The Impact of Hurricane Irma and Hurricane Maria on Coral Habitats of the US Virgin Islands

The United States Virgin Islands (USVI) was impacted by two category 5 storms in September 2017 (Fig. 2). Hurricane Irma (Sep. 6) passed 32 km N. of St. Thomas and brushed St. John, with sustained wind speeds of 150 kt (278 km h-1). Wave heights at Oceanographic Buoy 41058 northwest of St. Thomas reached 12 m before sensor failure. Hurricane Maria (Sep. 20) passed 20 km SE of St. Croix, with sustained wind speeds of 140 kt (259 km hr-1). Wave heights at Oceanographic Buoy 41052 south of St. John reached wave heights of 7.9 m. Personal losses and infrastructure damage to the USVI was severe. This included heavy damage to the marine research infrastructure at the University of the Virgin Islands, where the TCRMP is coordinated (Fig. 3). Hurricane damage also extended below the water and affected reef-forming corals at TCRMP sites (Fig. 3). Other research on the coast of St. John found that previous degradation of coral reefs led to a minimal response to the storms, although there was an increase in fleshy macroalgae (Edmunds 2019). Across TCRMP sites assessed in early 2018, coral damage was measured as corals fragmented or loose on the substrate. The prevalence of this type of coral damage increased significantly following the storms (Fig. 4). There was high variability in damage across sites that likely reflected different surface wave conditions and site depths, which influence the seafloor orbital velocities experienced at a site.

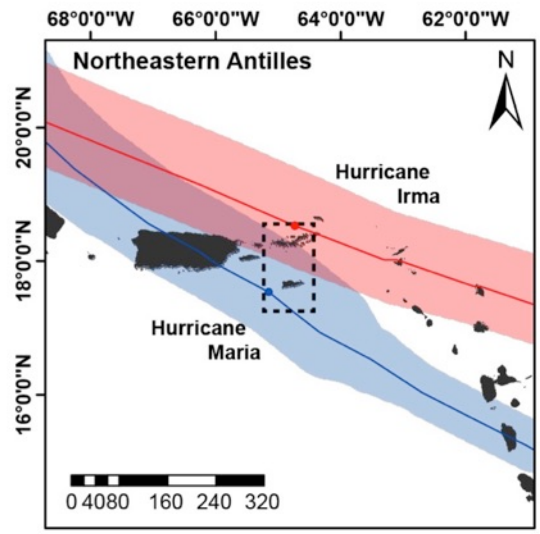

Figure 2. Hurricane strength wind swaths and storm centers for Sep. 2017 (Data from NOAA NHC, 2019).

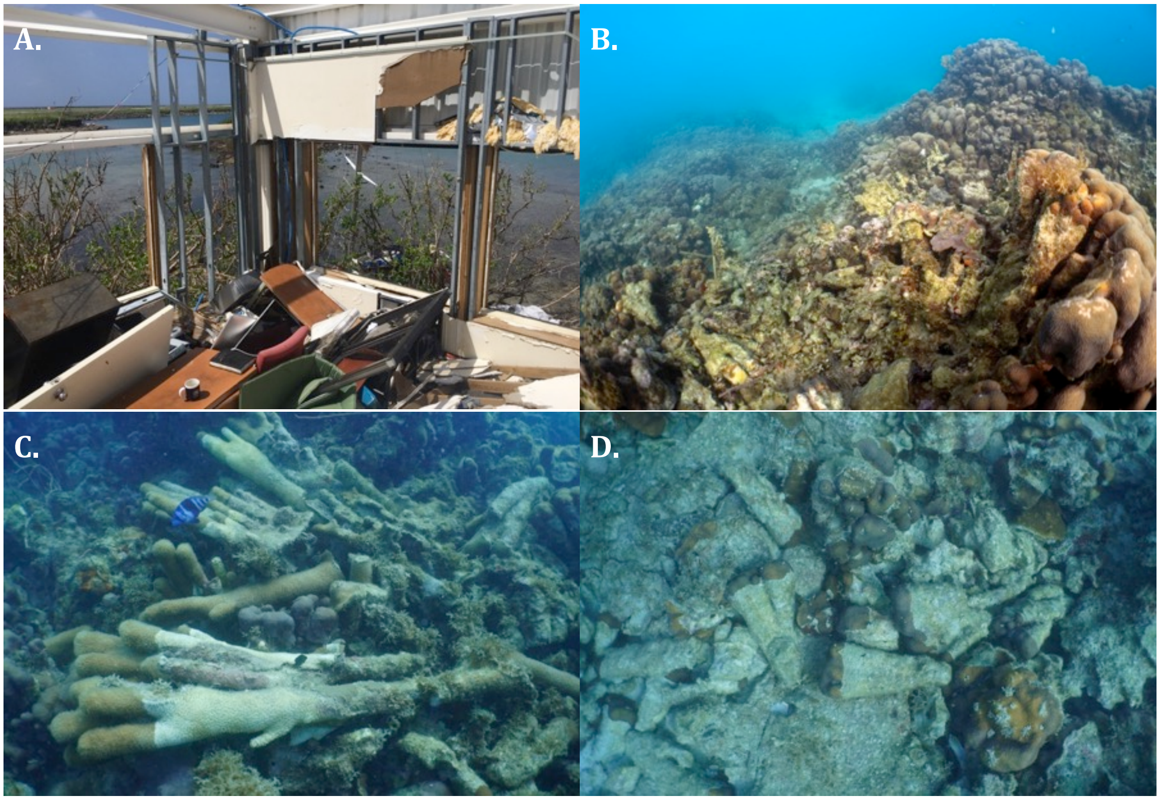

Figure 3. The damaged research infrastructure and coral reefs of the US Virgin Islands following Hurricanes Irma and Maria in September 2017.
(A) The office of TCRMP research coordinator Tyler Smith at the UVI MacLean Marine Science Center, St. Thomas following the storms (Oct. 3, 2017; credit: T. Smith). (B) – (D) Examples of coral reef damage in Brewers Bay, St. Thomas. (B) A destroyed section of *Orbicella annularis* fringing reef (Nov. 28, 2017). (C) A broken colony of *Dendrogyra cylindrus*. (D) A fragmented colony of *O. annularis* (Dec. 13, 2017; credits: R Ennis).

Using the Simulation of Wave Nearshore Model (Booij et al. 1999) operationalized for the US Caribbean (Canals et al. 2012), surface wave conditions over Hurricanes Irma and Maria were calculated (Fig. 5). Bathymetry (depth) and the surface wave conditions were used to calculate seafloor orbital velocities using linear wave theory (as in Smith et al. 2016b; Fig 5). Seafloor velocities reached as high as 6 m s^{-1} in some locations.

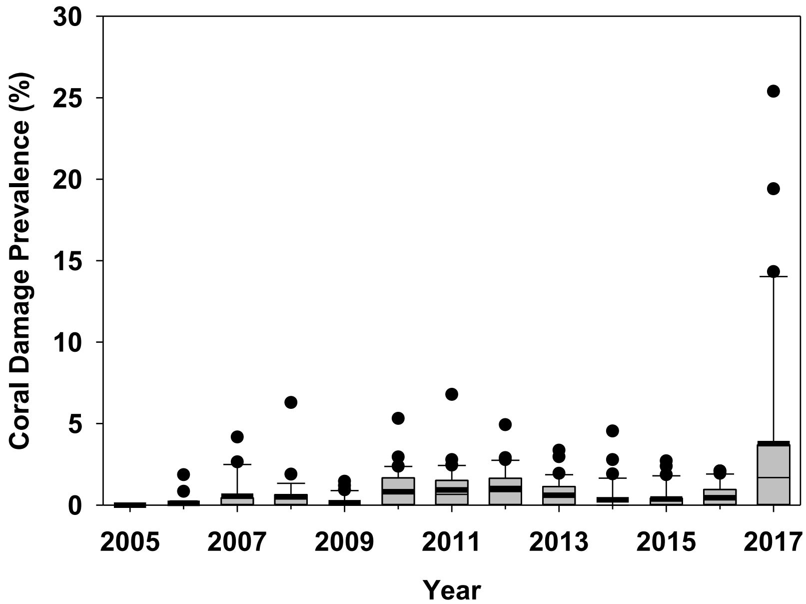

Figure 4. The prevalence of coral damage at individual TCRMP sites. Elements are 90th percentile (whiskers), 75th percentile (box top/bottom), mean (thick black line), median (thin black line), outliers (points). The prevalence of damage was significantly different between years ($p < 0.0001$) and 2017 had a higher prevalence than all other years.

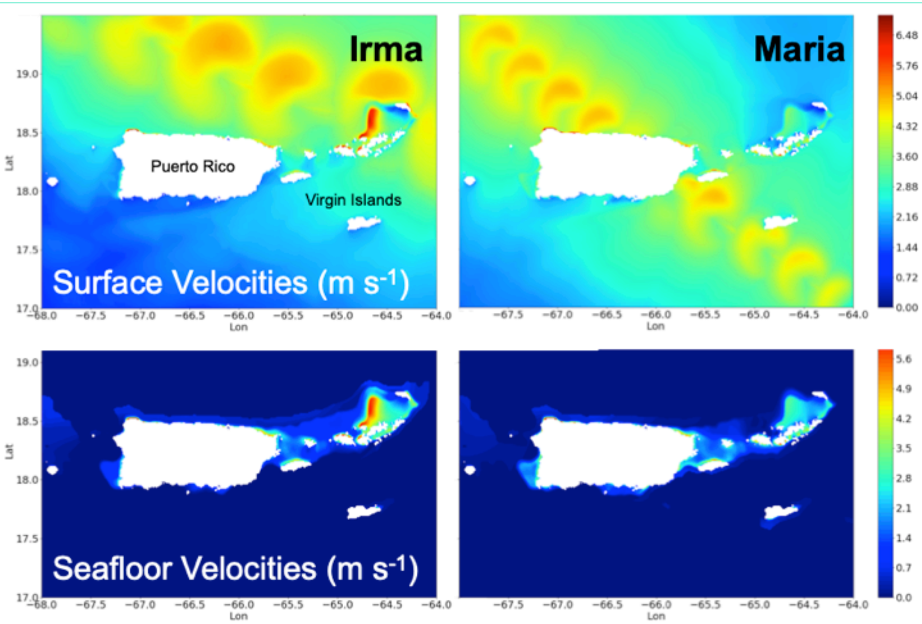

Figure 5. Modeled surface (top) and seafloor (bottom) orbital velocities over Hurricane Irma (left) and Hurricane Maria (right).

In situ assessments of coral damage at TCRMP sites were compared with modeled benthic orbital velocities and an approximate threshold of 2 m s^{-1} was identified as a velocity above which coral damage started to increase. The threshold value was used to extrapolate the area of affected coral habitat affected across the USVI (Fig. 6).

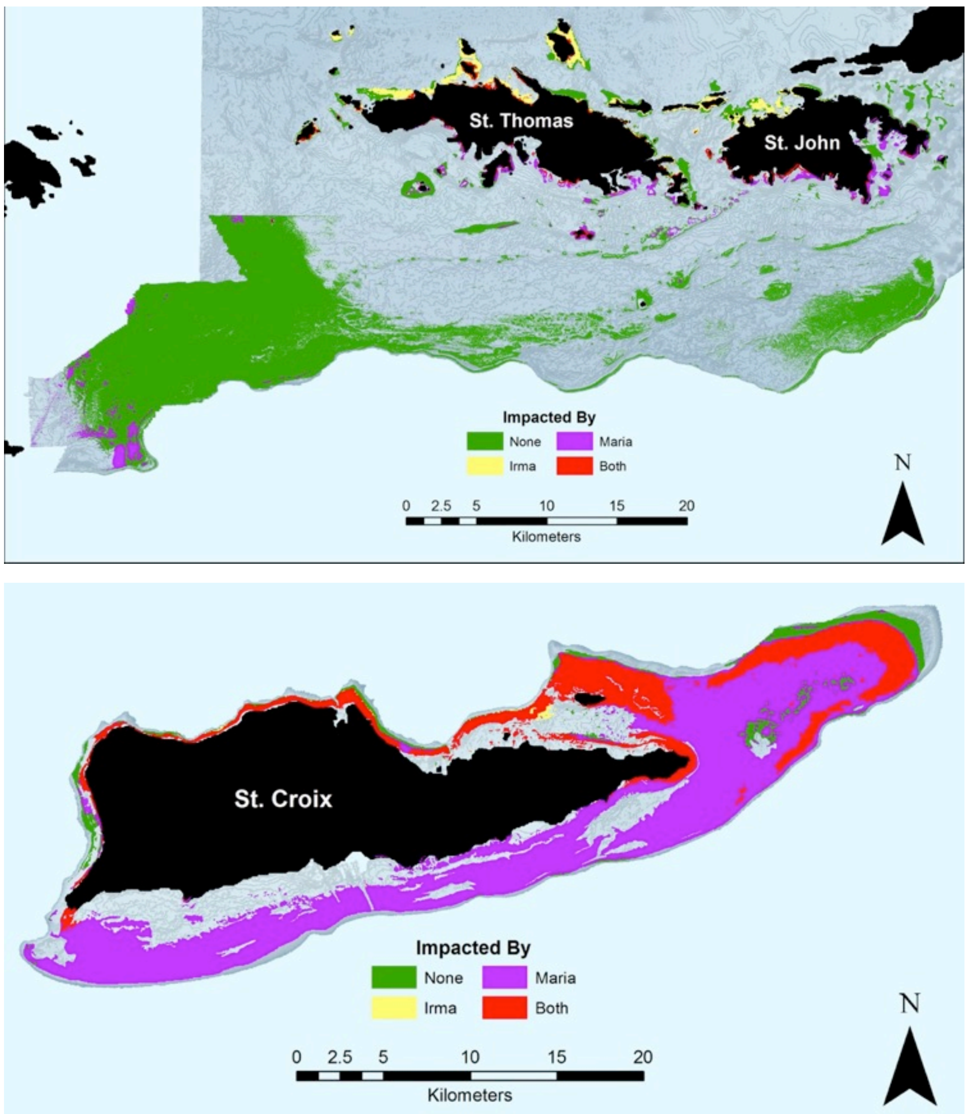

Figure 6. Coral reef habitats potentially damaged by storms (>2 m s^{-1} seafloor velocity).

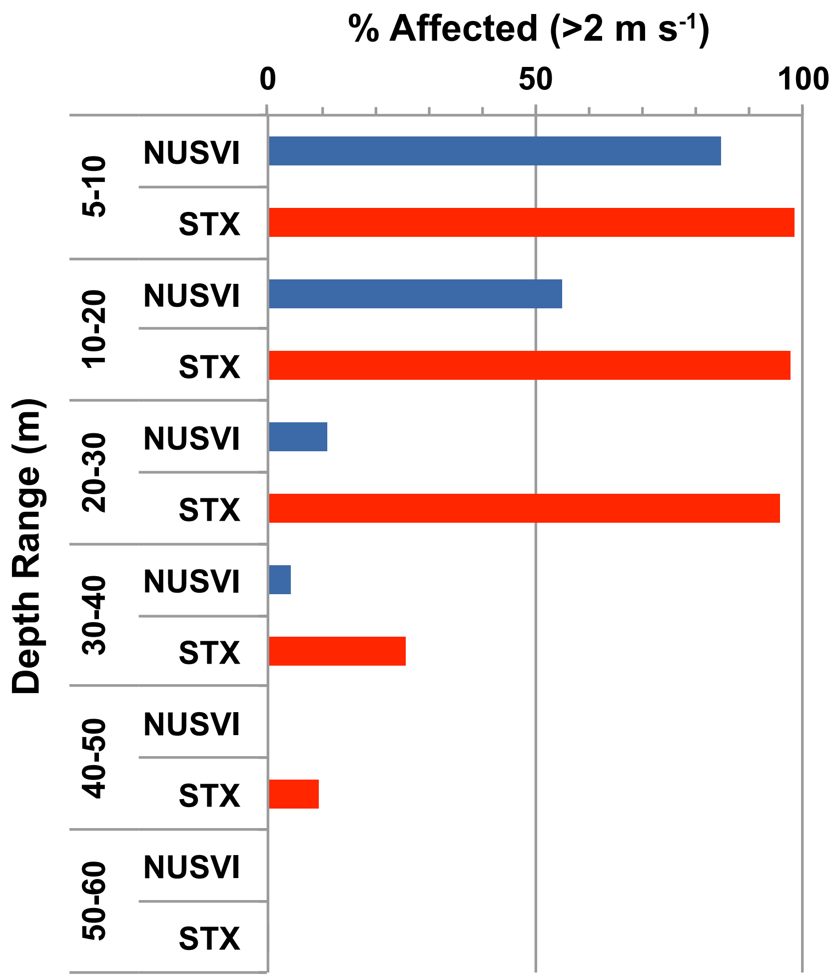

Figure 7. Proportions of coral reef habitat potentially damaged by storms (seafloor velocity > 2 m s^{-1}) by depth category and island group (NUSVI = northern USVI – St. John and St. Thomas; STX = St. Croix).

The proportion of potentially impacted coral reef habitats varied between the northern USVI and St. Croix. In the northern USVI there was a high proportion of damage to reefs (85%) in shallow water (5 – 10 meters depth), but this declined rapidly with depth, with about 10% damage below 20 m. In St. Croix there was high predicted damage (> 90%) to corals in depths shallower than 30 m.

RESEARCH HIGHLIGHTS

Modeled seafloor velocities can be a good predictor of coral damage and can be used to extrapolate damage to the scale of the seascape. Spatial distribution of damage can help to guide restoration activities, evaluate the economic costs of storms to coral reef natural resources, and inform ecological studies of the health and distribution of corals. Future activities will use higher resolution, higher frequency wave model runs and more refined estimates of coral damage by coral species to refine the spatial predications. This analysis is one of the first to extrapolate storm damage across a seascape and was largely made possible by the synoptic research conducted by the TCRMP.

Update: Invasion of the Indo-Pacific Red Lionfish

The first Indo-Pacific lionfish reported in USVI waters was found in 2009 on the west end of St. Croix under the Frederiksted pier. The species (Fig. 8) had been rapidly spreading throughout the Caribbean from the believed introduction point of Florida, and was already common in the Bahamas, Jamaica, and Hispanola. Several more of the fish were seen over the next few weeks; however, it was not until early 2010 that the first lionfish was reported in St. Thomas. By early 2011, divers and fishermen from around the territory were finding lionfish commonly, and although a concerted effort was made to eradicate the fish, the population continued to increase. Today, the invasive species is quite prevalent throughout the territory and Caribbean region; however, both divers and fishermen say they are seeing fewer fish than 2011-2013, and that they are smaller in general.

Figure 8. Indo-Pacific red lionfish (*Pterois volitans*) on Seahorse Cottage Shoal, 2017; depth 22m.

There continues to be an effort to control the lionfish through fishing. A growing market for the species as a food fish exists on all three islands, it is selling in an increasing number of restaurants, and fillets fetch a high market price. Ciguatoxin that causes Ciguatera Fish Poisoning is present in in about 12% of fishes from toxic areas, such as the south coast of St. Thomas and St. John (Robertson et al. 2013); however, poisonings from the fish have not been reported in the Caribbean, suggesting the threat to human health is not large.

The lionfish invasion is particularly important because of the ability of lionfish to consume large quantities of native reef fish. Lionfish are gape-limited stalking predators capable of consuming prey that are almost half their total length, yet lionfish are themselves largely protected from predation by venomous fin spines (Morris and Whitfield 2009). Lionfish have rapidly spread over more than 4,000,000 km^2 of marine habitat across the Western Atlantic, Caribbean and Gulf of Mexico, and are now undergoing exponential increases in abundance at many locations (Betancur-R et al. 2011; REEF 2012). Invasive lionfish occupy a range of habitat types and depths, where they consume an array of native fishes and crustaceans at very high rates, including those species that are important as food for commercial fish species, or as foragers of algae that compete with and limit coral growth (Schofield 2009; Green et al. 2011). There is growing concern that predation by lionfish will nullify efforts to protect vulnerable fish populations from anthropogenic threats in the region.

Lionfish were first observed in the TCRMP data on roving dives at two sites in 2010, Lang Bank and Kings Corner, both located off St. Croix. By 2011, seven sites out of 32 held lionfish, including four sites in the northern USVI. Both numbers of lionfish and the number of sites they were observed on increased over the years from 2012 through 2015; only slightly in St. Croix but dramatically in the northern USVI. In 2015, 112 lionfish were counted on transects at ten sites off the northern USVI, and 15 at seven sites off St. Croix (Fig. 9). In the latest year of sampling (2017/18) lionfish encounters were lower on both the northern USVI sites and the St. Croix sites than in any year since 2012, suggesting that predation is occurring, and a population equilibrium had been reached. A caveat however in the northern USVI data, is that Ginsburg's Fringe, a mesophotic site with generally high densities of lionfish, was not sampled in 2017. In St. Croix the number of lionfish observed on transects dropped from 21 at seven sites in 2016 to 6 at four sites in 2018.

Mesophotic sites off St. Thomas continue to have the highest abundances of lionfish, and two of these sites (Hind Bank FSA and Ginsburgs Fringe) had large increases in 2015.

The Grammanik Bank had a notable decrease in lionfish in 2015, 2016, and 2017, possibly due predation by the spawning aggregations of large piscivorous fish that occur on the reef. Lionfish across the territory have ranged in estimated size from less than 5cm to 40cm TL, but the majority of fish now are between 11 and 20cm TL (51% in 2017/2018). It appears that the average size has decreased since 2014. In 2014, the majority of fish (40%) were estimated to be between 20 and 30cm TL and 3% were over 30cm TL. Seventeen lionfish (13%) were recorded over 30cm TL in 2015. In 2016 and 2017, there were no lionfish reported to be this large. In 2016, 44% of lionfish were estimated to be between 21 and 30cm TL, while in 2017/18 the percentage in this size range dropped to 38%.

Little data has been collected and analyzed regarding preferential habitat for lionfish in the western Atlantic; however, based on the TCRMP data and many other dives conducted across the USVI shelves by the authors, it appears that the species utilizes a variety of habitats and uses any available structure within the area. They are common on hard bottom areas (generally associated with the largest rock /coral around) as well as coral reefs and are found to be particularly abundant on submerged man-made structures. They may be somewhat limited from turbulent or high current environments by their large fins. It is unknown if their high densities on mesophotic reefs represent a preference for deepwater habitats, or a reduced fishing pressure. The Grammanik Bank and Hind Bank are marine reserves where bottom fishing is prohibited and large snappers, groupers, and sharks are observed regularly. Predation by large piscivores could partially control the recruitment or growth of lionfish at the Grammanik Bank, but the data is equivocal. There is current research being conducted by the Center for Marine and Environmental Studies to help determine if the reduced fishing pressure of these mesophotic reserves is affecting lionfish populations and fish community structure. The study is conducting fish counts at random points within the MCD and the Virgin Islands Coral Reef National Monument as well as outside the reserves in similar habitats, with an emphasis on detection of lionfish densities and size frequencies. This study should help elucidate whether marine reserves are protecting lionfish populations, or if they are allowing potential lionfish predators to exist at high enough densities to control the invasive species.

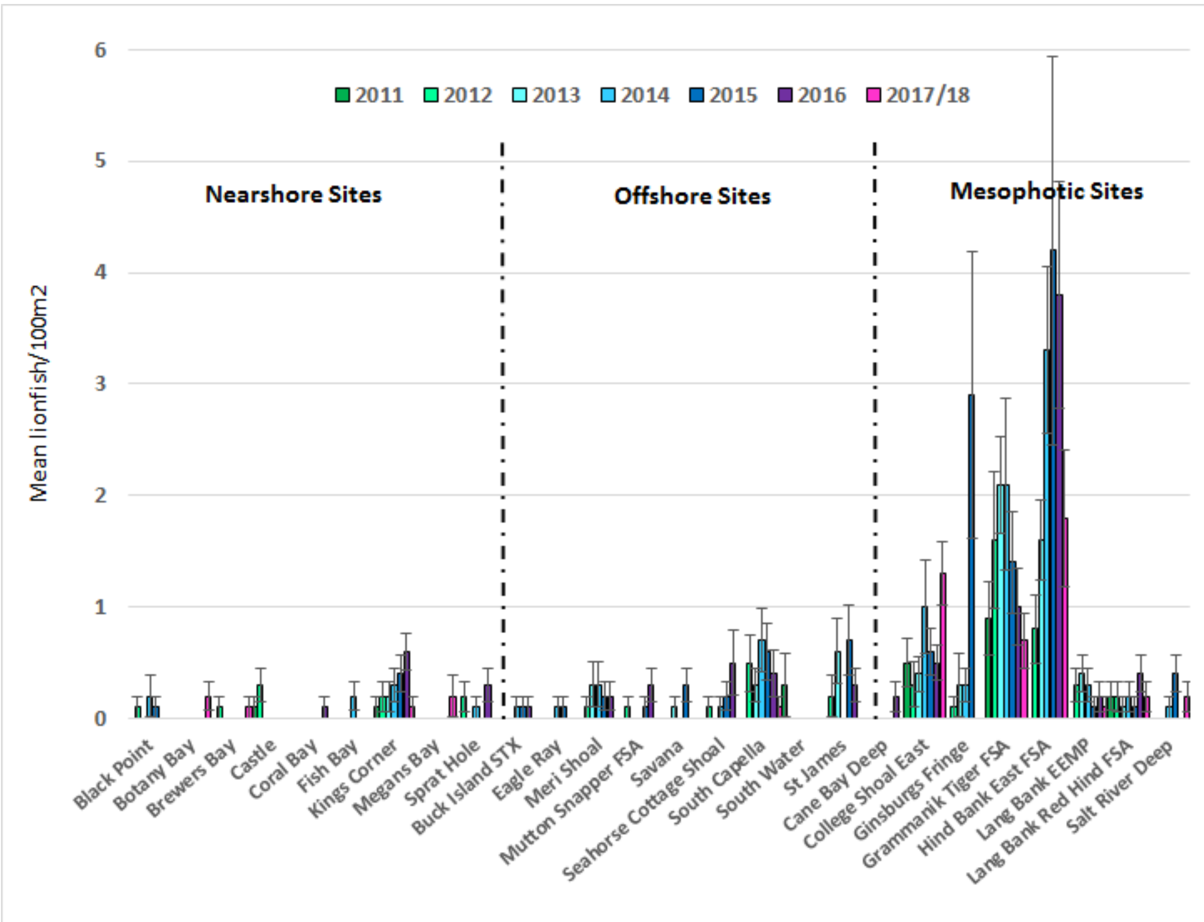

Figure 9. The abundance (±SEM) of red lionfish on TCRMP transects from 2011 to 2018.

Improved Signs for the Threatened Nassau Grouper

The once prolific Nassau grouper (*Epinephelus striatus*; Fig. 10), is today commercially extinct over much of its range. Historically this species has been dominant both culturally and economically in Caribbean fisheries. Although protected in federal waters of the United States since the 1990's, the Nassau is still considered to be one of the most threatened groupers worldwide, is listed as endangered on the IUCN Red List, and is a candidate for the US Endangered Species Act. The fish was at one time the most common grouper on reefs of the US Virgin Islands. The Nassau fishery collapsed in the 1980's, shortly after a large Nassau grouper spawning aggregation site located south of St. Thomas was extirpated by overfishing in the 1980's. As a likely consequence, the fishery collapsed shortly afterwards. The territorial government of the USVI protected the Nassau grouper from all fishing in 2006. The Caribbean Fisheries Management Council closed the south St. Thomas Grammanik Bank yellowfin grouper spawning aggregation site in 2005, inadvertently protecting a small spawning aggregation of Nassau grouper. These fish may have relocated from the extirpated historic Nassau aggregation located on a few kilometers to the west.

Figure 10. Nassau grouper on the Grammanik Bank, St. Thomas during spawning season.

There is evidence that these management measures may be positively affecting both Nassau and yellowfin grouper populations in the US Virgin Islands. Over the past three years there have been reports by divers of the both groupers being seen commonly on reefs around the territory, and fishermen continue to report regular occurrences of Nassau grouper in their fish traps. In TCRMP survey data from 2015, 2016, and 2017, substantially more Nassau grouper were observed than in earlier years, and they were observed on more sites, including nearshore sites (Figure 11). Additionally, juvenille young-of-the-year Nassau were commonly seen in nearshore areas of St. Thomas and St. John in 2006, 2014, 2015, and 2016 (R. Nemeth, unpub data).

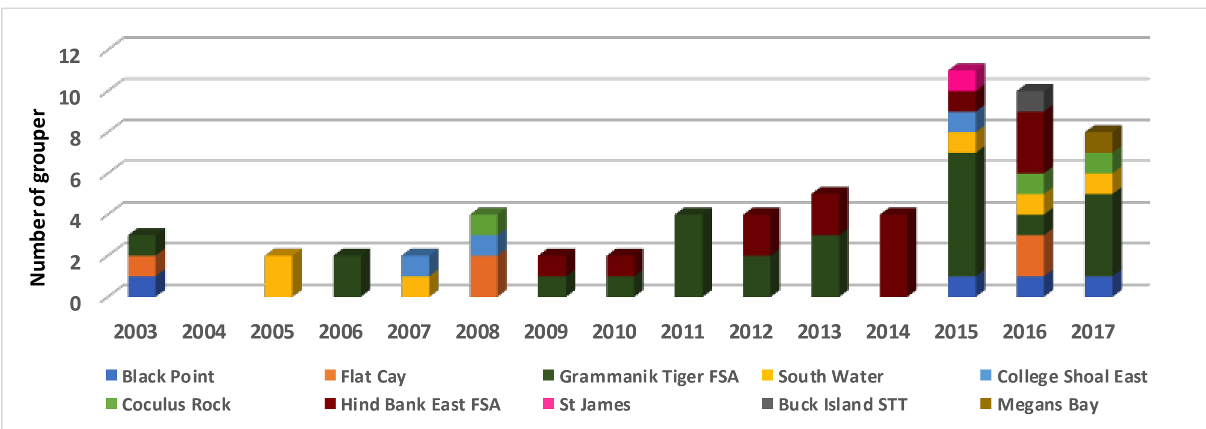

Figure 11. Nassau grouper observed across all northern USVI sites on belt transects, conducted annually from 2003-2017.

Nassau grouper in the northern USVI may be recovering in part because of a growing spawning aggregation at the Grammanik Bank. The Grammanik Bank, located approximately 4 km east of the historic Nassau grouper spawning site, is a multi-species aggregation area hosting spawning of several species of fish including yellowfin grouper (*Mycteroperca venenosa*), tiger grouper (*Mycteroperca tigris*), dog snapper (*Lutjanus* *jocu*), cubera snapper (*Lutjanus cyanopterus*), and Bermuda chub (*Kyphosis sectatrix*). Nassau grouper also aggregate on the site and spawn there shortly after dark in the months of January through April. The bank is closed seasonally to fishing from February 1 to April 31 and is closed to bottom tending gear year-round, thus providing partial protection for the aggregating Nassau grouper.

Nassau may have shifted to spawning at the Grammanik bank after their nearby historic aggregation was fished down. The Nassau grouper spawning aggregation site at the Grammanik Bank is of disputed age, and some local fishermen claim that the bank is not a historical location for Nassau spawning, whereas others suggest that a small number of Nassau have always spawned in that location (anon). The historic Nassau grouper aggregation site is 4 km to the west, but no fish have been observed to aggregate in this area after over a decade of observation (R. Nemeth, unpub. obs.). One hypothesis is that the Nassau grouper now utilizing the Grammanik Bank are a small sub-population of that original spawning group from the historic bank.

The Nassau grouper have increased in number on the Grammanik Bank during the week after the full moon of January through April since 2002 (Figure 12). In January, February, March, and April of 2018, between 200 and 450 fish were observed on single dives on the western end of the bank. This represents an over 200% increase from the number of fish observed during the early and mid-2000's.

The early and tentative recovery of the Nassau grouper in the northern USVI is indeed positive, but is far from complete. While fisheries closures have helped, targeted conservation actions may also be important for locking in and building on these gains for this threatened fish. Nassau grouper caught incidentally from deeper water (>20m deep) usually need to have their swim bladders deflated to allow them to submerge and survive when released. Thus, avoiding incidental capture, even with release, is important. In the northern USVI, a more complete fishing closure of the Grammanik Bank that encompasses the full seasonal cycle of Nassau grouper spawning activities (December to May) would ensure minimal incidental capture. Additionally, creating a migratory corridor between the nearby Hind Bank Marine Conservation District would also limit fisheries impacts, as this no-take area appears to support a relative high adult population of Nassau (Fig. 11). In St. Croix, a struggling small population of Nassau grouper is present. Closing an area at the tip of the Lang Bank where there is a small aggregation of about 10 individuals (Kadison, unpub. observations) would help to ensure that they are not taken incidentally or poached. Throughout the USVI, more education on Nassau grouper and their protected status would be very helpful. The early life cycle of Nassau grouper typically involves settling in shallow, nearshore structures surrounded by seagrass. These juveniles are vulnerable to recreation line fishing and spearfishing before they migrate to offshore locations. Education and citizen science opportunities to get the community behind the recovery of Nassau would greatly enhance the protections already in place by encouraging compliance. Nowhere else in US waters is the chance to protect and recover the Nassau as strong as in the USVI and the territory could lead a huge conservation success story for ailing fish populations.

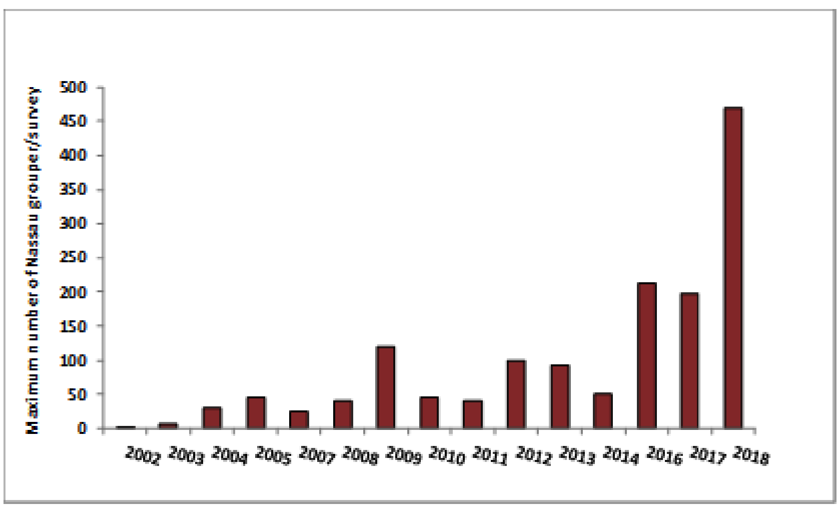

Figure 12. Maximum number of Nassau grouper observed on a single point count during the spawning season (January- April) on the Grammanik Bank from 2002 through 2018.

Emergence of the Invasive Red Algae *Ramicrusta* spp.

Many nearshore coral reefs throughout the Caribbean region have been experiencing increases in macroalgae cover. This increase in macroalgae has been linked with negative impacts to living stony corals through abrasion, shading, and chemical release. While the majority of macroalgae cover at TCRMP locations is dominated by *Dictyota* spp. and *Lobophora* spp., several have experienced relatively rapid increases in an encrusting red algae *Ramicrusta* spp (hereafter *Ramicrusta*) (Fig. 13). The genus *Ramicrusta* is present in multiple locations in the Pacific Ocean (Dixon and Saunders 2013), but was not reported in the Caribbean until 2009 at Discovery Bay, Jamaica (Pueschel and Saunders 2009). The genus has since been documented in Bonaire (Eckrich and Engel 2013) and Puerto Rico (Ballantine David et al. 2016). At present, three *Ramicrusta* species have been identified: *Ramicrusta textilis* (Pueschel and Saunders 2009) in Jamaica and Puerto Rico, *Ramicrusta bonairensis* (Ballantine, Ruiz, Lozada-Troche & Norris 2016) in Bonaire, and *Ramicrusta monensis* (Ballantine, Ruiz, Lozada-Troche & Norris 2016) in Puerto Rico. Morphological and genetic identification of specimens from the northern USVI has suggested the presence of *R. textilis* (D. Ballantine from St. Thomas samples; P. Edmunds from St. John samples). There is very little known about the biology of *Ramicrusta* and the environmental factors that determine its presence.

Ramicrusta ranges in color from red to brown and primarily forms thin crusts, though frondose edges may be present (Fig. 13). *Ramicrusta* appears to be a strong competitor relative to most other benthic organisms, rapidly colonizing and expanding on open substrate. It has been observed overgrowing live coral tissue, sponges, gorgonians, zoanthids, and other kinds of macroalgae. Interactions with live coral colonies appear to be indiscriminate, and often cause bleaching and partial, if not complete, colony mortality. Successful recruitment of coral larvae or other benthic organisms has not been recorded on *Ramicrusta* substrate with the exceptions of occasional short fronds of

Dictyota spp. (Ennis, pers. obs. 8 Dec 2016). This combination of factors has the potential to be particularly devastating to reef ecosystems that are already under stress from other environmental conditions.

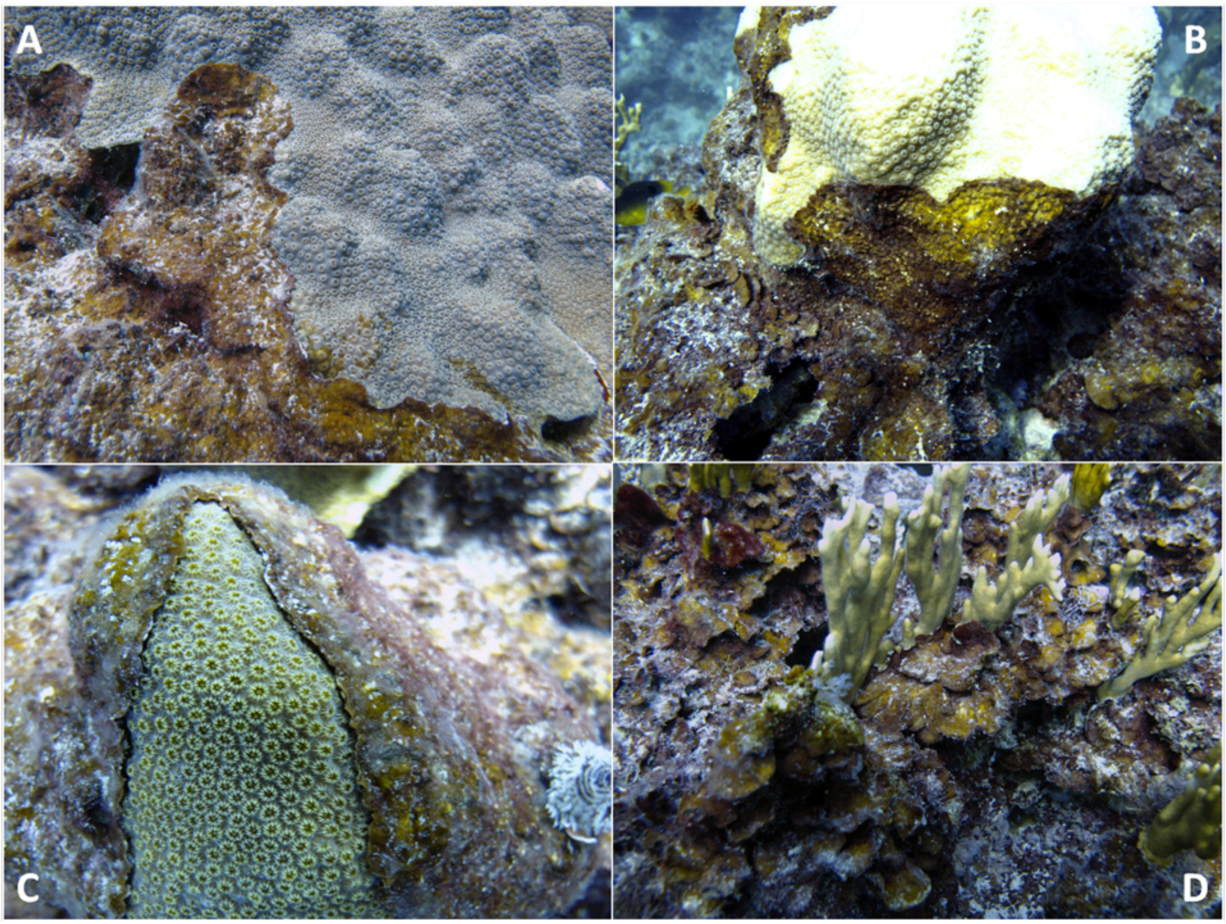

Figure 13. Representative photos of *Ramicrusta* spp. overgrowing *Orbicella faveolata* (A), *Orbicella annularis* (B), *Orbicella annularis* (C), and *Millepora alcicornis* (D) at the TCRMP location Savana.

A preliminary investigation into *Ramicrusta* presence, abundance, and impacts in the TCRMP benthic cover dataset has revealed its presence at nearly 60% of TCRMP locations in 2016, but abundance seems to be variable (Fig. 14). While the majority of locations had less than 25% presence of Ramicrusta in TCRMP non-overlapping video images, College Shoal East and Savana had prevalence of *Ramicrusta* in benthic cover clips of 87.3% and 98.25%, respectively.

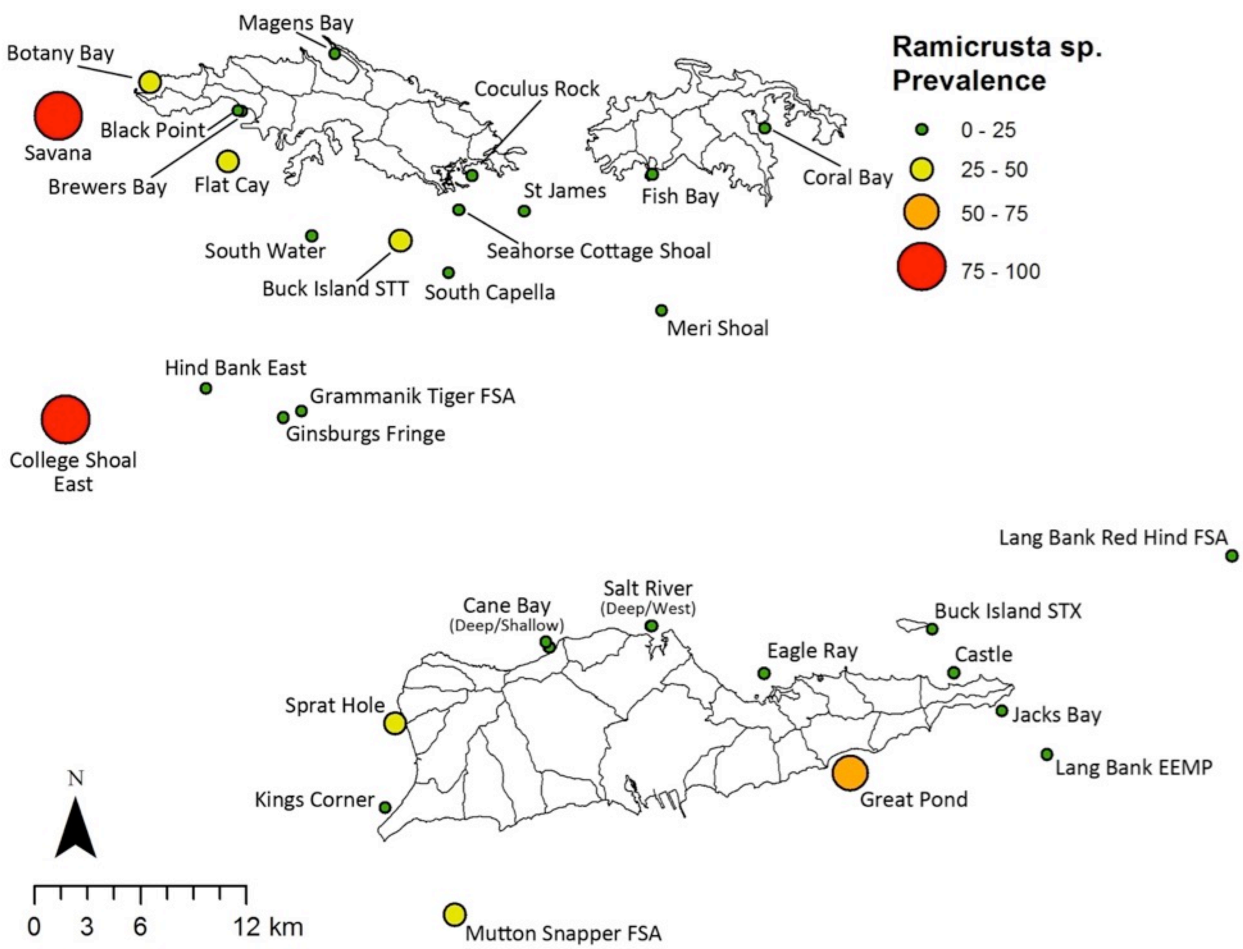

Figure 14. Abundance of *Ramicrusta* sp. presence in non-overlapping video clips at TCRMP locations in 2016.

Further analysis of benthic cover at Savana, which is an offshore site with little apparent human impacts, has shown that *Ramicrusta* has been present at low cover since the location's first sampling in 2003 (Fig. 9). *Ramicrusta* cover at Savana was less than 10%

until the 2005 bleaching event, after which cover increased nearly five-fold by 2008, peaked at ~60% of the total benthic cover in 2016, and decreased after storms in 2017-2018 (Fig. 15). The increase in *Ramicrusta* cover after the 2005 bleaching suggests a tipping point was reached when coral cover declined from 20% to 10%. *Ramicrusta* has increased linearly, depressing all other benthic categories, until 2017. Corals are in high contact with the algae and are being overgrown on the margins. Ramicrusta is likely driving the decline in coral cover since 2010.

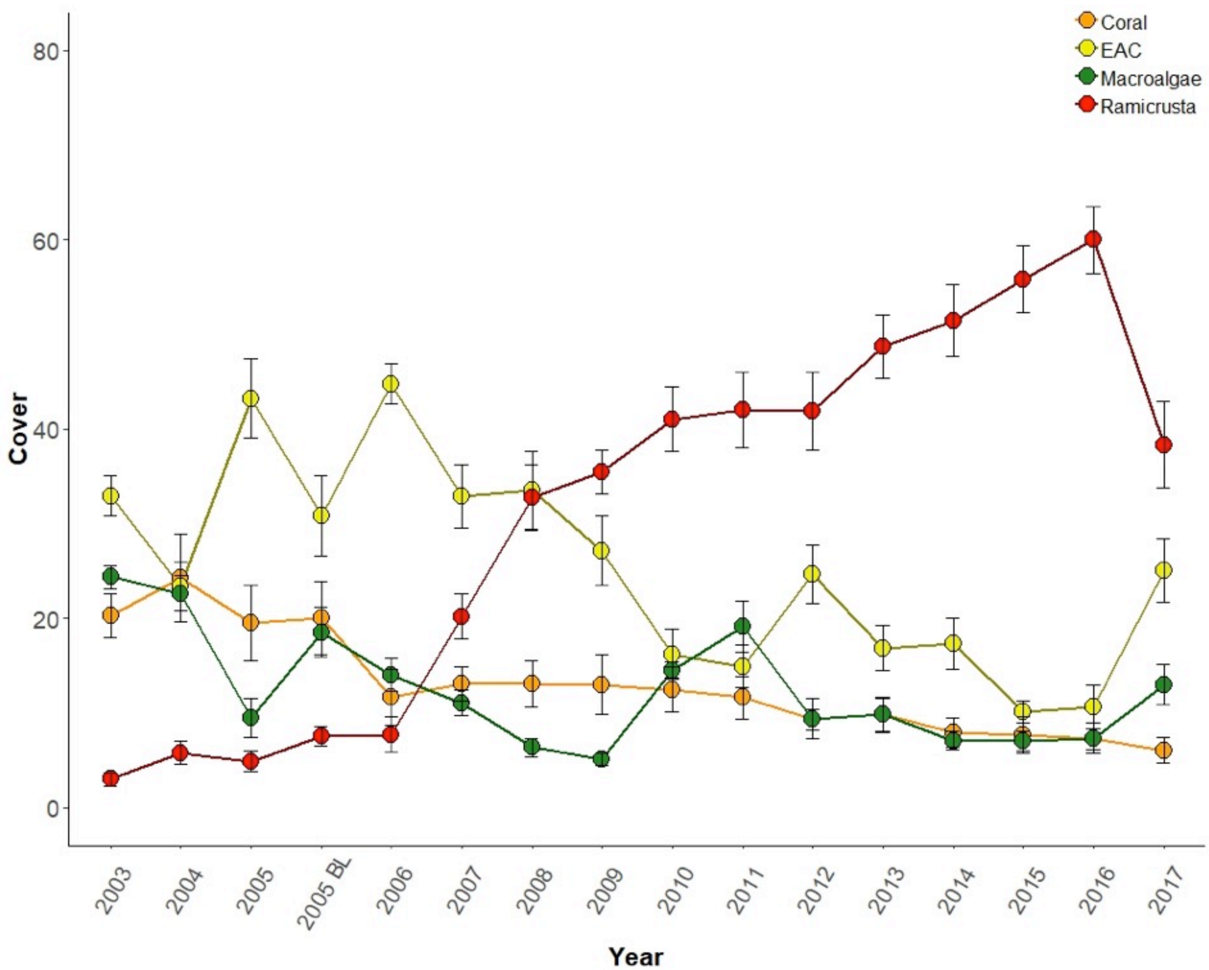

Figure 15. Benthic cover (±SEM) of *Ramicrusta* sp., coral, epilithic algae community, and fleshy macroalgae at Savana from 2003-2016.

Although the change in *Ramicrusta* benthic cover at Savana is an extreme case relative to all other TCRMP locations, it demonstrates the need for continued monitoring of changes in the cover of this alga. This is especially relevant given the potential devastation of overgrowth and the general lack of information regarding the life history of the genus in the Caribbean. Further examination of the long-term TCRMP dataset could provide valuable insight into the factors driving or controlling *Ramicrusta* sp. abundance. Future work by TCRMP and UVI will attempt to experimentally determine the mechanisms of impacts on corals and factors controlling the growth of *Ramicrusta*, such as productivity and impacts of herbivores. It is not clear if *Ramicrusta* was introduced to the Atlantic Ocean or has always been present in low abundance. However, it is clear that *Ramicrusta* is rapidly increasing in abundance at the expense of stony corals.

INTRODUCTION

Introduction

The U.S. Virgin Islands consists of three large islands, St. Thomas, St. John and St. Croix, and numerous smaller islands surrounded by a diverse, tropical marine environment that includes coral reefs, seagrass beds, and mangrove forests (Fig. 16). The islands of St. Thomas and St. John lie on the Puerto Rican Shelf, an extensive shallow water platform that connects them to Puerto Rico to the west and the British Virgin Islands to the east. St. Croix lies on an isolated platform sixty-five kilometers to the south of St. Thomas and St. John and separated by the 4000m deep Anegada Passage and the Virgin Islands Trough. This forms an effective barrier to the migration of adult coral reef fishes and invertebrates. The coral reefs of the Virgin Islands represent a wide range of characteristic coral reef habitats of the Caribbean, including patch reefs, fringing reefs, barrier reefs, shelf reefs, and extensive bank and slope mesophotic coral reef ecosystems.

The economy of the US Virgin Islands is reliant to a large extent on maintenance of vibrant marine ecosystems. Tourism drives the economy of the Virgin Islands, famous for white sand beaches that give way to clean, clear marine waters. The diverse marine life of the coral reefs and other habitats attracts thousands of skin and scuba divers each year. Sport fishing on charter boats and private vessels also makes an important contribution to the economy. In addition, the coral reefs and other habitats in the Virgin Islands are essential to the lives of hundreds of thousands of species including economically important queen conch, whelk, spiny lobster, snapper, and grouper. Over three hundred full-time or part-time commercial fishermen work in territorial and federal waters surrounding all three islands (Tobias 1997). In tough economic times and after natural disasters, fishing is an important means of supplemental income or extra protein for many people.

Over the last few decades, major hurricanes, coral disease outbreaks, mass coral reef bleaching, and invasive species introductions have caused extensive coral mortality to the coral reefs surrounding the Virgin Islands (Gladfelter 1982; Edmunds and Witman 1991; Rogers et al. 1991; Rothenberger et al. 2008; Woody et al. 2008; Miller et al. 2009; Smith et al. 2013b). Recovery from these disturbances is hindered by a multitude of human impacts that affect coral reefs, such as overfishing of ecologically important species, physical damage to reef structure, and pollution (Hatcher 1984; Pastorok and Bilyard 1985; Rogers and Garrison 2001; Mumby 2006; Mumby et al. 2006; Mumby and Harborne 2010). Moreover, rapid development of steep island slopes has dramatically increased soil erosion and sedimentation into nearshore waters (Brooks et al. 2007; Gray et al. 2008; Smith et al. 2008), particularly below unpaved road surfaces (Anderson and Macdonald 1998; Ramos-Scharrón and MacDonald 2007a). Chronic sedimentation affects the abundance and diversity of corals and other reef organisms, increases coral stress and susceptibility to diseases and bleaching, and reduces the ability of corals and other reef organisms to recover and regenerate after natural disturbances such as hurricanes (Acevedo and Morelock 1988; Rogers 1990; Nemeth and Sladeck Nowlis 2001; Fabricius 2005; Sabine et al. 2015; Ennis et al. 2016). The first sightings of the invasive Indo-Pacific lionfish (*Pterois volitans*) occurred in the US Virgin Islands in 2009. This predator has the ability to dramatically alter coral reef fish community structure (Cote and Maljkovic 2010) and these alterations may have additional, indirect impacts on benthic communities (Albins and Hixon 2011). In addition, the invasive red algae *Ramicrusta* has increased in abundance at some locations and is killing coral tissue through competitive overgrowth (Eckrich and Engel 2013; Ballantine David et al. 2016).

High thermal stress and coral bleaching events affected the northeastern Caribbean in 2005, 2010, and 2012, but these events had contrasting signatures in the United States Virgin Islands. These events and the species-specific responses of Caribbean corals are summarized in Smith et al. (2013) for shallow corals and Smith et al. (2016) for shallow and mesophotic corals. The year 2005 was the most severe high sea surface temperature (SST) event on record for the northeastern Caribbean (Eakin et al. 2010). In the Virgin

Islands a peak of 10.25 Degree Heating Weeks (DHW) was registered from satellite SST records (NOAA, 2012) and a period of approximately 59 days above the local bleaching threshold of 29.5°C (Aug. 20 – Oct. 18); a level of thermal stress accumulation associated with severe coral bleaching and some mortality. The warm season of 2010 started as warm or warmer than 2005, with the bleaching threshold surpassed for 21 days between August 12 and September 2. In a clear example of ameliorative storm cooling (Manzello et al. 2007), the passing of the storm center of Hurricane Earl on August 30th, approximately 100 km to the northeast of the St. Thomas-St. John, caused a rapid decline in SST's below the bleaching threshold to 29.3°C, and then from October 5 - 8, the passage of Hurricane Otto caused windy and cloudy weather that further reduced SST below 29.1°C. Total DHW accumulated in 2010 began to decrease after the beginning of October, when it had reached 5.1 DHW, a level associated with some bleaching and limited mortality. Recent research developed bleaching threshold temperatures for 24 of 33 TCRMP monitoring sites dominated by star corals of the genus *Orbicella* (Smith et al. 2016a). This research showed that mesophotic reefs bleached in 2005 with shallow reefs and then bleached again during a mesophotic coral reef bleaching event in 2012, when shallow reefs were unaffected. The study concluded that mesophotic reefs of the USVI are unlikely to be long-term climate change refugia because they are not immune to high temperature thermal stress.

Most research around the Virgin Islands has focused on fringing reefs (5 – 30 m depth) located along the shoreline of the three main islands, St. Thomas, St. John, and St. Croix. In contrast, very little information exists for offshore and deeper reef systems, which can be quite extensive. These other reef systems include mid-shelf reefs (5 – 30 m depth) located 2 to 10 km from the shore of the main islands and mesophotic reefs (>30 m depth) located from 0.5 to 15 km offshore along the edge of the insular platform (Armstrong et al. 2002; Herzlieb et al. 2005; Armstrong et al. 2006; Armstrong 2007; Menza et al. 2007; Menza et al. 2008; Nemeth et al. 2008; Smith et al. 2010b; Smith et al.

2016b). Distance from shore may be a factor in the historical degeneration of coral reef systems in the Virgin Islands (Herzlieb et al. 2005; Calnan et al. 2008; Smith et al. 2008; Sabine et al. 2015; Ennis et al. 2016). A systematic approach to investigating these cross-shelf coral reef systems allows us to evaluate the variable impacts and synergistic effects of natural impacts and human-induced stress that influence the decline or recovery of Caribbean coral reef systems. The first two years of this project (2001 and 2002) concentrated on the fringing reefs surrounding St. Croix. In 2003, monitoring continued at St. Croix reefs and began at reef systems distributed across the insular platform surrounding St. Thomas. In 2004, 2005 and 2006 monitoring continued at reefs surrounding both islands, with additional reefs surrounding St. Thomas added in 2004, 2005, and 2011. Mesophotic coral reef monitoring sites were added to St. Croix during the 2008 and 2009 monitoring, as well as an additional monitoring site in the St. Croix East End Marine Park. In 2011, the TCRMP also expanded to include sites established under separate funding that will be continued in the core TCRMP monitoring activities funded by USVI DPNR and NOAA CRCP.

OBJECTIVES FOR MONITORING CORAL REEFS

Effective management is necessary to maintain the resources in the territorial and federal waters of the Virgin Islands in an ecologically and economically sustainable manner. Monitoring programs are essential for successful management because they provide managers with fundamental information with which to make and reinforce decisions. Standards for resource protection can be measured by comparison to baseline data established by monitoring. Monitoring also provides the means to assess the status and trends of ecological resources, allowing managers to determine the effectiveness of current management and to develop effective management plans for the future. The Territorial Coral Reef Monitoring Program monitors the condition of coral reefs throughout the U.S. Virgin Islands and provides key information to better manage these ecosystems. The TCRMP is complimentary to the National Coral Reef Monitoring Program (NCRMP) that started in 2013 and is co-coordinated in the USVI by the University of the Virgin Islands. TCRMP focuses on fixed sites and repeatedly samples the same corals to generate the most in-depth metrics of change over time. NCRMP uses a stratified-random sampling design to spread out samples and gain an understanding of change through time, with predictions that can be applied spatially. NCRMP does not sample reefs below 30m at this point, and therefore misses the dominant habitat in the northern USVI, which is only sampled in the TCRMP.

This report presents monitoring results from 2001-2016 in St. Croix and from 2003-2016 in St. Thomas and St. John. For both islands, temporal changes from year to year in the conditions of the reef communities are assessed.

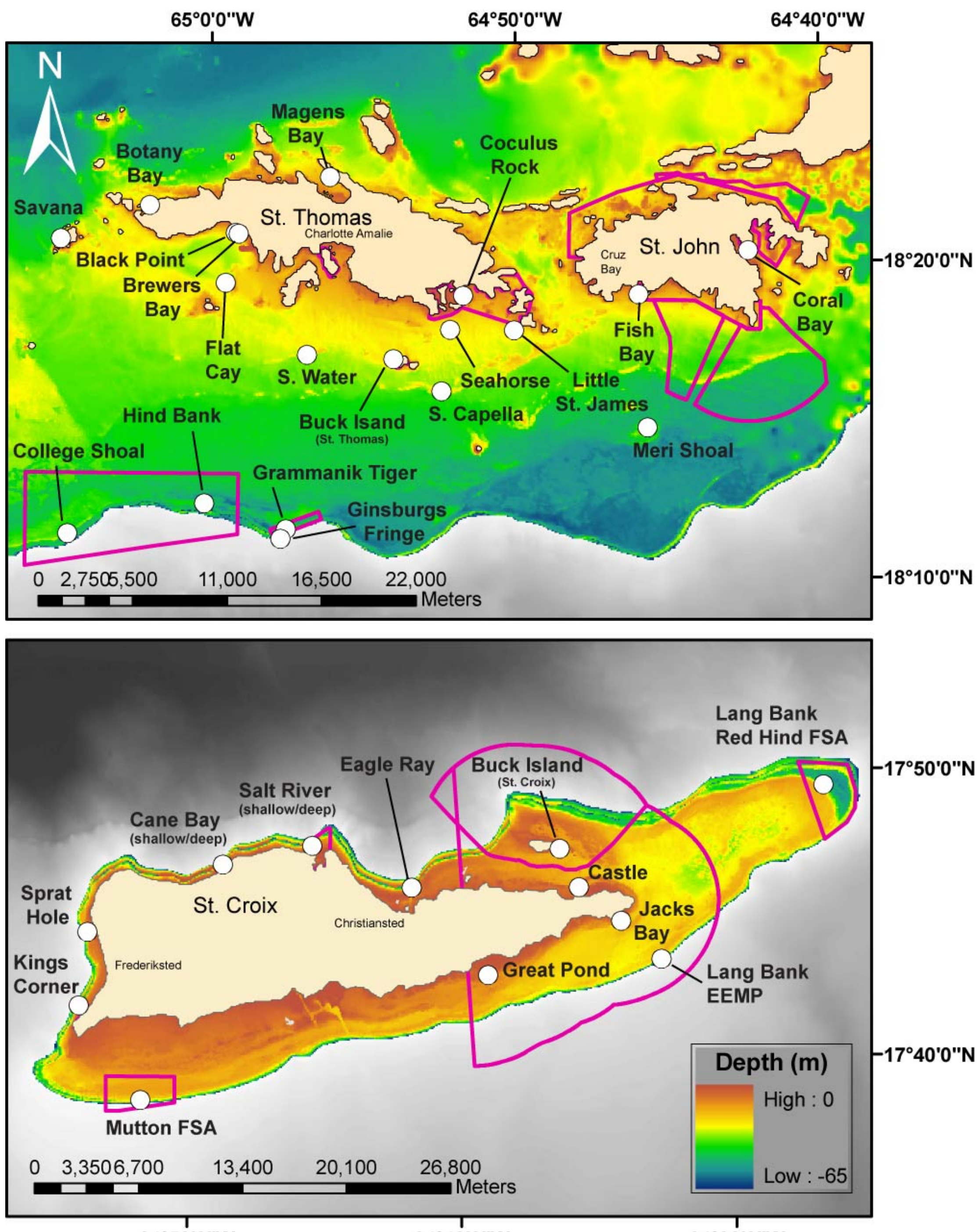

Figure 16. Locations of Territorial Coral Reef Monitoring Sites in the US Virgin Islands. Boundaries indicate federal and territorial marine protected areas.