Island story revolves closely around the fate of *A. palmata*, historically, the most important shallow water coral species in the Caribbean.

Research on *Acropora palmata*

In the 1960s and 1970s, *Acropora palmata* (Elkhorn Coral) was the main reef-building coral at depths of less than 10 m in the U.S. Virgin Islands, growing in nearly monospecific stands on the reef crest and in the upper and lower forereef zones of well-developed fringing reefs and on isolated patch

reefs (Figure 2). Some of the most valuable contributions to coral reef ecology from BUIS focus on *Acropora palmata*, the species that defines the reef. As noted above, BUIS was established in 1961 as a unit of the NPS primarily in recognition of the fringing reef that surrounds the eastern end of the island. The reef at that time was characterized by dense, inter-locking colonies of living *Acropora palmata*. Shallow *A. palmata* habitat is present on reef crest formations and “haystack” features in addition to the reef surrounding Buck Island. However, the majority of *Acropora palmata* habitat within the monument is found on the Buck Island Bar to the north of Buck Island, at a depth of 5–10 m.

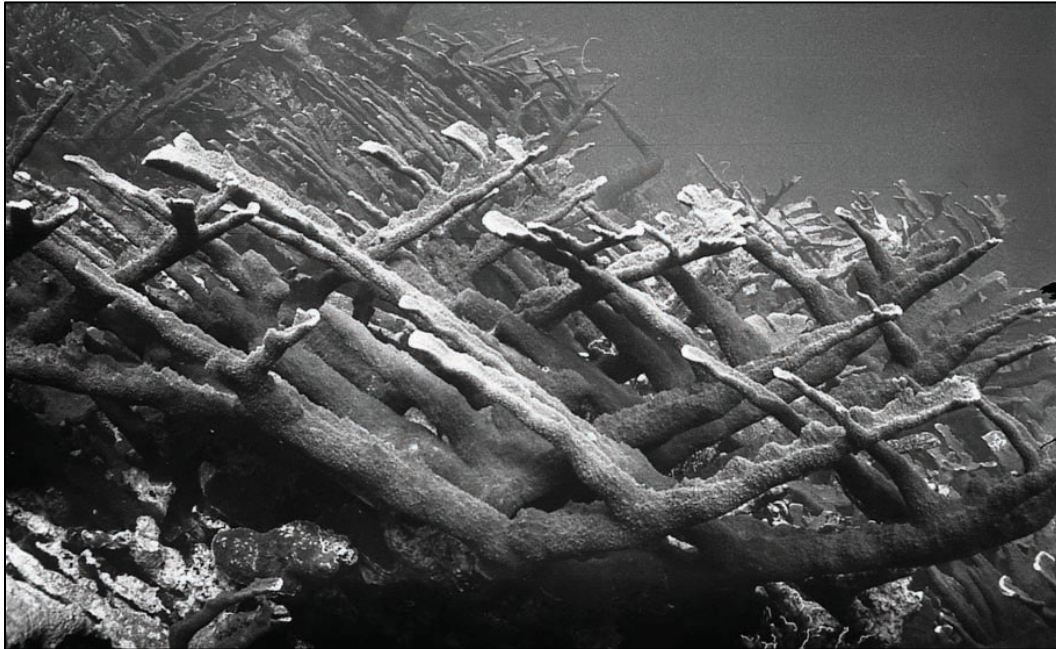


Figure 2. *Acropora palmata*, Buck Island Reef National Monument, 1970 (Photo: W. Gladfelter).

Acropora palmata is unique in terms of its complex morphology, with dense, intertwining branches up to a few meters across. Its rapid growth rate and ability to colonize through attachment of fragments contributed to its dominance in shallow, mostly high energy zones in many Caribbean locations. The most significant change to occur at BUIS since 1970 has been the demise of the *A. palmata* colonies that formed the shallow portions of the fringing reef. Percent cover of *A. palmata* in the 1970s around St. Croix ranged from about 7–9% on the southern forereefs, to about 33% on the backreef in Isaac’s Bay (estimated from Adey et al. 1981). It was about 25–35% throughout much of the north shore and the offshore reef area (Rogers et al. 2003). Maximum documented cover was 62% on the eastern forereef of Buck Island (Gladfelter et al. 1977), although in some relatively large areas the percent cover approached 100%. Total live tissue cover was even higher, as there were often several overlapping tiers of branches, covered on both sides. There was an average of 1.75 m² of live *A. palmata* tissue per m² of reef (Rogers et al. 2003). The colonies in this forereef zone had extremely long branches oriented perpendicular to the approaching wave fronts (i.e., parallel to the direction of the prevailing waves, Figure 3). The largest colony measured (in 1988; Rogers et al. 2003) had a length of 7.1 m. In 2002, cover at all St. Croix sites ranged from 0.1% to 3.6% with

1.0% at BUIS. Therefore, overall tissue reduction in the reef zones formally dominated by *A. palmata* is almost catastrophic, having decreased by two orders of magnitude or more.

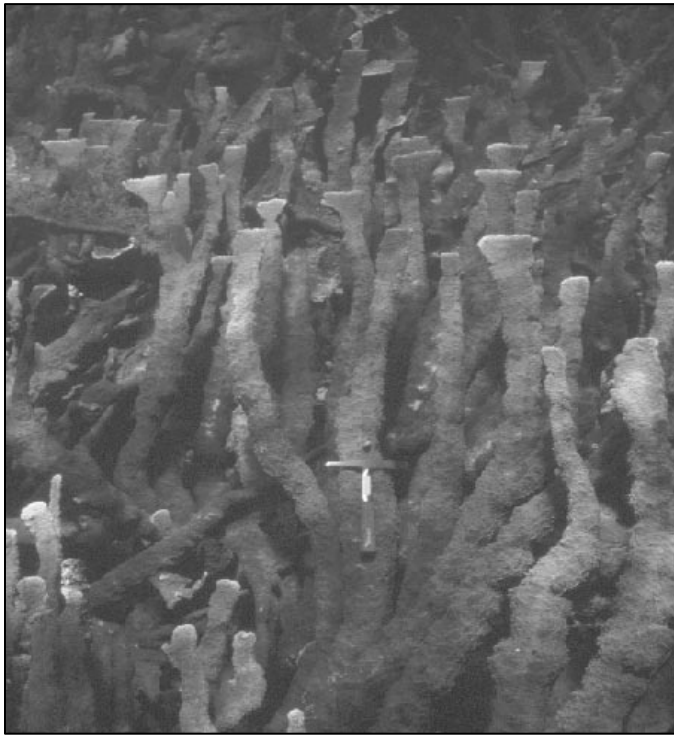


Figure 3. *Acropora palmata* colonies on the eastern forereef of Buck Island in 1977 (Photo: W. Gladfelter).

No reefs in the U.S. Virgin Islands currently have densities of *A. palmata* as high as those recorded in the 1960s and 1970s at BUIS and other sites (Rogers et al. 2003, Bruckner 2003). Its decline in the late 1970s and 1980s was primarily the result of hurricanes and WBD, first reported from St. Croix, which affects acroporid corals exclusively.

White-Band Disease (WBD)

A 1973 report on Buck Island includes what is apparently the first reference to a condition later labeled “white band disease” by Dr. William Gladfelter. Photographs and a rough drawing show the distinctive narrow white band separating the living end of an Elkhorn branch from the algal-encrusted dead base (Robinson 1973). In 1976, Gladfelter et al. (1977) found incidences of WBD at Buck Island but reported that only a few colonies in any area were affected. Impressive stands of living Elkhorn were present at Buck Island at this time. Gladfelter began to measure the rate of progression of WBD on individual colonies and to monitor its effect on the populations of *Acropora palmata* on Buck Island and Tague Bay Reefs (Gladfelter et al. 1977; Gladfelter 1982). The disease progressed at a rate of about 1 to 14 mm/ day (with an average of c. 6 mm/day). Similarly, Davis et al. (1986) estimated a progression of 4–5 mm/day for the disease based on data from Buck Island.

Gladfelter documented that WBD resulted in a decrease of 85% to 5% elkhorn cover in a 200 m² study plot first established in 1988, and then quantified a further decrease to less than 1% after Hurricane Hugo in 1989 (Gladfelter et al. 1991b). This study plot was subsequently monitored in 1991, 1996 and 2002 documenting some recruitment but also decreases in the population and in coral cover from the effects of four hurricanes (details available in Bruckner 2003).

Informal observations around St. John (and videotape documentation around Buck Island) showed some increase in number of Elkhorn colonies in the 1990s although densities were very low.

Bythell et al. (1989) summarized some of the major changes in coral cover between 1976 and 1988 in their report based on data from 1976, 1984 and 1988 (see also Gladfelter et al. 1977; Anderson et al. 1986). In 1976, five cross-reef transects were established at Buck Island, three on the north (BI-3, BI-4, BI-5) and two (BI-1, BI-2) on the south side (Figure 4, Gladfelter et al. 1977). At that time, the coral cover of the crest of the north and south reefs and the northern forereef was composed of greater than 50% live *A. palmata*.

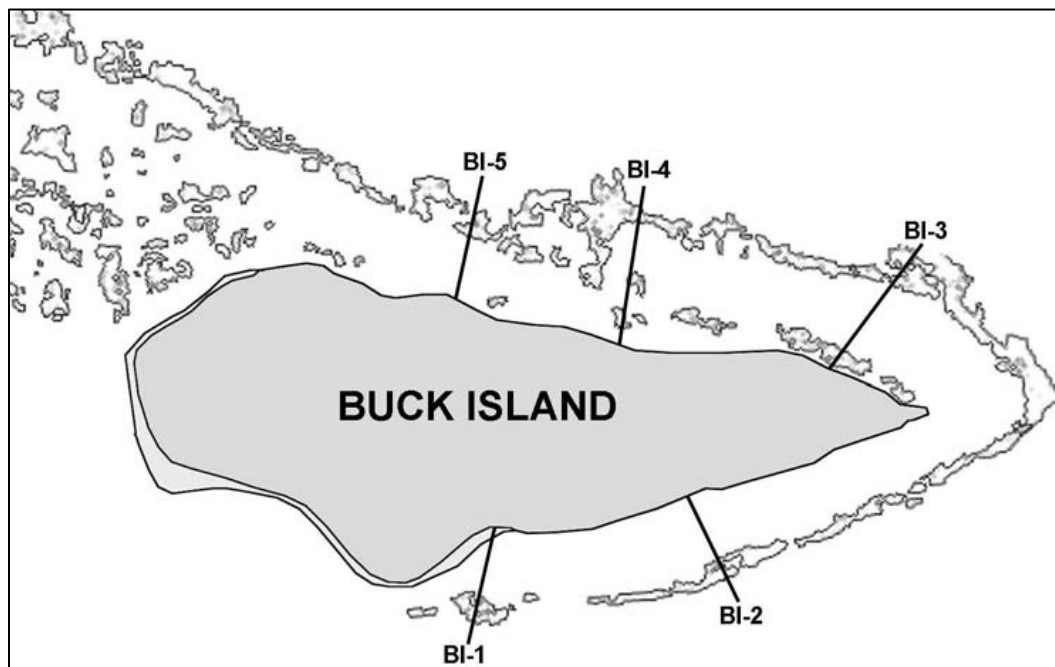


Figure 4. Map of Buck Island showing placement of the five permanent transects (from Gladfelter et al. 1977).

Acropora palmata was the most abundant coral on the forereef slope down to the bank at a depth of 10 to 15 m in the north and east sections of the reef. In the south, this species was dominant to depths of 3 to 4 m. About 75% of the total live coral cover of 44% on the northern forereef slope was *A. palmata*. By 1984, when Anderson et al. (1986) surveyed the reef, the cover of *A. palmata* was dramatically reduced in the region of transect BI-3. In the forereef area, cover by hard corals was reduced to 20%, although *A. palmata* was still dominant (>10%). Patches of Elkhorn coral with 80% live cover were present but most of the forereef had stands that were almost completely dead.

Surveys in the fall of 1988 (Bythell et al. 1989) confirmed many of the findings of Anderson et al. (1986), and showed additional declines in the *Acropora* spp. In 1988, live coral cover was less than 12% with only about 3% *A. palmata* on the forereef near transects BI-3 and BI-4 (Figure 5). In contrast, along transect BI-5, *A. palmata* comprised 72% of the total cover of 27% on the upper forereef, suggesting that this area was less affected by the mass mortality which devastated most of the reef. This species was only rarely seen below a depth of 3–4 m on any part of the reef.

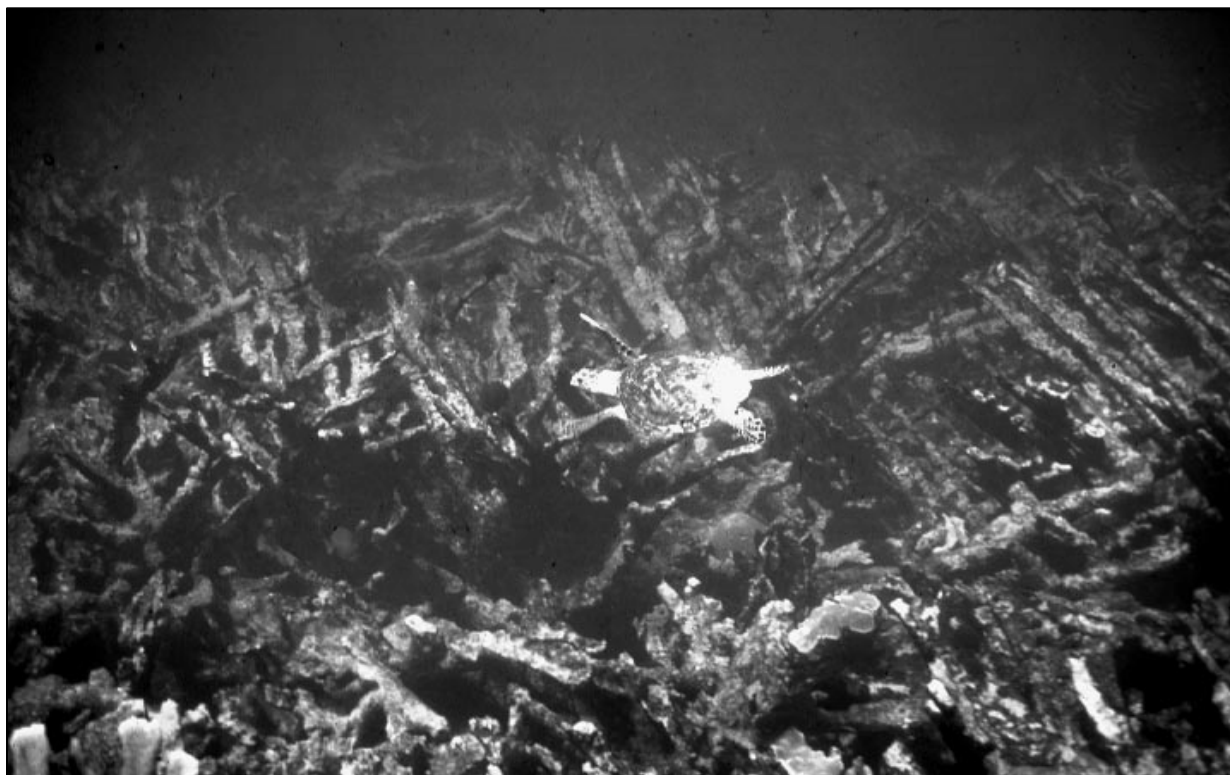


Figure 5. Intact dead *Acropora palmata* stand, east end Buck Island in 1988 (from Gladfelter, Bythell, Archer et al. 1991).

In 2004, 2,492 large Elkhorn colonies (greater than 1 m maximum dimension) were recorded along randomly selected transects at depths of 10 m or less within BUIS (Mayor et al. 2006). Density ranged from 0.004 to 0.160/m². The overall prevalence of WBD was 3%, but along transects with WBD an average of 15% of the colonies were affected. Gladfelter et al. (1977) found 3% prevalence within the initial BUIS boundary but 42% at Tague Bay. White pox disease was not quantified in the 2004 study but appeared more common than WBD.

In 2005, at BUIS (and elsewhere in the U.S. Virgin Islands), *A. palmata* bleached extensively for the first time (Figure 6). In a study of *A. palmata* colonies around Buck Island, Lundren and Hillis-Starr (2008) noted that colonies located in the backreef benthic zone bleached earlier and suffered greater tissue loss than those elsewhere. They suggested that increased water temperature coupled with reduced water flow and increased light penetration caused higher mortality in backreef locations.

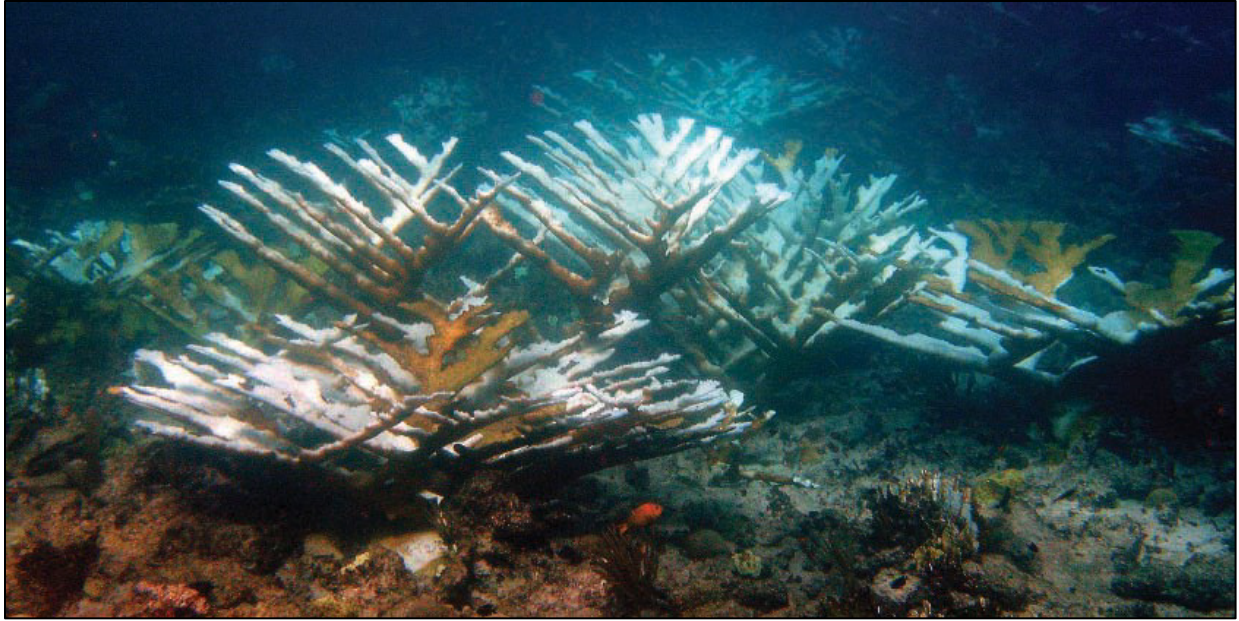


Figure 6. Extensive bleaching of *Acropora palmata* at Buck Island Reef National Monument, November 2005 (Photo: E. Muller).

White band disease and white pox are now rare, but other undescribed diseases are still affecting *A. palmata* colonies. Physical damage from storms (see more below) and boat groundings are hindering the regrowth of this species. To date, the devastating stony coral tissue loss disease (see below) has not been observed on acroporid species. Unlike WBD which affected only two (albeit key reef-building) coral species (*A. palmata* and *A. cervicornis*) with the most pronounced effects in depths less than 10 m, the 2005 disease outbreak (most likely white plague) affected virtually all coral species except the acroporids to depths over 30 m.

Data on the status of acroporids from BUIS helped make the case for these species to be listed in 2006 as threatened under the U.S. Endangered Species Act (Bruckner 2003, Federal Register 2006). The monument was one of eight locations with quantitative data included in the graph showing percent loss of *A. palmata* and *A. cervicornis* in the Acropora Biological Review Team (2005, page 60).

Other Acroporid Species and Hybrids

Although *A. palmata* was the major framework building species at BUIS and on many shallow reefs in the U.S. Virgin Islands, *A. cervicornis* has historically fluctuated in its abundance. It is also listed as threatened under the U.S. Endangered Species Act. In 1976, *A. cervicornis* was noted in patches on the mixed coral/gorgonian bank seaward of the reef and comprised 2% of the total coral cover of 27 %. Surveys in 1988 indicated virtual disappearance of this species on the north side of Buck Island and large reductions in abundance on the south side, although it comprised up to 2–3% of the coral cover in some localized areas off the southern reef (Bythell et al. 1989). *Acropora cervicornis* is now rare around St. Croix, at least in shallow water.

Acropora prolifera, now considered a hybrid of the two other Atlantic *Acropora* species, was not common around Buck Island in the 1970s, although in the lagoon off the east end of the island cover of this hybrid reached about 60%. Bythell et al. (1989) suggested that this was perhaps the best-developed stand of *A. prolifera* on St. Croix. Anderson et al. (1986) noted thickets of mostly dead *A. prolifera* here in 1984. In fall 1988, cover of this species was less than 1% (Bythell et al. 1989).

No comprehensive assessment of the status (abundance and condition) of the acroporid corals is underway at BUIS.

Hurricanes David (1979) and Hugo (1989)

Hurricanes have also caused significant deterioration of coral reefs at Buck Island. In 1979, Hurricane David caused extensive physical damage to shallow Elkhorn coral stands there (Rogers et al. 1982). Off the southeastern forereef, monitoring of storm-damaged Elkhorn branches showed 66% of them were still alive 11 months after the storm and many of these had begun healing and initiating new branches (Rogers et al. 1982). However, Elkhorn Coral recovery was hindered by WBD which devastated this primary reef-builder (see above).

In 1989, Hurricane Hugo, an exceptionally powerful storm, caused further destruction (Hubbard et al. 1991, Hubbard 1992) (Figure 7). The storm passed over St. Croix with winds of 138–173 mph possibly gusting to over 200 miles per hour. The five cross-reef transects established in 1976 (described above) were re-surveyed in 1988 the year before Hugo (Gladfelter et al. 1991b). The shallow forereef on the south side of Buck Island was reduced to pavement by the storm, and the coral rubble generated was transported up onto the reef crest, forming a raised berm 30 m landward of the crest (Hubbard et al. 1991). No *A. palmata* was recorded on the south reef in locations where it had previously been dominant. As noted above, on the eastern shallow forereef, *A. palmata* cover fell from 5% to 0.8% (Gladfelter et al. 1991b) in an area that had once supported 85% cover of this species. The north reef at Buck Island was less severely damaged by Hurricane Hugo, but *A. palmata* populations were still reduced from approximately 1.8% to 1.0% cover on the forereef of transect BI-3, an area that had previously supported about 36% cover of this species (Gladfelter et al. 1991b). These surveys clearly showed the effects of the storm, but most of the *Acropora* spp. mortality had already occurred.

Interestingly, many of the *A. palmata* colonies killed by WBD remained upright, even in exposed areas like Buck Island Bar to the north, and many remain in growth position to this day.

When Bythell et al. (1992, 1993) established more, permanent sites at Buck Island in 1988, *Acropora* species were no longer a dominant part of the coral community. There were further reductions in cover during the following decade coincident with intense hurricane activity (Bythell et al. 2000a, b). One of the sites on the northern reef was established near cross-reef transect BI-5 (see above), and showed that hurricanes and disease have destroyed at least some of the stands that were still intact in 1988 (Bythell et al. 1989). [The role of the mortality of the sea urchin *Diadema antillarum* (Lessios et al. 2016, Carpenter 1990) in 1983–84 in affecting the corals and macroalgae at BUIS has not been studied comprehensively. Bythell et al. (2000b) suggested that WBD played a greater role at BUIS than some other Caribbean reefs, perhaps because of greater herbivory by fish.]



Figure 7. Elkhorn Coral fragments at Buck Island Reef National Monument after Hurricane Hugo (1989) (Gladfelter et al. 1991b).

Beginning in 1993, *Acropora palmata* colonies were observed in the southeast forereef in the area scraped clean by Hurricane Hugo, although they were only a minor component (0.4%) of the coral community recruiting to the area (Bythell et al. 1993, 2000b). In 1995, after Hurricane Marilyn, some colonies were up to 1 to 2 m across but exhibited physical damage from the storm. Additional colonies have recruited to this area and appear to be in relatively good condition although they have been affected by subsequent storms and snail predation. Northwest of Buck Island, numerous, large Elkhorn colonies, some reaching 2 m across, can be found (K. Ewen, NPS, written communication, 2022).

Hurricane Hugo also caused significant changes to other coral species. Permanent, haphazardly selected transects and individual colonies of *Montastraea (Orbicella) annularis*, *Diploria strigosa*, and *Porites astreoides* were monitored at three sites from 1988 until 2000 (Bythell et al. 1993, 2000a, b). Hurricane Hugo (1989) was responsible for the most significant changes up through 2000. These three sites with permanent transects differed greatly from each other in terms of coral cover and coral species composition. Coral cover increased from 32% to 40% at one site, but decreased from 25% to 15% at another. Although Hurricane Hugo caused more loss of *Porites porites* than of the more abundant *O. annularis*, bleaching in 1998 caused more loss of *O. annularis* than of other species along the transects. Within five years of Hurricane Hugo an increase in coral cover was noted, but bleaching in 1998 and additional hurricanes caused more declines. Bythell et al. (2000b) suggested that in spite of the variations along the transects the reef assemblages over a scale of tens to hundreds of meters were relatively stable, with changes over time being less than differences among sites (Rogers 1992).

Long-Term Monitoring Trends for BUIS Coral Reefs

Insights into the past and current condition of the coral reefs in BUIS and the effects of storms, thermal stress, and disease outbreaks comes primarily from two major monitoring programs, one by

the NPS and one associated with the University of the Virgin Islands, referred to as the Territorial Coral Reef Monitoring Program (TCRMP) (Figure 8, Appendix B).

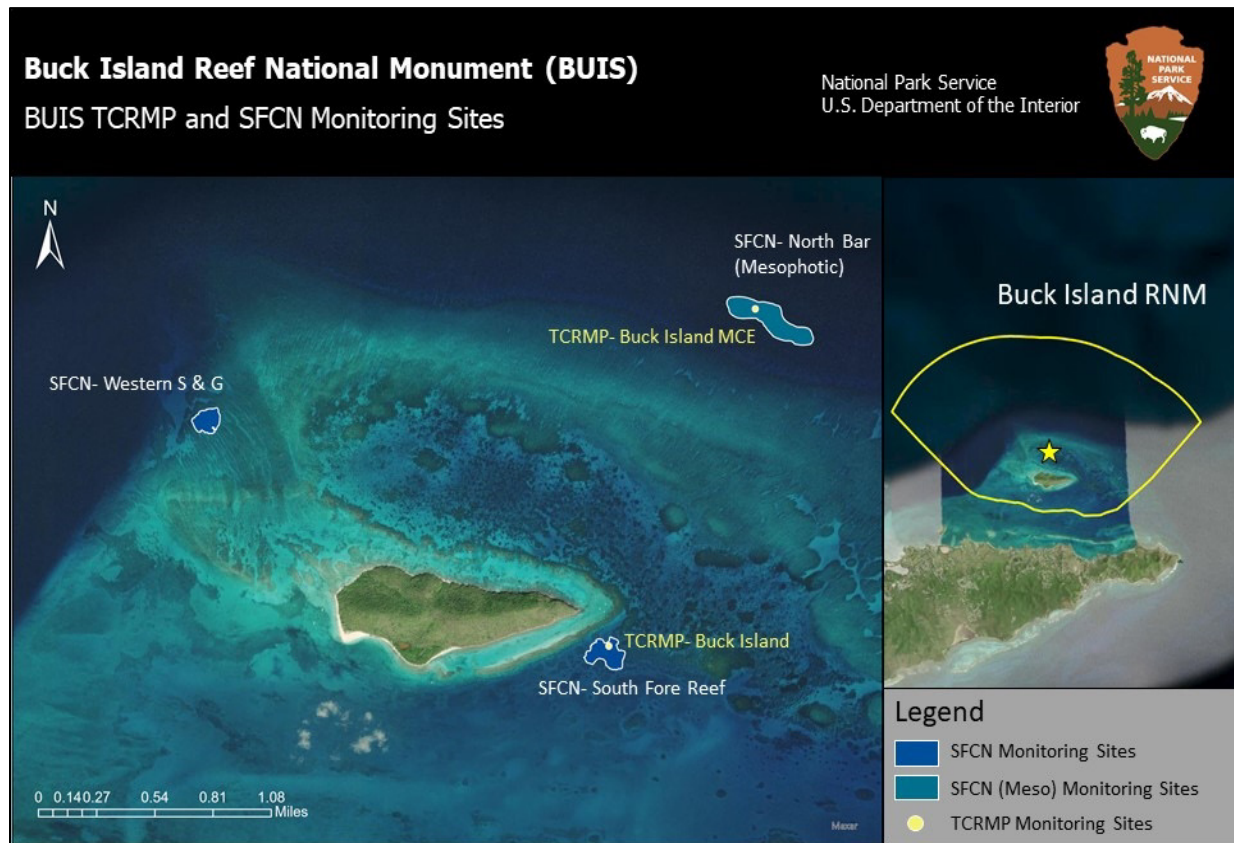


Figure 8. Location of sites of long-term monitoring by National Park Service and Territorial Coral Reef Monitoring Program. SFCN = South Florida Caribbean Network, RNM = Reef National Monument, Western S & G = Western Spur and Groove, MCE = Mesophotic Coral Ecosystem (Map by K. Ewen, NPS).

National Park Service Inventory & Monitoring Program

The NPS SFCN Inventory & Monitoring Program has over 20 years of data on trends in coral cover and cover by other benthic organisms and substrate at BUIS. Long-term sites were established with a rigorous protocol (Miller et al. 2017) in 2000 (Western Spur and Groove, Figure 9) and 2002 (South Fore Reef, Figure 10). Annual monitoring ceased at the Western Spur and Groove in 2014 but continues at the South Fore Reef.



Figure 9. Western Spur and Groove long-term monitoring location. (Photo: L. Richter).



Figure 10. South Fore Reef long-term monitoring location. (Photo: L. Richter).

In 2017, a site was established at a mesophotic reef (c. 33 meters deep) at the Buck Island Bar (Figure 11). This deep site is dominated by *O. annularis* and has the highest coral cover in the monument.



Figure 11. Buck Island Bar, deep long-term monitoring location. (Photo: M. Feeley).

At each site, randomly selected, permanent transects (10 m long) are videotaped and percent cover of coral species, algae (turf, crustose coralline, macroalgae), octocorals and sponges are quantified (Miller et al. 2017). Hobo temperature sensors collect data at both sites. Data are also collected on coral bleaching and diseases, and the Long Spined Sea Urchin *Diadema antillarum*. [Note that very few monitoring programs are based on transects or other sampling units that were randomly (not haphazardly) selected resulting in rigorous quantitative results that can legitimately be extrapolated to the sampling area (Rogers and Miller 2016)].

Figure 12 displays the changes in coral cover occurring with major events affecting the long-term sites including disease outbreaks and hurricanes. Currently, the coral cover at these monitoring sites ranges from $7.2 \pm 0.8\%$ (SE) at the South Fore Reef (in Feb 2022) to $27.3 \pm 8.1\%$ (SD) at the Bar (in Feb 2021) (SFCN 2022a).

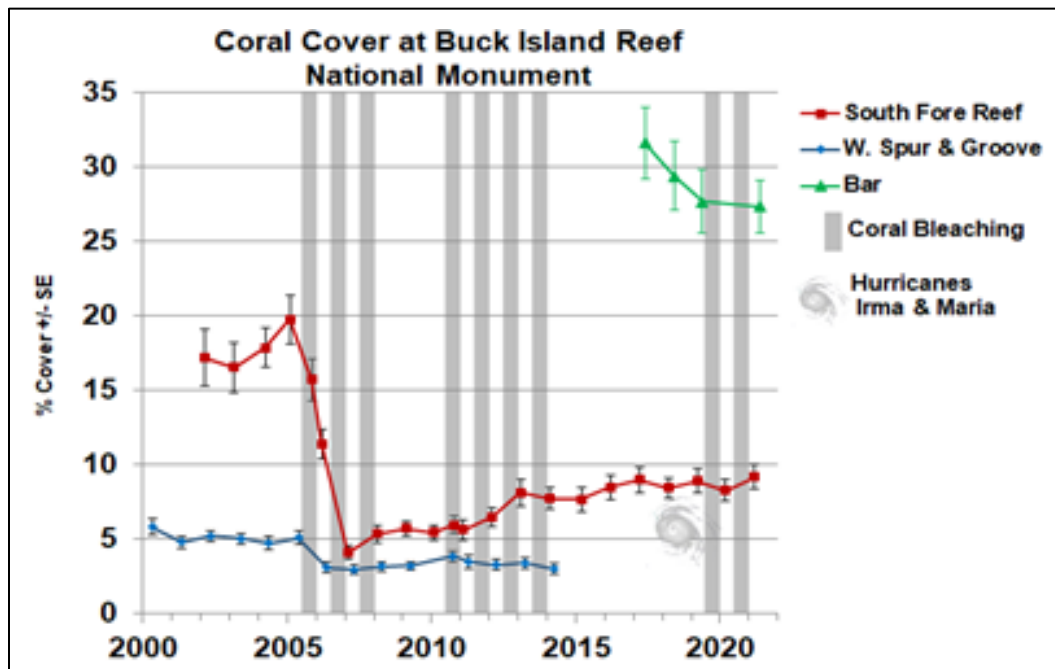


Figure 12. Coral cover at NPS long-term monitoring locations and time of hurricanes and major bleaching events (SFCN 2022a).

Monitoring by SFCN of the South Fore Reef since 2002 (at depths from 11.3 m to 14.0 m) revealed the decline associated with coral disease following the 2005 bleaching event (Miller et al. 2009) and

a gradual increase in coral cover until 2020, but cover remains less than half of what was present before 2005. The Deep Bar Site (at a depth of about 30 m and monitored since 2017) has the highest cover of any site within BUIS but coral diseases have caused significant loss of live coral (SFCN 2022a).

Over the last 20 years, despite the effects of Hurricane Maria (2017), coral diseases have been associated with the largest declines in coral cover at the South Fore Reef as well as at four long-term monitoring sites around St. John (Miller et al. 2009). (All of these long-term sites are forereef zones with an overall depth range of 3.7 m to 18.9 m.).

The South Fore Reef and two St. John sites were surveyed in early 2005 before the most severe bleaching event ever observed in the northeastern Caribbean (Eakin et al. 2010).

At these long-term monitoring sites, most of the (non-acroporid) coral colonies that survived the bleaching and disease that began in September 2005 had begun to regain some of their normal coloration by February/March 2006. However, many coral colonies remained pale as late as December 2006. The severity of disease peaked on the deeper reefs (dominated by *O. annularis* complex) within 2 to 7 months after the maximum seawater temperatures and associated bleaching. Disease following the severe 2005 bleaching event caused drastic losses (an average of 50% within one year) in living coral, the most substantial declines on these reefs in the last 40 years. Prevalence of active disease varies, but disease now seems to be present on the reefs year-round. Diseased corals began to appear on the thermally stressed reefs a few months after most corals regained their normal coloration. An average of 68.8% of all lesions and 65.6% of the disease-induced mortality occurred within 6 months after bleaching was first observed.

Declines in mean coral cover continued at all sites from July 2006 through 2007; however, only the South Forereef showed a statistically significant change, decreasing from 11.6% (March 2006) to 4.1% (February 2007). This site had the largest cumulative loss during the study with a 79.3% decline. Two years after the bleaching event, the mean loss in coral cover across all sites reached 61.1%. The Western Spur and Groove with initial cover of 5.1% at Buck Island; Rogers et al. 2008) also showed dramatic coral cover loss of 41.5%.

The number of disease-lesions showed no correlation with the percent coral cover ($r_s = -0.065$, $N = 29$, $P = 0.734$), and there was no association between coral cover and area of disease-induced mortality over the entire sampling period ($r_s = 0.174$, $N = 29$, $P = 0.368$) (Miller et al. 2009).

Species-specific changes in coral cover affected the relative abundance of coral species on the reef. *Orbicella annularis* (complex) remains the dominant coral species within these reefs; however, the relative abundance of this species group declined from an initial average of 79.2 (2005) to 58.6% (2007) of live coral cover. *Colpophyllia natans* (*C. natans*) also decreased in relative abundance from 1.3% prior to the onset of bleaching to 0.9% in 2006 likely from high levels of disease-induced mortality. In contrast, *Undaria* (*Agaricia agaricites*) declined primarily from bleaching mortality, as 93% of *A. agaricites* (cover) bleached but this species was rarely seen with disease. *M. cavernosa*, *S.*

siderea, and *Porites* spp. bleached less than *O. annularis* (complex), *C. natans*, and Agariciids. They were less affected by disease than the *O. annularis* (complex) and increased in relative abundance.

Interestingly, peak coral mortality associated with the 2006 disease event did not coincide with peak bleaching activity and mortality was rarely a direct result of bleaching. Most of the mortality occurred after water temperatures had returned to normal, and corals had regained some color. In fact, in 2006 there was a negative correlation between water temperature and number of disease lesions ($r_s = -0.707$, $P = 0.004$). This association, however, was not observed during any other year of monitoring, only in 2006 after severe coral bleaching occurred.

Although white plague was the disease associated with the greatest decline in coral cover in 2005/2006 at BUIS and other long-term monitoring locations, Caribbean yellow band disease (CYBD) was also present (Miller et al. 2009). This disease was particularly severe in Puerto Rico, although it is now much less prevalent. Experimental field treatments within BUIS have contributed to an increase in evaluating success/efficacy of various treatments for CYBD. Three treatments were evaluated for their potential in stopping the advance of this disease on colonies of *Orbicella faveolata*: shading, aspiration of diseased tissue, and trenching (Randall et al. 2018). Trenching, the creation of a “firebreak” or barrier between diseased and apparently non-diseased portions of a colony, was the most effective, but had limitations.

Monitoring at all of the NPS SFCN sites in 2020 showed mortality from coral bleaching in 2019 coupled with significant SCTLD mortality. All the common reef-building coral species were affected by SCTLD: star corals (the three *Orbicella* spp. and *Montastraea cavernosa*), brain corals (*Pseudodiploria strigosa*, *P. clivosa* and *Colpophyllia natans*), pillar coral (*Dendrogyra cylindrus*) and massive starlet coral (*Siderastrea siderea*).

The greatest current stressor at BUIS is SCTLD (see below).

Territorial Coral Reef Monitoring Program (TCRMP)

More information on trends in coral and other benthic cover is available from long-term monitoring sites maintained by scientists with the University of the Virgin Islands (UVI) and the Virgin Islands Department of Planning and Natural Resources under the Territorial Coral Reef Monitoring Program (see Figure 13; Smith et al. 2016, Ennis et al. 2019, 2020; Ogurcak et al. 2022, <https://sites.google.com/site/usvitrmp/home>, for details). One site, monitored since 2001, is near the NPS South Fore Reef site south of the fringing reef at a similar depth and also dominated by *Orbicella annularis*. The other site, monitored since April 2017, is close to the mesophotic NPS site in 33 m, and *O. franksi* is the most abundant coral species (Ennis et al. 2020).

Trends in coral cover at the shallower site indicated a clear decline in coral cover after 2005 with no significant increase up through 2021. (Macroalgal and cyanobacterial abundance varied with no clear trends.)

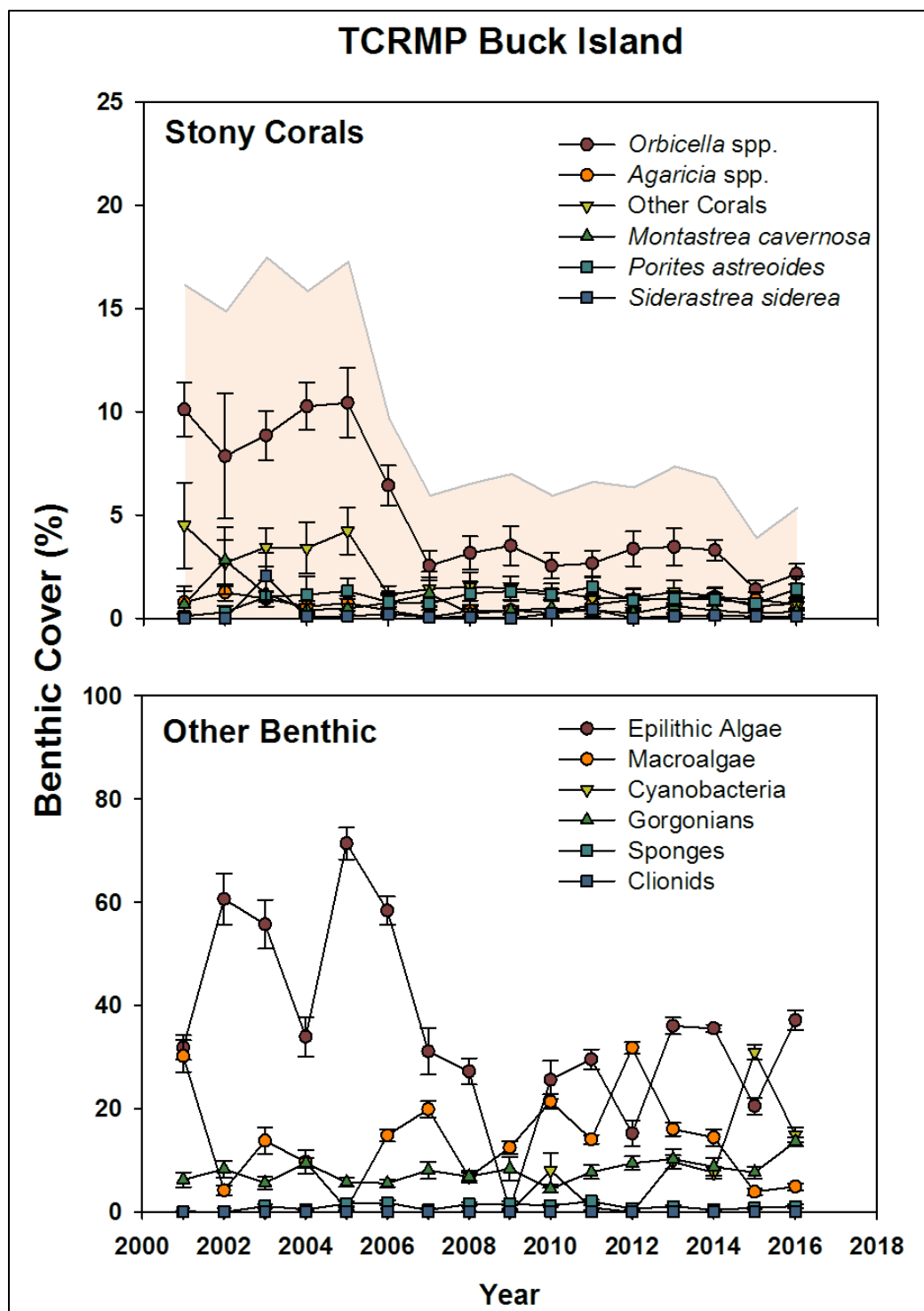


Figure 13. Trends in coral cover, cover by macroalgal and other benthic components at TCRMP long-term monitoring locations (from Ennis et al. 2020).

Thermal Stress and Disease

A careful examination of the results of monitoring by NPS and UVI (up until the recent advance of SCTLD) shows that NPS attributes most of the losses in coral cover at BUIS to disease while UVI

(TCRMP) states that most of the mortality has been from thermal stress associated with changing climate (reflected in bleaching), with the decreases in coral exceeding that from storms, sedimentation, and overfishing. [For example, in TCRMP results presented in Smith et al. (2016), the largest overall disease prevalence, the proportion of diseased colonies out of the total present or examined, is shown in 2009 (page 82) rather than in association with the 2005 bleaching event for which the NPS documented the most extensive bleaching of coral cover (prevalence and cover are not the same, but both would be expected to reflect bleaching extent).] While the NPS clearly ascribes an overall average loss of coral cover at 60% to white plague, TCRMP suggests (on page 81) that a loss of 65.5% was from direct bleaching mortality (see text box).

Diseases are often referred to as causes of coral mortality, but they are in fact the end result of sometimes unknown stressors, such as nutrient input. Coral diseases are increasing in number and severity (Weil and Rogers 2011). Burge et al. (2013) noted: “The biological and physical changes to the world’s oceans, coupled with other anthropogenic influences, will likely lead to more opportunistic diseases in the marine environment.”

Disease has a broad definition. Based on Stedman (2006 and earlier references therein), Peters (1997) defined disease as “any impairment (interruption, cessation, proliferation, or other disorder) of vital body functions, systems, or organs,” and added that “Diseases are usually characterized either by (1) an identifiable group of signs (observed anomalies indicative of disease), and/or (2) a recognized etiologic or causal agent, and/or (3) consistent structural alterations (e.g. developmental disorders, changes in cellular composition or morphology, and tumors).” Diseases result from complicated interactions among the host, the environment, and an abiotic or biotic agent. The number of diseases of scleractinian corals and octocorals in the Caribbean/western Atlantic exceeds 20 (Sutherland et al. 2004; Weil 2004; Weil and Rogers 2011; Weil et al. 2017) with other less well defined or characterized conditions referred to as “compromised health conditions” (Raymundo et al. 2008; Weil and Hooten 2008).

Bleaching is a disease under the definition presented above. For the purposes of this report, the term “disease” is used to refer to cases where tissue is lost originating from a lesion, and the term “bleaching” to refer to the appearance of coral colonies that have lost the symbiotic zooxanthellae or zooxanthellar pigments, a condition that does not necessarily lead to morbidity and mortality. Corals only have few visible signs of stress.

Thermal stress leads to paling or bleaching with recovery possible if the stress is removed after a short enough time period. Bleaching is a sign of stress, typically a thermal anomaly (high or low temperatures), but corals can recover. There are degrees of bleaching, with colonies ranging from slightly pale, to blotched and completely white.

Single surveys of bleaching cannot provide a complete picture of the reef’s condition. In general, it is not as alarming as the appearance of new disease lesions.

It is challenging to differentiate these two major stressors (thermal stress and disease) for many reasons. Primarily, it is hard to quantify prevalence and extent (total area) of disease lesions,

particularly for *Orbicella annularis*, which is overall the most abundant coral species at most of these monitoring sites, because of the columnar morphology of this species and the difficulty of distinguishing individual colonies (Rogers 2010). It is also important to note that prevalence over time can be indicative of different levels of disease, and therefore coral mortality. If prevalence is 5% each year over several years and different coral colonies are affected each year, then this seemingly low value would be masking the severity of the effects. Some corals could die entirely from one evaluation of prevalence to the next. Actual measurement of individual lesions as in Miller et al. (2009) is very time-consuming and seldom done. However, quantifying the total area of corals killed by disease is expected to give the most accurate picture of the effects of diseases (see Miller et al. 2009). The relationship among thermal stress (higher sea water temperatures), bleaching, and diseases has not been completely determined. The peak of disease at U.S. Virgin Island sites (although not documented at SARI) occurred in 2006 a few months after the most extensive bleaching was observed at these locations.

The NPS and UVI use different protocols to evaluate coral condition, with UVI using Kramer et al. (2005) and the NPS using the SFCN I & M protocol (Miller et al. 2017). It is suggested that these two long-term monitoring programs should carefully compare their approaches. While both groups aspire to correlate trends in coral cover with temperature, storms, and coral diseases, it could be worthwhile to carefully analyze results from these two long-term monitoring programs to find and explain commonalities and differences.

Temperature Trends and Changing Climate

Bleaching events (and major storms) are expected to become more frequent in the future. More research on diseases and their interaction with thermal stress and bleaching, which could undermine the benefits of the marine reserves and other protected areas in the U.S. Virgin Islands (see below), and on the effects of the reef degradation on fishes and other organisms could help to further our scientific understanding and inform resource management.

Water temperature data from temperature sensors at each study site indicate that thermal stress is increasing as predicted with changing climate. Maximum temperatures and duration affect the degree of stress. Thermal stress is often, although not always, followed by bleaching events that in turn are followed by disease outbreaks (Muller et al. 2008, Miller et al. 2009).

Over the 30 years that water temperature data have been collected by the SFCN, the number of years where the average monthly temperature has exceeded the “bleaching threshold” (29.5°C) has dramatically increased. For example, 4 years were above the threshold from 1990–1999, 8 years in 2000–2009 and 9 years in 2010–2019. Temperatures in 2020 have also exceeded the threshold.

The TCRMP results presented in Ennis et al. (2019) indicate that sea surface temperatures of the U.S. Virgin Islands have been increasing at a rate of about 0.2°C per decade since the 1980s, increasing the incidence of coral thermal stress, measured as degree heating weeks (DHW), and coral bleaching. Major bleaching events, with heat stress values above 8 DHW, have occurred in 2005, 2010, and 2019.

National Oceanic and Atmospheric Administration (NOAA) Contributions

In addition to the long-term monitoring by the NPS and UVI, NOAA scientists have been monitoring marine benthic resources in the U.S. Virgin Islands in a variety of projects since 1999. Using aerial photography collected in 1999, Kendall et al. (2001) created updated benthic habitat maps for Puerto Rico and the U.S. Virgin Islands (specifically BUIS). From 2001 to 2006, Pittman et al. (2008) conducted 716 benthic surveys in and around BUIS using five 1m² quadrats at each site to quantify abiotic and biotic cover, and rugosity. Using the same method in 2012, a NOAA-led multi-agency effort conducted an additional 290 benthic surveys including some in BUIS (Hile 2013). These efforts were the precursor to regular biennial monitoring in the U.S. Virgin Islands under the National Coral Reef Monitoring Program (NCRMP).

According to the NOAA website (www.coris.noaa.gov/monitoring), the NCRMP is designed to provide an ecosystem perspective derived from an integrated monitoring of climate, fish, benthic, and socioeconomic variables based on coordination of various Coral Reef Conservation Program (CRCP) activities through a cohesive NOAA-wide effort. A primary goal is to communicate results of national-scale monitoring to national, state, and territorial policy makers, resource managers, and the public on a periodic basis. The NCRMP is a framework for conducting sustained observations of biological, climate, and socioeconomic indicators at 10 priority coral reefs across the U.S. and its territories. This integrated approach will consolidate monitoring of coral reefs under a uniform method in the Pacific, Atlantic, Caribbean, and the Gulf of Mexico for the first time.

Under the NCRMP in the U.S. Virgin Islands, a new benthic monitoring methodology was adopted in 2013 to assess benthic abiotic and biotic cover and coral demographics (size of colony, percent dead, etc.). Under this program, cooperative multi-agency monitoring (led by NOAA) has been conducted in the U.S. Virgin Islands in 2013 (St. John and St. Thomas only), and in all three islands in 2015, 2017, and 2019. Abbreviated (due to COVID-19 restrictions) sampling occurred in 2021. There have also been several seafloor characterization efforts throughout the U.S. Virgin Islands, using a variety of remote sensing methods from the NOAA Ship *Nancy Foster* with specific projects taking place in 2004, 2005, 2006, 2010, 2011, 2014, 2015, and 2016. Researchers from NOAA also documented the effects of the 2005 coral bleaching event in four U.S. Virgin Islands areas, including BUIS. The substantial efforts by NOAA to characterize and monitor coral reefs in the U.S. Virgin Islands cannot be covered in full by this document. The most recent report covers results through 2019 (Figure 14, Edwards et al. 2021). For further information, consult <https://www.coastalscience.noaa.gov/research/>.

In addition to the NPS and UVI monitoring activities, NOAA scientists have been monitoring fish and habitat within BUIS every 2 years. They documented the effects of the 2005 coral bleaching event over a more extensive area (~50 km²) using random (not permanent) transects on linear reefs, patch reefs, bedrock, pavement, and scattered coral/rock habitats during October 2005, and April and October 2006 (Clark et al. 2009). In October 2005 approximately 51% of live coral cover was bleached, and 19 of 23 coral species exhibited this sign of thermal stress.

Coral cover for *Montastraea* (now *Orbicella*) *annularis* and species of the genus *Agaricia* were the most affected. Bleaching was evident over the entire depth gradient (1.5–28 m), with more in

shallower water. Bleaching prevalence decreased over time with 15% in April 2006 and only 3 % in October 2006. The following species did not bleach over this time period: *D. cylindrus*, *Eusmilia fastigata*, *Mussa angulosa*, *Mycetophyllia aliciae*, and *Scolymia* spp.

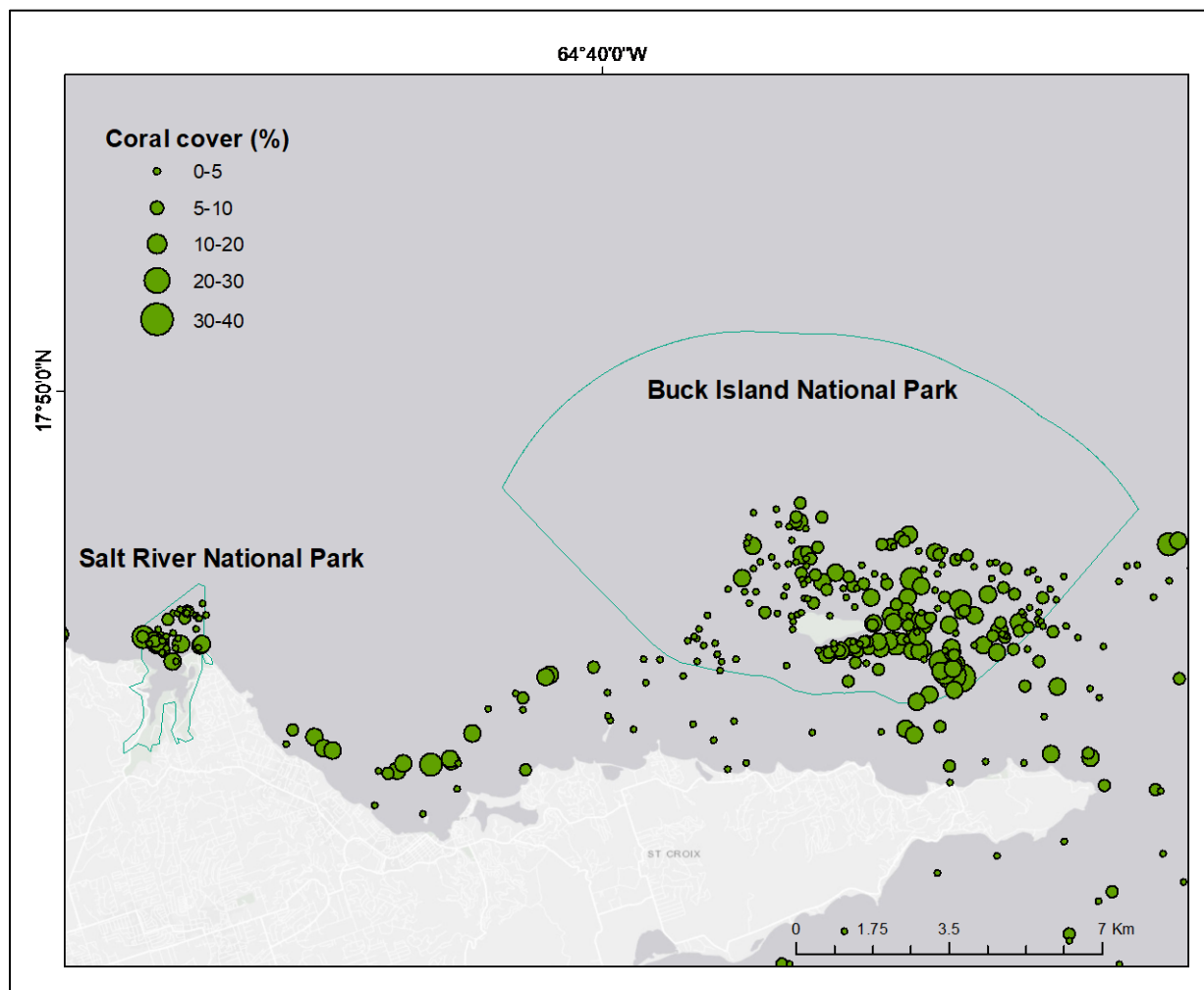


Figure 14. Stony coral cover recorded at randomly selected hardbottom sites for northeastern St. Croix and BUIS. Data from the National Coral Reef Monitoring Program covering years 2015, 2017, and 2019 (Data and Map courtesy of S. Groves, NOAA, Sep. 4, 2020).

In 2000, NOAA completed an extensive seafloor mapping project around all the U.S. Virgin Islands (Kendall et al. 2001). This project mapped 485 km² of benthic habitats in the U.S. Virgin Islands to a nominal depth of 30 m based on visual interpretation of color aerial photography. In 2005, multibeam and remotely operated vehicle (ROV) video surveys conducted off the north side of Buck Island, St. Croix, revealed colonies of the deepwater coral *Lophelia* at depths greater than 1,000 m.

Between 2004 and 2006, NOAA's research vessel *Nancy Foster* conducted extensive sea floor mapping around Buck Island, Salt River Bay, and Lang Bank (St. Croix).

Between 2010 and 2012, NOAA's Center for Coastal Monitoring and Biogeography Branch in partnership with the NPS generated three seamless habitat maps of the Bank/Shelf and the Bank/Shelf Escarpment inside BUIS (see Costa et al. 2012). The objective of this effort was to provide spatially-explicit information describing the benthic habitat types and live coral cover present in the full extent of BUIS boundaries. The three resulting habitat maps, generated using a combination of semi-automated classification and visual interpretation techniques, represent the first digital maps of the moderate and deep-water areas inside the monument.

Costa et al. (2012) describe the creation and assessment of a shallow ($0 \leq 50$ m), moderate ($50 \leq 1,000$ m) and deepwater ($1,000 \leq 1,830$ m) benthic habitat map for BUIS. This work is part of the NOAA CRCP's national coral reef ecosystem integrated mapping and monitoring studies throughout the U.S. Caribbean. While this mapping effort marks the fourth time that the shallow-water habitats of BUIS have been mapped, it is the first time that habitats deeper than 30 m have been characterized. Consequently, this habitat map provides information on the distribution of mesophotic and deep-water coral reef ecosystems and serves as a spatial baseline for monitoring change in the monument.

This benthic habitat map was developed for approximately 74.3 km² or 98% of the monument. The majority of the area that was characterized was deeper than 30 m on the Bank/Shelf Escarpment. This escarpment area was dominated by uncolonized sand which transitioned to mud as depth increased. Bedrock was exposed in some areas of the escarpment, where steep slopes prevented sediment deposition. Mesophotic corals were seen in the underwater video, but were too sparsely distributed to be reliably mapped from the source imagery. Habitats on the Bank/Shelf were much more variable than those seen on the Bank/Shelf Escarpment. The majority of this shelf area was comprised of coral reef and hardbottom habitat dominated by various forms of turf, fleshy, coralline or filamentous algae. Even though algae was the dominant biological cover type, nearly a quarter (24.3%) of the monument's Bank/Shelf benthos hosted a cover of 10% to <50% live coral. The final deliverables for this project, including the benthic habitat maps, source imagery and in situ field data, are available on the NOAA Biogeography Branch website

(<http://ccma.nos.noaa.gov/ecosystems/coralreef/stcroix.aspx>)

The Buck Island BIOMapper, is an interactive, online feature designed to let users explore these benthic habitat mapping data

(<https://maps.coastalscience.noaa.gov/biomapper/biomapper.html?id=BUIS>).

According to the website, "This portal contains a comprehensive collection of data, including aerial imagery, acoustic imagery, benthic habitat shapefiles, ground validation sites, underwater video, and still photography. In addition, the BIOMapper tool provides the ability to create customized, printable PDF maps. These data products provide a detailed, contemporary evaluation on the status, abundance, and distribution of marine benthic habitats for Buck Island. The results of these efforts will provide resource managers, scientists, and the public increased understanding and technical capacity for ocean exploration, management and stewardship."

Recently, NOAA and the NPS have created a data visualization tool based on a web-based Coral Conservation and Management Dashboard that uses maps and charts to help managers and others

visualize and query data from numerous monitoring programs in NPS units in Florida and the U.S. Virgin Islands. Data include coral cover and density, and coral condition (diseased, bleached). This new, innovative tool should enable easier access to data.

Marine Protected Areas

Another useful product from NOAA's Center for Coastal Monitoring and Assessment was the comprehensive report by Pittman et al. (2014). Buck Island Reef National Monument was one of the first Marine Protected Areas (MPA) established in the United States (1961), along with Virgin Islands National Park (after the addition of submerged lands in 1962).

Numerous studies have been done in the Caribbean to evaluate the effectiveness of marine reserves, usually defined as MPAs within which fishing is prohibited. These areas are established with different objectives but generally with the intention of increasing the abundance and biomass of groupers, snappers and other fish that are "targeted" by fishers. Increases in fish assemblages typically occur if fishing pressure is removed, enforcement is sufficient, and other stressors do not come into play. In some cases, a spillover effect is noted with fish traveling outside the boundary of the MPA to support fishing.

Efforts have been made to evaluate if MPAs are reversing degradation of marine resources in the U.S. Virgin Islands. Although recent studies are lacking, these MPAs have not resulted in increases in fish biomass, and in general coral cover on these reefs has declined since the establishment of the protected areas (Pittman et al. 2014). Diseases could undermine the benefits of MPAs and pose significant challenges for resource managers as there is still little known about the causative pathogens and environmental factors and no ready solutions. The coral losses associated with white plague following bleaching in 2005 (and now with SCTLD) could adversely affect the structure and function of coral reefs within BUIS and VICR and undermine the positive results of reductions in fishing. In addition, numerous hurricanes have affected these MPAs.

The very small marine reserve within BUIS understandably did not result in effective protection for reef fish based on an examination in 2000 (see Tobias et al. 1988, Rogers and Beets 2001). The expansion of BUIS (and the creation of VICR) in 2001 offered hope of reversing declines in fish assemblages around St. John and Buck Island. However, Pittman et al. (2014) did not find evidence that the increase in protected area had positive results. Their study assessed trends from 2003 through 2009, and recent trends remain undocumented.

The Hurricanes of 2017

Hurricanes Irma and Maria caused unprecedented destruction in the U.S. Virgin Islands in September 2017. Irma, a Category 5 storm, with sustained winds of 185 mph and gusts over 220 mph, was followed less than two weeks later by Hurricane Maria, a Category 4 storm in St. John and a Category 5 in St. Croix and Puerto Rico (Figure 15) (Browning et al. 2019).

The 2017 hurricanes caused damage to reefs at all long-term study sites in the U.S. Virgin Islands, toppling, up-ending, and removing corals from the substratum, yet only one site (in St. John) revealed a statistically significant decline in coral cover (SFCN 2022b).

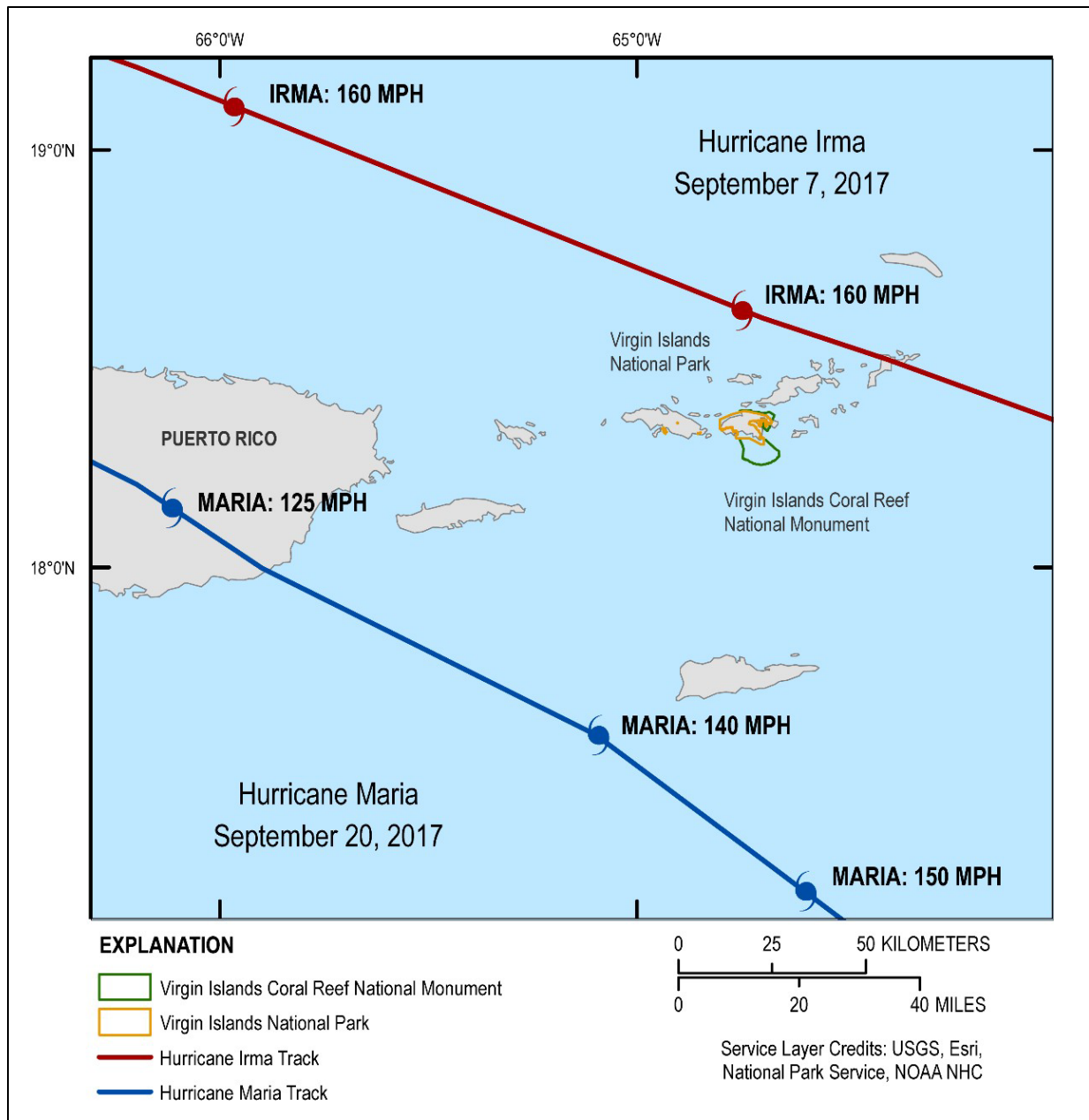


Figure 15. Tracks of Hurricanes Irma and Maria, September 2017 as the storms moved through the U.S. Virgin Islands and Puerto Rico. (credit, B. Williams and B. Boynton, Cherokee Nation Technologies, contracted to the USGS).

NPS Restoration Plan and Priority Sites

In 2020 a team of scientists developed a Restoration Plan for the national parks and monuments in St. Croix and St. John that focused on attempting to promote recovery of coral reefs, shorelines, and mangroves damaged during Hurricanes Irma and Maria in September 2017 (Caribbean Restoration Plan 2020). The initial plan was for team members to visit the sites as a basis for recommendations on “restoration”. (Note that the word “restoration” is being used here in the narrow sense to refer to outplanting of coral fragments propagated in nurseries.) As a result of the COVID-19 pandemic, it

was not possible for these visits to occur. The team members had to rely on available information regarding effects of the storms, and in many cases the sites selected by the NPS lacked data or observations from shortly before and after the passage of these storms. The team used benthic habitat maps from NOAA (Kendall et al. 2001) to estimate the size of the different zones that were to be considered for coral restoration, and then used their best judgement to recommend the numbers of fragments of each appropriate coral species that would be required to reach a coral cover of 10% or more over a 10 year period.

The site summaries prepared for the plan include site descriptions (depth, habitats/zone), historical information and the most recent observations of hurricane effects. AT BUIS and SARI, the hurricane damage was primarily from Hurricane Maria (September 19, 2017), rather than Hurricane Irma which passed through the U.S. Virgin Islands about 2 weeks before. For example, a video taken at the South Forereef (<https://youtu.be/THfML-8QCuw>) a few days after Irma shows an impressive stand of *A. palmata* which was severely damaged by Maria a few days later.

The Restoration Plan should be consulted for more details. As of the beginning of 2022, the funding levels have not been determined or announced.

The BUIS sites selected by NPS resource managers and scientists for restoration with the priority level in parentheses were as follows:

Brain Garden (High), South Forereef (High), Haystacks (High), Underwater Trail (High), Lagoon Barrier (High), South Patch Reef (Moderate), North Bar (Low), and Western Spur and Groove (Low). [Note that the long-term monitoring site designated South Forereef maintained by the NPS Inventory & Monitoring Network is within the South Patch Reef not the South Forereef referred to here.]

A few of these sites are discussed below in more detail because of their higher significance for recreational use or because of the greater extent of storm damage they sustained.

The South Forereef

The South Forereef was hit more directly by Hurricane Maria, fragmenting the large remaining *A. palmata* colonies and pushing substantial amounts of coral over the reef crest and into the back reef.

A post-hurricane site assessment was conducted on 10/27/2017. The damage overall was severe with over 50% of all live coral colonies damaged. All the large branching colonies lost all branches leaving “trunks”, head corals were tumbled and dislodged, gorgonians uprooted, and all along the fringing reef coral rubble was piled upwards of 1–2 meters with live and dead fragments. Most of the damage was to *A. palmata*, but many small colonies of *Dichocoenia stokesii*, *Pseudodiploria strigosa* and *Millepora alcicornis* were overturned.

This same area was literally re-structured as a result of Hurricane Hugo in 1989. The storm scoured the forereef clear of almost all corals from about 8 m to the surface and deposited a rampart of live

and dead coral fragments 30 m shoreward of the original reef crest and is emergent at low tide, creating a new barrier to water exchange (Gladfelter et al. 1991b).

South Patch Reef

Hurricane Maria caused extreme damage to portions of the South Patch Reef southeast of Buck Island. The site starts at the base of the south forereef and extends southeast. It has relatively high coral cover and coral species diversity. The average depth of the site is between 10–15 meters. The site is dominated by *O. annularis* but also supports many other coral species (*O. franksi*, *C. natans*, and *D. cylindrus*). The SFCN long-term monitoring transects are here, at depths from 10–15 m. Monitoring has occurred from 2002 through 2021 (see Figure 12, above).

The 2005–2007 thermal stress/disease event was associated with dramatic declines in coral cover (from about 20% down to 4%) (Miller et al. 2009, SFCN 2022a) from which this reef has not recovered, although there has been a statistically significant increase in cover since 2007. Stony coral tissue loss disease has now been observed here.

This monitoring site suffered some of the greatest impacts from the 2017 hurricanes, although damage was moderate. Most of the damage was to *Orbicella annularis* colonies with several columns being toppled. A post-hurricane site assessment was done by SFCN on 3/21/18.

Although NPS scientists reported devastation in many coral communities around Buck Island, with the exception of the South Forereef and South Patch Reef locations, damage to study sites was moderate.

The Haystacks

The haystacks are northeast of Buck Island on the outside of the fringing reef (Figures 16 and 17). This site includes the iconic *A. palmata* haystack structures unique to Buck Island. Haystacks are complex, inverted conical structures formed from *A. palmata* branches, and extend from the bottom (~10 m) to near the surface. These seaward patch reefs are present outside the fringing reef that extends around two-thirds of Buck Island and out to the Buck Island Bar, a submerged reef approximately 500 m to the north. The haystacks are presently composed of almost 100% dead *A. palmata*; it is believed that they originated in shallow water as lagoon patch reefs behind a barrier reef in the vicinity of Buck Island Bar (Hubbard 1991).

Historically, the haystack patch reefs had greater than 50% live *A. palmata* cover. The topmost corals used to break the surface during low tides prior to Hurricane Hugo, 1989, but have not done so since. Several other coral species (*Orbicella* spp., *Porites astreoides*, *Pseudodiploria strigosa*), and abundant octocorals are present on the haystacks today.

The geological formation of Buck Island and surrounding reef complexes on Lang Bank is very complex and has been described in several papers, including Hubbard et al. (2013). Dennis Hubbard (Oberlin College, written communication, 2021) suggests that these haystacks were patch reefs when the now submerged outer reef to the north was a barrier.



Figure 16. Examples of haystack formations (Photo: I. Kuffner).



Figure 17. Examples of haystack formations (Photo: I. Kuffner).

Mayor et al. (2006) conducted the first full *A. palmata* distribution survey at BUIS finding 2–5 colonies per 25 m by 10 m transect within the haystack area. In the 2005 bleaching event, many of these colonies were lost and this species has not fully recolonized the area, although park staff observed some new sexual recruits or possible re-sheeting over existing dead structure on topmost levels of the haystacks in this zone before the 2017 hurricanes.

The Underwater Trail

The Underwater Trail is off the eastern tip of Buck Island. The site, from 3 m to 10 m deep, includes a colonized hardbottom portion in the lagoon as well as the backreef and forereef of the fringing reef. This is the most visited site at Buck Island with close to 50,000 visitors snorkeling the trail each year. It is dominated by dead *A. palmata*, with a few large living *A. palmata* colonies. Several other stony coral species, and octocorals, primarily sea fans, are also present. Degraded remains of the reef crest are emergent at exceptionally low tides. The colonized pavement in the lagoon is dominated by *P. strigosa* and *P. clivosa*.

The Underwater Trail sustained minor damage from the 2017 hurricanes. An assessment was conducted on 10/2/17. Some fragmented *A. palmata* and overturned *Pseudodiploria strigosa* colonies were seen. Most of the damage occurred on the forereef, with some damage in the lagoon.

We now turn to a discussion of the history of coral reef research at SARI.

Salt River Bay National Historical Park and Ecological Preserve

Salt River Bay National Historical Park and Ecological Preserve includes the unique submarine canyon that indents the narrow northern shelf of the island of St. Croix. The origin of this unusual feature is thought to be related to a river that flowed here during a time of lower sea level. Now only ephemeral streams introduce materials from the watershed. Hubbard (1989) described the accretionary history of Salt River submarine canyon noting that from 10,000 to 6,500 ybp accretion was dominated by *A. palmata* followed by the steepening of the reef face and the establishment of a new zone with *Montastraea* (now *Orbicella*) *annularis*. Net accretion of the reef is now very slow (Hubbard 1989).

Research by Hubbard (1989) provides the overall geological context for the development of coral reefs within SARI and highlights the key controlling factor of sediments that are transported from the east along the coast and from the watershed that feeds into the bay and the seaward canyon. The currents and associated transport of sediments lead to poorer reef growth on the western wall than the eastern wall of the canyon. These have resulted in a submarine landscape that is controlled as much by patterns of local sediment transport and reef accretion as by antecedent topography (Hubbard et al. 1986, Hubbard 1989). This area, particularly the canyon walls, was the focus of a substantial amount of research from NOAA's National Undersea Research Habitats, Hydrolab and Aquarius, from 1977 until 1989 (see Kendall et al. 2005 and mission reports cited therein).

Early Studies of SARI

Scientists from NOAA produced a very comprehensive summary of research and assessments (including maps) done within SARI from about the 1970s to 2004 (Kendall et al. (2005). They describe many short-term projects from the underwater saturation facilities Hydrolab and Aquarius. Most of these projects focused on fish, but there are a few early studies on corals (Boulon 1978, Rogers et al. 1984, Kesling 1990, Coulston et al. 1990) and sediment transport in the canyon (Hubbard 1986, Hubbard et al. 1986) for which final reports or publications are available. Some projects were followed by surveys from the surface after the mission was over. Most studies focused on the walls of the canyon over a variety of depths.

In addition to studies on benthic organisms and substrate, some studies were focused on reef processes such as coral recruitment. For example, Rogers et al. (1984) quantified recruitment of corals to tiles deployed from 3 to 26 months at four depths on each canyon wall: 9 m, 18 m, 27 m and 37 m. The density of juvenile corals present on the substrate was also documented.

Hubbard and Scaturo (1985) quantified growth rates of seven coral species from 9 m to 30 m and found that rates in SARI were lower than those in Cane Bay to the west. Although *Montastrea annularis* (now *Orbicella annularis*) was the fastest growing species, it grew less than 1 cm/year at depths shallower than 12 m and less than 0.20 cm/yr below 18–20 m. Coral growth in general decreased with depth.

On September 18–19, 1989, Hurricane Hugo passed over St. Croix with winds of 138–173 mph with gusts estimated at over 200 mph (Hubbard et al. 1991, Hubbard 1992), devastating the island and damaging the Aquarius habitat which was later moved to North Carolina. Only limited information on the effects of the storm at SARI is available some of it from two studies done from the habitat and followed by surveys after the storm (Kesling 1990, Aronson et al. 1995). Aronson et al. (1995) documented declines in coral cover along (non-permanent) transects from 8 m to 33 m deep from about 22 to 34% before the storm to 8 to 15% afterward. Kesling (1990) found declines of 10 to 28% in coral cover by several different species over 10 m to 40 m. Hubbard (1992) documented removal of substantial amounts of sediment transported by down canyon currents along the base of the canyon's west wall.

Long-Term Monitoring Trends for SARI Coral Reefs

Insights into trends in the condition of the coral reefs in SARI and the effects of storms, thermal stress, and disease outbreaks come primarily from the NPS South Florida/ Caribbean Inventory & Monitoring Network (SFCN) and TCRMP. The NPS program has 10 years of data on trends in coral cover and cover by other benthic organisms and substrate. This program is presented in more detail here than TCRMP because comprehensive results for TCRMP are available in Ennis et al. (2019) and (2020). The NPS and UVI use different protocols to evaluate coral condition and reef status, with UVI using Kramer et al. (2005) and NPS the SFCN protocol (Miller et al. 2017). It is suggested that these two long-term monitoring programs could benefit from careful comparisons of their approaches and results.

NPS Inventory & Monitoring Program

The South Florida/Caribbean Network has annually monitored SARI's combined site since April 2012. This site encompasses 26,437 m², and consists of 20 randomly placed permanent transects, located within three sections: Canyon West Wall, Canyon East Wall, and Northwest Spur and Groove (Figure 18). These areas were constrained to ≤ 33 m depth and were chosen because of relatively high coral cover, reef complexity, and historical scientific significance. The 10 m transects are monitored annually using underwater video. Percent cover of living coral by species (see list in Appendix A), macroalgae, turf and coralline algae, octocorals, and sponges are calculated. Data on coral disease, bleaching, water temperature, and long-spined sea urchins are also collected (see <https://www.nps.gov/im/sfcn/index.htm>).

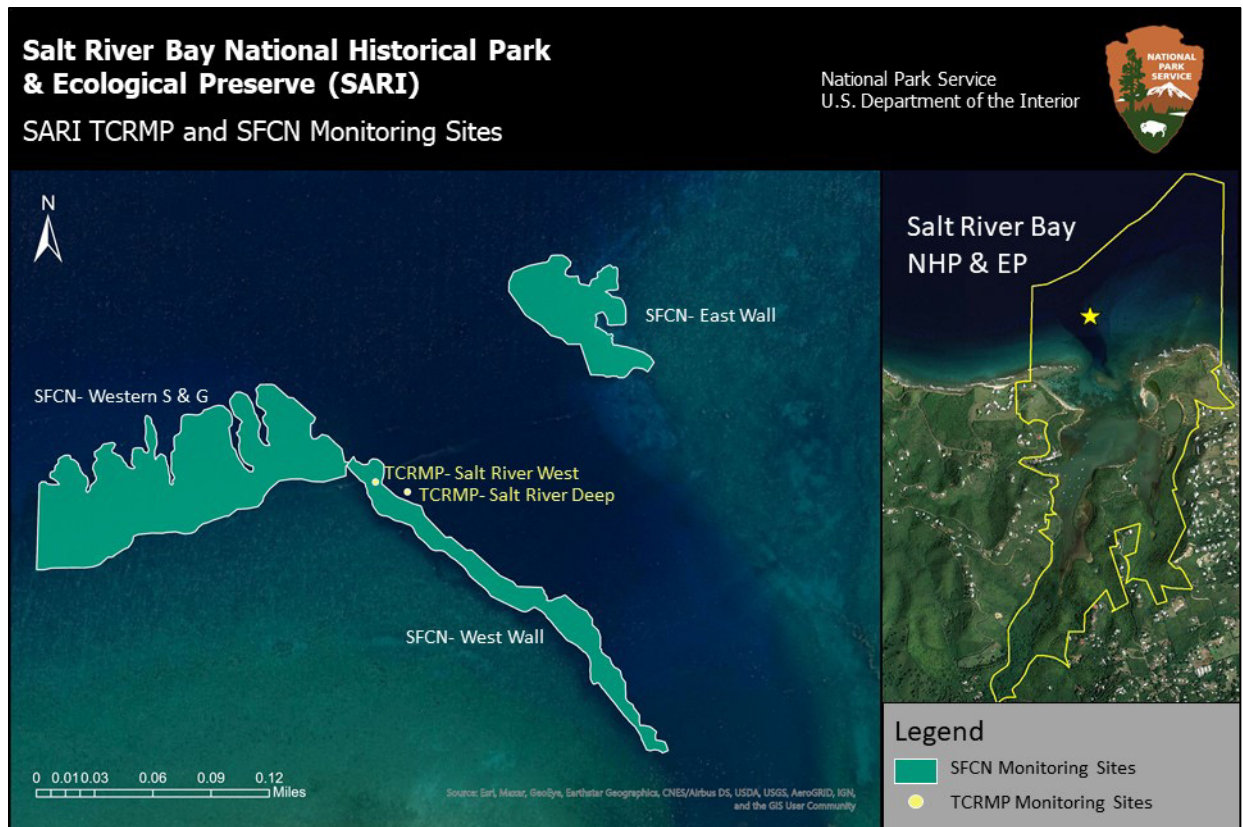


Figure 18. Location of long-term monitoring transects maintained by the National Park Service and the Territorial Coral Reef Monitoring Program in Salt River Bay National Historical Park and Ecological Preserve (map by K. Ewen, NPS).

Despite the passing of two Category 5 hurricanes (Irma and Maria) in September 2017 (see below), live stony coral cover remained stable at between 10–12% through the 2019 sampling period. Coral cover was highest in 2019 ($11.9\% \pm 1.3$) and declined to the lowest value in 2021 ($10.3\% \pm 1.6$). No statistically significant change in coral cover has occurred over the monitoring period (2012–2021); however there was an upward trend in coral cover until the 2021 monitoring (Figure 19, SFCN 2022c). Coral cover of 10.3% at the NPS SARI site is similar to cover at the BUIS South Forereef monitoring location, similar to or above the VIIS locations, and lower than that documented for the BUIS Deep Bar site (27%). Stony coral tissue loss disease began killing corals in late 2020 (Figures 20 and 21). Coral species vary in their susceptibility to this disease, and a recent analysis of changes in coral cover by species at SARI indicates that many of the most vulnerable species are no longer present on long term transects (Jeff Miller, National Park Service, written communication, 2021).

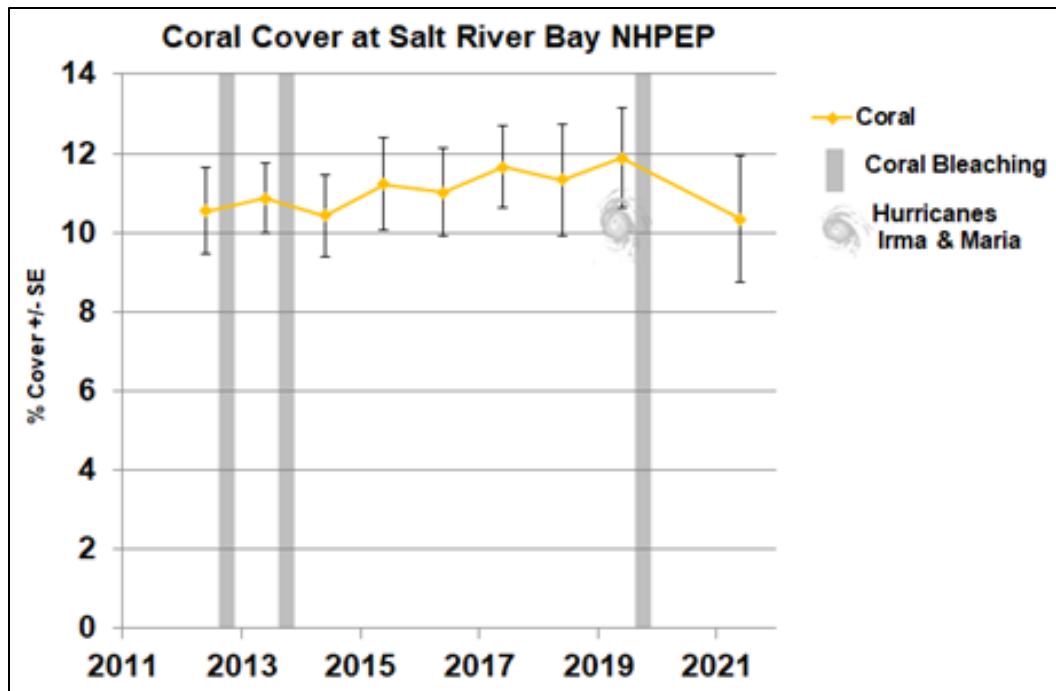


Figure 19. Coral cover at the National Park Service long-term site from 2012 to 2021 (SFCN 2022c).

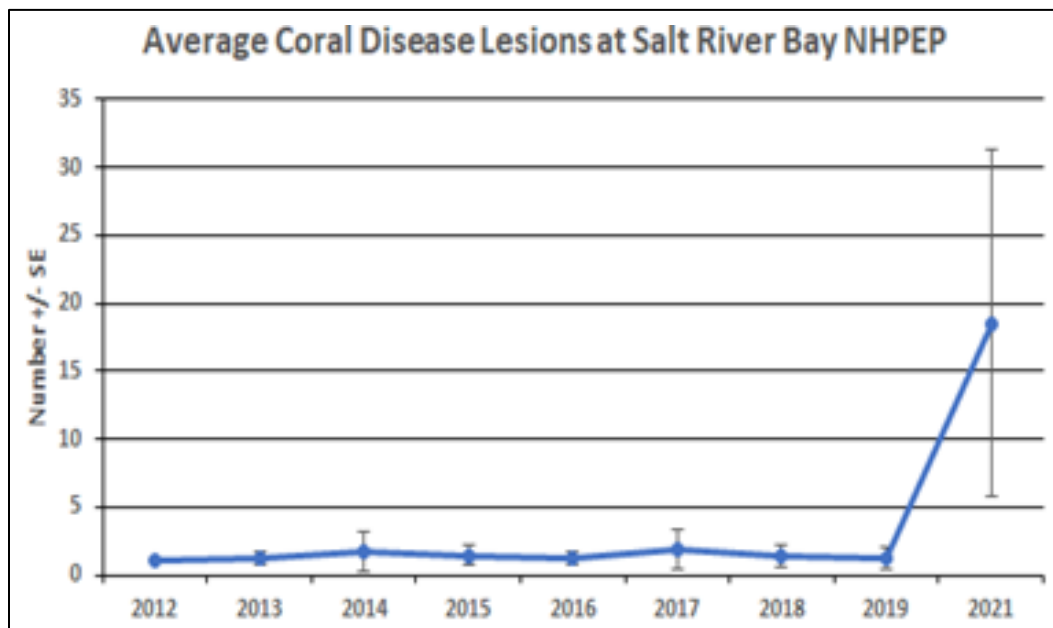


Figure 20. Average number of disease lesions observed in Salt River Bay National Historical Park and Ecological Preserve over time (SFCN 2022c).

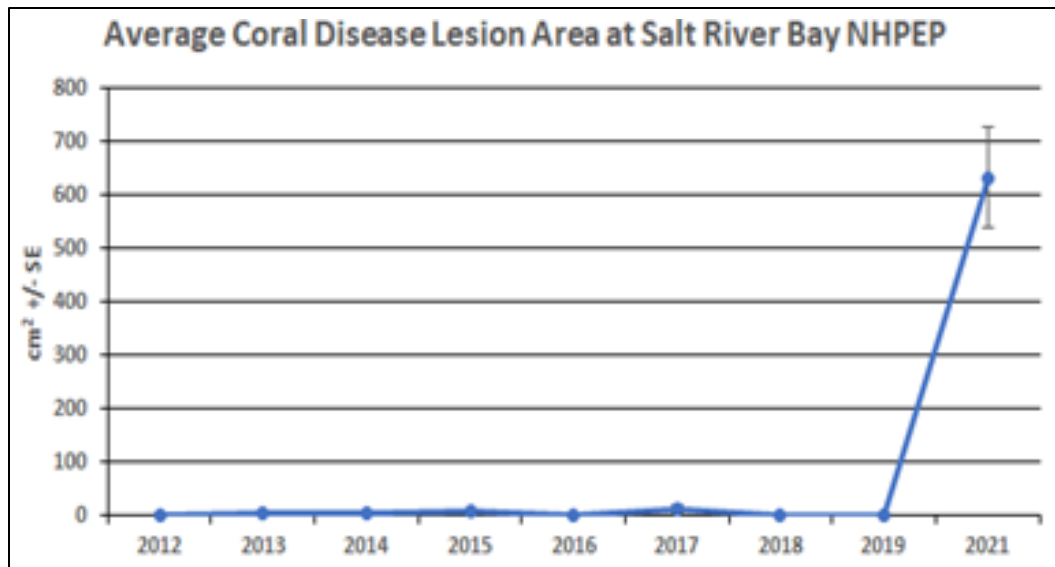


Figure 21. Average size of lesions observed in Salt River Bay National Historical Park and Ecological Preserve over time (SFCN 2022c).

Although coral cover has declined, it did not decrease significantly (statistically) because the least vulnerable coral species, *Orbicella* spp. group, *Montastraea cavernosa*, and *Siderastrea siderea*, make up the primary reef building corals at this site. However, each of these species declined from 2019 to 2021. Data from SFCN also show macroalgae cover decreasing from a high of 36.1% in 2015 to a low of 20.7% in 2018. Notably, macroalgae was not listed as a benthic component in any historical report (early 1980s) for SARI. The walls of the canyon in SARI have some of the largest plate corals (*Agaricia* and *Undaria* spp.) found in any SFCN monitoring site in the U.S. Virgin Islands (Figure 22). The cover of these plating corals has remained relatively constant through the study period. Until the recent severe outbreak of stony coral tissue loss disease, the number of coral disease lesions and area killed by disease were relatively low at SARI.



Figure 22. *Agaricia* corals along one of the deep monitoring transects in Salt River Bay National Historical Park and Ecological Preserve. Photo credit: J. Miller.

Territorial Coral Reef Monitoring Program (TCRMP)

More information on trends in coral and other benthic cover within SARI is available from two long-term monitoring sites maintained by scientists with UVI under the Territorial Coral Reef Monitoring Program. Comprehensive information on trends in coral cover and other benthic components are available for Salt River West established in 2001 (9 m) and Salt River Deep (30 m) established in 2009 (Figures 23 and 24).

Information on trends in total coral cover and cover by individual species through 2016 is shown below (Ogarcuk et al. 2022). These values do not include the recent time period in which SCTLTD was associated with extensive coral mortality. For details, see Smith et al. 2016 and Ennis et al. 2019, website <https://sites.google.com/site/usvitermp/home>, and http://www.uvi.edu/files/documents/Research_and_Public_Service/CMES/uvi_cmes_tcrmp_description.pdf. (The latest TCRMP report, Ennis et al. 2020, is more comprehensive and up to date, but it just became available and will not be incorporated into this document.)

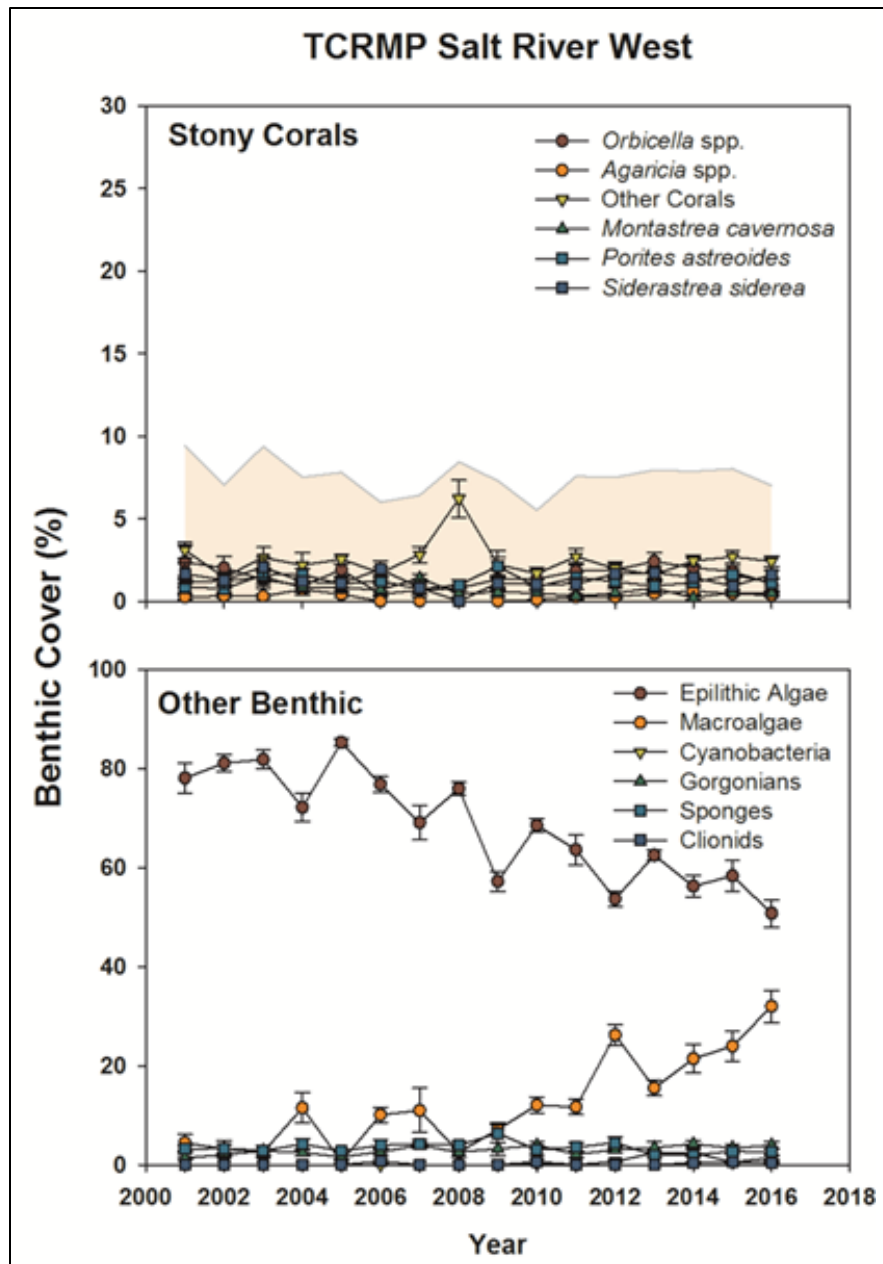


Figure 23. Trends in total coral cover, cover by individual coral species, and cover by other benthic organisms at Salt River West. Top: trends in total coral cover (line delineating shaded area in graph above) and cover by individual coral species at Salt River West. Bottom: trends in cover by other benthic organisms, including algae, gorgonians, and sponges at Salt River West (from Ogarcuk et al. 2022).

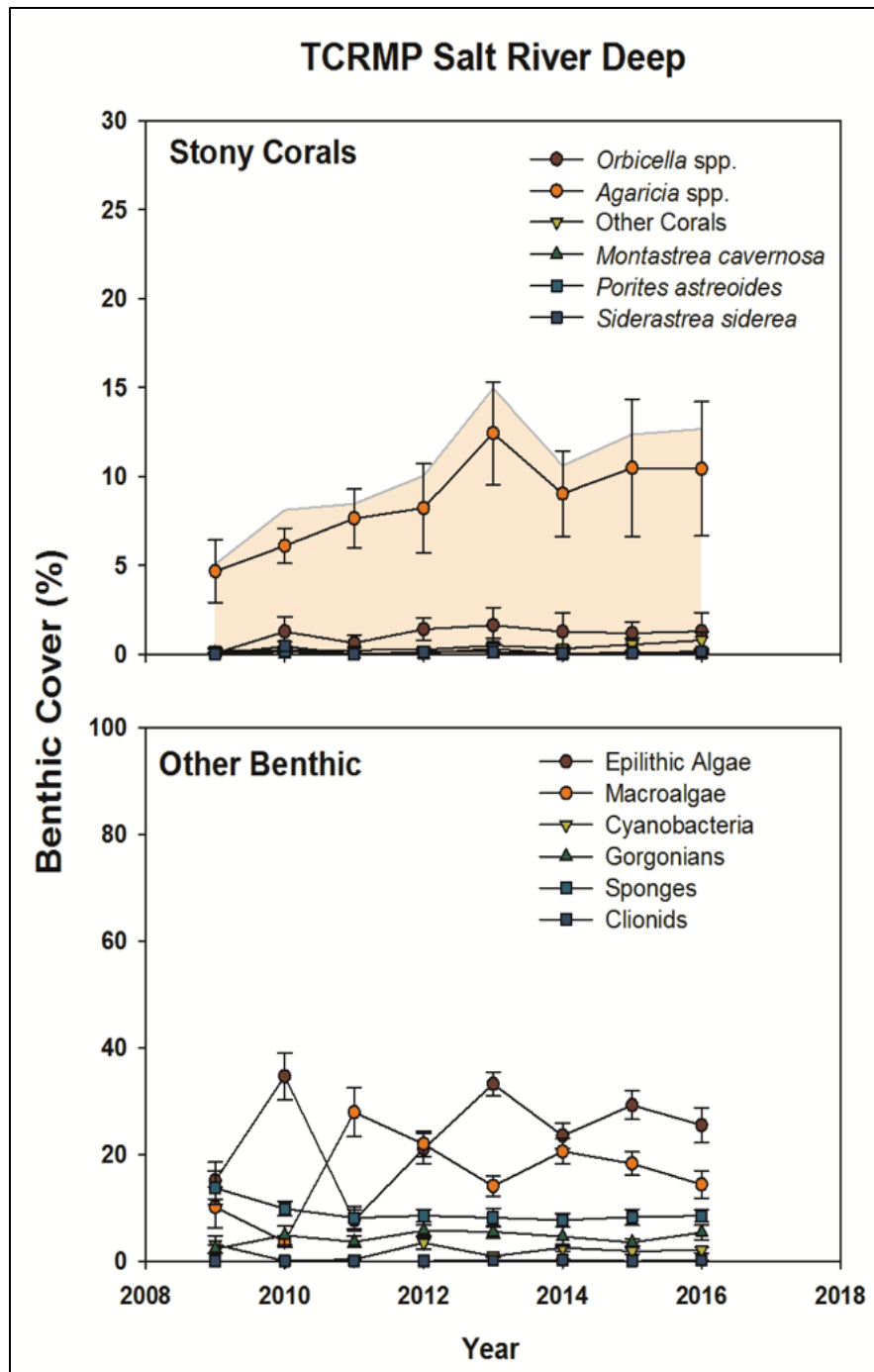


Figure 24. Trends in total coral cover, cover by individual coral species, and cover by other benthic organisms at Salt River Deep. Top: trends in total coral cover (line delineating shaded area in graph above) and cover by individual coral species at Salt River Deep. Bottom: trends in cover by other benthic organisms, including algae, gorgonians, and sponges at Salt River Deep (from Ogarcuk et al. 2022).

Overall, the coral reefs of SARI have shown damage from hurricanes and thermal stress from surface to 30 m depth, and no evidence of substantial recovery. Climate change is anticipated to bring more

ocean warming that will increase the frequency and severity of damaging coral bleaching events (Ogarчук et al. 2022).

In general, the NPS has attributed more loss of coral cover over time to disease while TCRMP has emphasized thermal stress (bleaching mortality). (Different results may reflect the timing of data collection.) This is particularly clear for long-term monitoring sites at BUIS where monitoring has been in place for longer than at SARI (Miller et al. 2009, SFCN 2022a,c). The role of diseases at BUIS has been documented far more than at SARI.

NPS Restoration Plan and Priority Sites

As described earlier, in 2020 a team of scientists developed a Restoration Plan for the national parks and monuments in St. Croix and St. John that focused on attempting to promote recovery of coral reefs, shorelines, and mangroves damaged during Hurricanes Irma and Maria in September 2017 (Caribbean Restoration Plan 2020). Please refer to discussion above for more details. Here are brief descriptions of the sites selected by NPS scientists for possible restoration. The five sites were East Wall, East Forereef, West Wall, West Forereef, and West Spur and Groove. The Inventory & Monitoring team visited these sites on March 18, 2018 and took photos at some of the locations.

Hurricane effects were characterized as severe = >50% damage to corals and reef ; moderate = 10%–50% damage to corals and reef; minor = <10% damage to reef. Although the Plan states that the 2017 hurricanes devastated many coral communities around Salt River, the SARI sites were all described as having had minor damage, although it may have been less conspicuous because observations did not occur until March 2018 (at the earliest), 6 months after the hurricane impacts. The only references for these site descriptions, notably the ecological histories of the locations, were Boulon (1978), Rogers et al. (1984), and Kendall et al. 2005)

Descriptions of Sites for Possible Restoration

Although the focus of restoration at the St. Croix NPS units is on BUIS, some outplanting of corals may occur in SARI. The following site descriptions are not complete and some are out of date, but they provide useful information that is not readily available elsewhere. They have been revised to be more concise than what appears in the Plan itself. Additional photos appear in the Plan.

SARI East Forereef

(Coordinates: Lat Long 18.364674 –64.732047)

The Salt River East Forereef site is on the east side of the canyon (Figure 25). The site includes the forereef and some colonized hardbottom. Depth ranges from 1 m to 7 m. The site is dominated by *Acropora palmata* and *Pseudodiploria strigosa*, although live coral cover is low. There are also octocorals present at the site. Turbidity can be high given the sediment inside the bay. Some fragmented and overturned corals were observed during the SFCN post-hurricane assessment on 3/18/18.



Figure 25. SARI East Forereef site. Photo taken during the SFCN post-hurricane assessment (3/18/18, Lee Richter).

SARI Western Spur and Groove

Coordinates: (Lat Long 18.364674 -64.732047)

The SARI Western Spur and Groove site is on the west side of the canyon (Figure 26). It is 10–15 m deep and predominantly colonized pavement with sand channels (spur and groove). Turbidity can be high.

The site is currently dominated by small coral colonies, mostly *P. strigosa*, *P. clivosa*, and some *Orbicella* spp. Most of the minor damage observed was to octocorals with some overturned *P. strigosa*. The SFCN program monitors transects in this location and conducted a post-hurricane assessment on 3/18/18.

This is one of the few locations with clear documentation of abundant *A. cervicornis* in the past (Coulston et al. 1990). (It is not known if this species has been observed in this location recently.)



Figure 26. Pictures taken at the SARI Western Spur and Groove site during the SFCN post-hurricane assessment (3/18/18, Lee Richter).

SARI West Forereef

(Coordinates: Lat Long 18.364674 –64.732047)

The Salt River West Forereef site, 1 m to 7 m deep, is on the west side of the canyon. The site includes the forereef and some colonized hardbottom. It is dominated by *A. palmata* and *P strigosa* although live coral cover is low. Turbidity can be high given the sediment inside the bay. A post-hurricane assessment has not been performed at this site. Hurricane impacts are unknown; however, based on observations and similar habitats, the impacts at this site were assumed to have been minor. No photos are available.

SARI West Wall

(Coordinates: Lat Long 18.364674 –64.732047)

The entire west wall is steep and composed of solid substrate which forms overhanging cliffs separated by sediment-filled cuts that extend from the top of the wall to the canyon floor (Figure 27).

Studies from the 1980s documented live coral cover along the west wall as typically between 20 and 60% (Boulon 1978; Rogers et al. 1983; Rogers et al. 1984). The dominant species included *Porites* spp., *Montastraea cavernosa*, *Madracis decactis*, and *Agaricia* spp., with the latter being most abundant offshore and with increasing depth (Boulon 1978; Rogers et al. 1983). A depth of 9 m appeared optimal for coral recruitment and survival on the west wall during a 1984 project (Rogers et al. 1984). Damage from the 2017 hurricanes at this site was minor. Some fragmented *Agaricia agaricites* and overturned *P. strigosa* were observed during the SFCN post-hurricane assessment on 3/18/18.

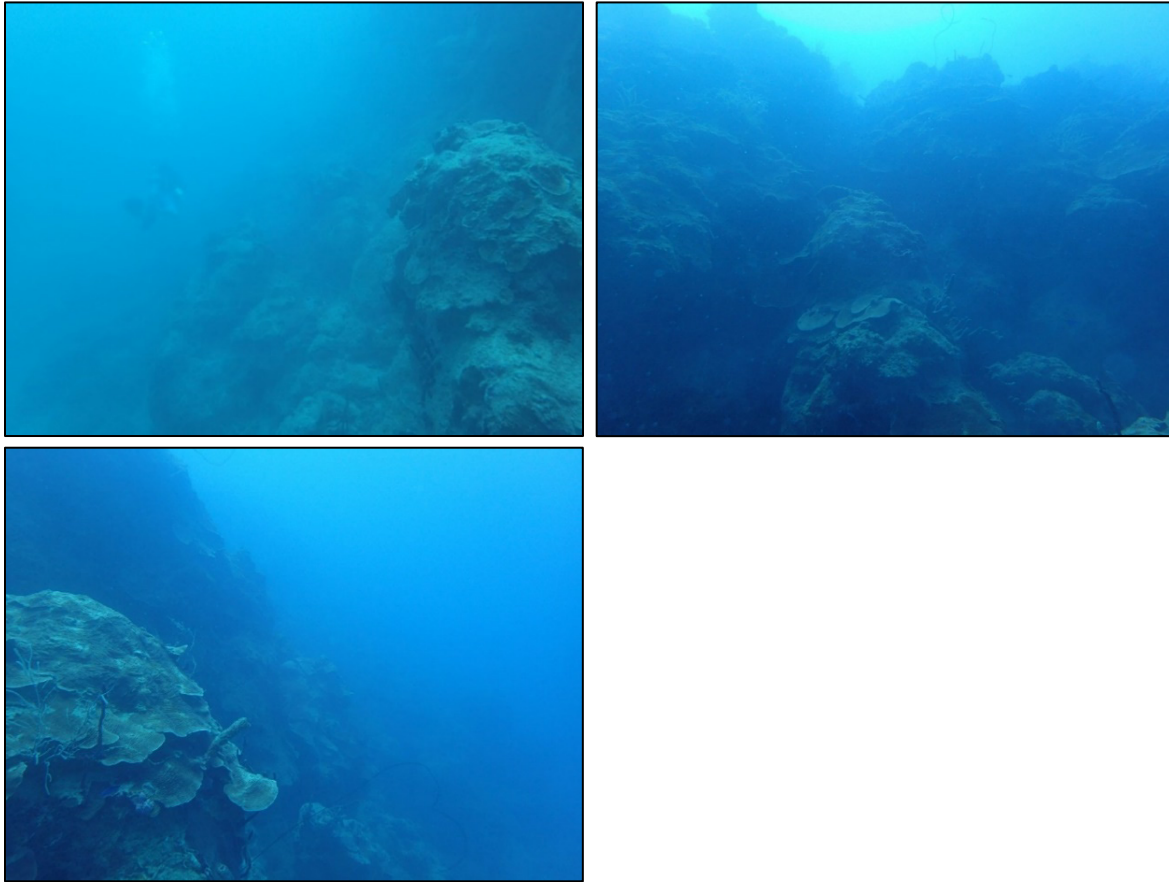


Figure 27. Pictures taken at the SARI West Wall site during the SFCN post-hurricane assessment (3/18/18, Lee Richter).

SARI East Wall

(Coordinates: Lat Long 18.364674 –64.732047)

The southern half of the east wall is gently sloping with an unconsolidated cobble/boulder substrate. The following description is based on reports from several decades ago and requires updating. Studies from the 1970 and 1980s reported percent cover of live coral in this area was relatively low, ranging from 0 to 7% (Boulon 1978; Rogers et al. 1984). Farther north, the wall becomes steeper, the substrate more solidified, and percent cover of live coral increases. At depths between 10 m and 18

m, live coral cover was usually less than 10% and was dominated by *Diploria* and *Montastraea* (now *Pseudodiploria* and *Orbicella*) species. Continuing northward along the east wall where depths reach between 19 m and 21 m, live coral cover was higher, typically between 10 and 70% and was dominated by *Montastraea cavernosa* and *Agaricia* spp. A depth of 18 m appears to have an optimal combination of light intensity, grazing pressure, and sedimentation rates for coral recruitment and survival on the east wall. Some fragmented *Agaricia* spp. and overturned *P. strigosa* were observed during the SFCN post-hurricane assessment on 3/18/18.

No pictures are available for this site.

The Most Recent Major Stressor: Stony Coral Tissue Loss Disease

A particularly devastating disease, referred to as stony coral tissue loss disease (SCTLD), is now spreading through the northern U.S. Virgin Islands and British Virgin Islands, having first been noted in Florida in 2014 (Precht et al. 2016) and 2019 in St. Thomas (see Townsend 2021, Brandt et al. 2021, and websites: <https://www.vicoraldisease.org> and <https://www.agrra.org> for information on spatial distribution). It is now considered the greatest single stressor affecting the reefs within BUIS and every other reef within the U.S. Virgin Islands (Figure 28).

At SARI, the disease is killing corals from the surface to a depth of at least 36 m. First observed on the West Wall in January 2021, by April 2021 the disease was severe on both walls (N. Hanna Holloway, National Park Service, written communication, 2021).



Figure 28. Stony coral tissue loss disease affecting a brain coral at Buck Island Reef National Monument (Photo: K. Ewen).

Dr. Erinn Muller and others with the Mote Marine Laboratory and the NPS are now testing several different treatments in an effort to stop the advance of this disease at BUIS.

Coral loss associated with SCTLD has the potential to exceed declines associated with the 2005/2006 bleaching event and subsequent disease outbreak and already has at some locations (Brandt et al. 2021). Some coral species may become locally extinct.

Throughout many of the areas affected, rates of coral mortality exceed any documented before, and some highly susceptible species are being eliminated from some locations. Although other less virulent diseases have been associated with sediment exposure or increased nutrient concentrations (Bruno et al. 2003; Kacmarzky et al. 2005; Voss and Richardson 2006), SCTLD has not been linked conclusively so far to any anthropogenic activity, sediment exposure, sewage, chemical pollutants, or any other environmental factor, and research continues. Recently viruses have been documented in endosymbionts in corals with SCTLD, but no definitive reason for a viral disease to appear in the endosymbionts has been determined (Work et al. 2021). This devastating disease has the potential to limit or perhaps eliminate entirely the reef accretion at Buck Island. Using a model of carbonate production based on empirical data and data from the scientific literature, Witcher (2017) concluded that the reef at BUIS is eroding faster than it is accreting, and it is not keeping up with sea level rise. Her study preceded the arrival of SCTLD. It is likely that the reef will therefore not continue to protect the shoreline, with possible consequences for the sea turtle nesting habitat.

Future Research at BUIS and SARI

It would be beneficial to convene a workshop with participants from the NPS, USGS, UVI, VIDPNR, NOAA and other researchers who have worked in BUIS and SARI to identify primary objectives and develop an overall, integrated research plan to guide further efforts and address research gaps in a more coordinated way. Scientists with the two major long-term monitoring programs (NPS and UVI) could present and discuss their findings and conclusions with regard to overall trends at long-term sites and consider if any changes in methods or focus are warranted. In addition to sustaining the long-term monitoring programs which document trends and overall reef status, and which are considered of the highest priority, it would also be of interest to focus once again on the dynamics of *A. palmata* populations at BUIS and to repeat the studies of coral reef processes such as those on coral growth rates by Hubbard and Scaturo (1985) and on coral recruitment at SARI by Rogers et al. (1984) to determine if these critical rates have changed, hindering recovery.

A current, overarching concern is changing climate, predicted to bring warmer seawater temperatures and more intense storms (Knutson et al. 2015). However, the most pressing environmental concern at both of these national park units is the coral mortality related to SCTLD. Some individual coral colonies and species have survived SCTLD (February 2022), and monitoring of possible recovery is critical. Recovery, if it occurs at all, will be slow as corals grow very slowly, and stressors will continue. No direct cause of this disease has been identified. Diseases can be linked to poor water quality from chemical pollutants and sediments. To date only a few studies have been conducted on such contaminants associated with the developed watershed affecting SARI (Pait et al. 2020, Bayless et al. 2021), and further evaluation of any potential links between poor water quality and the coral communities on the walls of the submarine canyon would require more research.

Given the unprecedented declines in coral cover by SCTLD, it is important to consider the feasibility of outplanting of corals or other restoration efforts. The threatened acroporid corals apparently have not been affected by SCTLD so far, and in general they have received little recent research attention

(see Smith et al. 2014, Woodley et al. 2021). Given that their relative abundance and importance may increase in the future, more studies of these threatened species are warranted.

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Appendix A

Scleractinian coral species within BUIS and SARI

(based on list supplied by Lee Richter, National Park Service)

Stephanocoenia intersepta

Madracis auretenra

Madracis decactis

Acropora palmata

Acropora cervicornis

Undaria agaricites

Agaricia spp.

Agaricia fragilis

Agaricia lamarcki

Helioseris cucullata

Siderastrea siderea

Siderastrea radians

Porites astreoides

Porites furcata

Favia fragum

Diploria labyrinthiformis

Pseudodiploria strigosa

Pseudodiploria clivosa

Manicina areolata

Colpophyllia natans

Orbicella annularis

Orbicella franksi

Orbicella faveolata

Montastraea cavernosa
Solenastrea bournoni
Meandrina meandrites
Meandrina jacksoni
Dichocoenia stokesii
Dendrogyra cylindrus
Mussa angulosa
Scolymia lacera
Scolymia cubensis
Isophyllia rigida
Isophyllia sinuosa
Mycetophyllia lamarckiana
Mycetophyllia aliciae
Mycetophyllia ferox
Eusmilia fastigiata
Tubastraea aurea

Appendix B

Table B-1. Coral reef monitoring sites of the NPS South Florida/Caribbean Inventory & Monitoring Network (SFCN) and the U.S. Virgin Islands Territorial Coral Reef Monitoring Program (TCRMP). From Ogarcuk et al. 2022.

Program	Island	Site	Latitude	Longitude	Depth (m)
NPS-SFCN	St. Croix	Buck Mesophotic 1	17.80542	-64.59779	31
NPS-SFCN	St. Croix	Buck Mesophotic 2	17.80480	-64.59623	34
NPS-SFCN	St. Croix	Buck Mesophotic 3	17.80632	-64.59853	33
NPS-SFCN	St. Croix	Buck Mesophotic 4	17.80669	-64.60041	33
NPS-SFCN	St. Croix	South Fore Reef	17.78456	-64.60960	13
NPS-SFCN	St. Croix	West Spur and Groove	17.79962	-64.63603	9
TCRMP	St. Croix	Buck Island-St. Croix	17.78500	-64.60917	15
TCRMP	St. Croix	Buck Island-MCE	17.80659	-64.59935	33

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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