Acroporid Monitoring & Mapping Program of the United States Virgin Islands 2011-2013

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Cover Photo: A stand of *Acropora palmata* that forms part of the Whitehorse Reef monitoring location. Depth: 3m, Date: March 17, 2013 (Photo Credit: T. Smith)

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Executive Summary

The Atlantic stony coral species staghorn coral (*Acropora cervicornis*) and elkhorn coral (*Acropora palmata*) were once the dominant reef building corals in shallow waters and had vital roles as essential fish and invertebrate habitat. Starting near the end of the 1970's researchers in the United States Virgin Islands (USVI) began to notice precipitous declines in acroporid corals, primarily as the result of white band disease. Thirty years later, populations of acroporids across the Western Atlantic were severely reduced in abundance and ecological function due to a combination of factors. This led to the listing of *A. cervicornis* and *A. palmata* as "threatened" under the United States Endangered Species Act on May 9, 2006. In order to assess the current status of acroporid coral populations and threats to their growth and survival in US governed waters, in 2009 the National Oceanic and Atmospheric Administration (NOAA) and the State of Florida collaborated to initiate a monitoring and mapping program. The State of Florida contracted with the United States Virgin Islands (USVI) Department of Planning and Natural Resources and the Center for Marine and Environmental Studies, University of the Virgin Islands to initiate and carry forward a program to monitor acroporid corals on the shallow shelves of the USVI.

Starting in 2012, permanent demographic monitoring sites for *A. palmata* were established at 10 sites in the northern USVI (St. John, St. Thomas, and numerous lesser islands and cays) and 10 sites around St. Croix. Northern USVI monitoring sites were monitored four times, including initiation of plots, two (2) interim plot assessments, and one final plot assessment and remapping. St. Croix monitoring sites were monitored once upon establishment between 2012 and 2013. In addition, 261 synoptic surveys randomly spread around St. Croix were used to assess the abundance of acroporid corals in waters less than 18 m depth and provide an estimate of the island-wide population size.

Northern USVI demographic sites showed an overall 12% increase in the total amount of live tissue in monitoring plots between March 2012 and October 2013. However, there was variability in the amount of *Acropora palmata* tissue lost or gained, with 30% of sites losing tissue and 70% of sites gaining tissue. Bleaching, feeding by the corallivorous snail *Coralliophila* spp., and disease affected the greatest proportion of colonies across sites. Colonies of *A. palmata* within monitoring plots within the Virgin Islands National Park tended to be the healthiest, suggesting the positive effects of land and marine management for this threatened species.

St. Croix demographic plots were set up in key managed and unmanaged zones. These plots were established but could not be re-monitored during this funding cycle, limiting conclusions that can be drawn. However, there were indications that the St. Croix colonies of *A. palmata* show signs of greater health than the overall northern USVI locations, as indicated by greater proportions of live tissue on colonies and less partial mortality. Given historical data and the potential to quantify the impacts of management on populations, long-term monitoring of plots set up around St. Croix in this program should be a priority.

Synoptic surveys around St. Croix provided the first comprehensive island-wide assessment of acroporid populations. In shallow waters around St. Croix (0-18 m depth), the population of *A. palmata* was estimated at 83,321 (± 23,591 SE) colonies, while the *A. cervicornis* population was estimated to be 21,439 (± 14,409 SE). Populations of *A. cervicornis* may be larger than estimated if deeper depths (19-30 m) were included in future surveys. Populations of both acroporid species were concentrated in northeast St. Croix, particularly along the northeast barrier reef complex that is part of the St. Croix East End Reserve and in the shallow waters around Buck Island that is part of the Buck Island National Park and Buck Island National Monument. Abundant, but possibly vulnerable, populations also are present on the barrier reef north of Christiansted (Long Reef). Assessment of threats to these populations may be important in future work. The majority of western and southern sides of St. Croix had very little or undetected populations of acroporids. This may indicate that this is not suitable habitat, such as along the western shore where shallow bedrock that would support *A. palmata* is limited, or it may indicate prior removal of the populations, a possibility in the waters near heavy industrial activities on the south coast. Determining whether acroporids are being excluded from west and south St. Croix by natural or anthropogenic activities is necessary to determine whether these areas constitute essential habitat and the feasibility of management or restoration to increase populations in these areas.

Northern US Virgin Islands Demographic Monitoring

Summary of Methods

On St. Thomas and St. John, USVI, ten sites with twenty-nine 7 m radius plots (154 m^2) were established for the monitoring of the threatened coral *Acropora palmata* between March and September 2012 (Fig. 1). Experimental design was based on the protocol in Williams et al. (2006). Sites were chosen in areas that met logistical and sampling design criteria, including a depth of at least 1 m to allow room for divers to assess the colony while preventing incidental damage and a density of 11-40 colonies in each of the three plots per site. Sites were established at known or reconnoitered *A. palmata* concentrations, seven fringing reef sites around St. Thomas and offshore cays (STT) and three sites around St. John (STJ) (Fig. 2). Only two plots were established at Green Cay, St. Thomas since colony densities in the area were too low for a third plot. Efforts were made to distribute sites around the islands to capture a range of sub-populations with multiple environmental regimes, anthropogenic pressures, and management strategies. One site on STT, Cow and Calf, was located within the St. Thomas East End Reserve (STEER) territorial marine protected area. Sites on STJ were restricted to the island's southeast side within the Virgin Islands National Park (VINP).

Figure 1. Researchers of the Acropora Monitoring and Mapping Program assessing the condition of permanently marked *Acropora palmata* colonies at Botany Bay.
(photo credit: Rossie Ennis)

Four periods of surveys were conducted between 2012 and 2013. Two plot mappings (Initial – Spring/Summer 2012, Annual – Fall 2013) assessed colony density along with size and % live tissue of all colonies; 11-12 colonies were randomly selected and marked in each plot during these mappings for condition assessments (measurements of disease, bleaching, predation, etc.) which were performed during both mapping surveys and condition assessment surveys. Marked colonies still present at the Annual mapping were automatically included as marked colonies for the subsequent year, with marked colonies which were dead or absent being replaced by random (extant or new) colonies. Two condition assessment surveys occurred between mappings (Fall/Winter 2012, Spring/Summer 2013), with data collection only on the 11-12 marked colonies for size, % live tissue, and condition parameters.

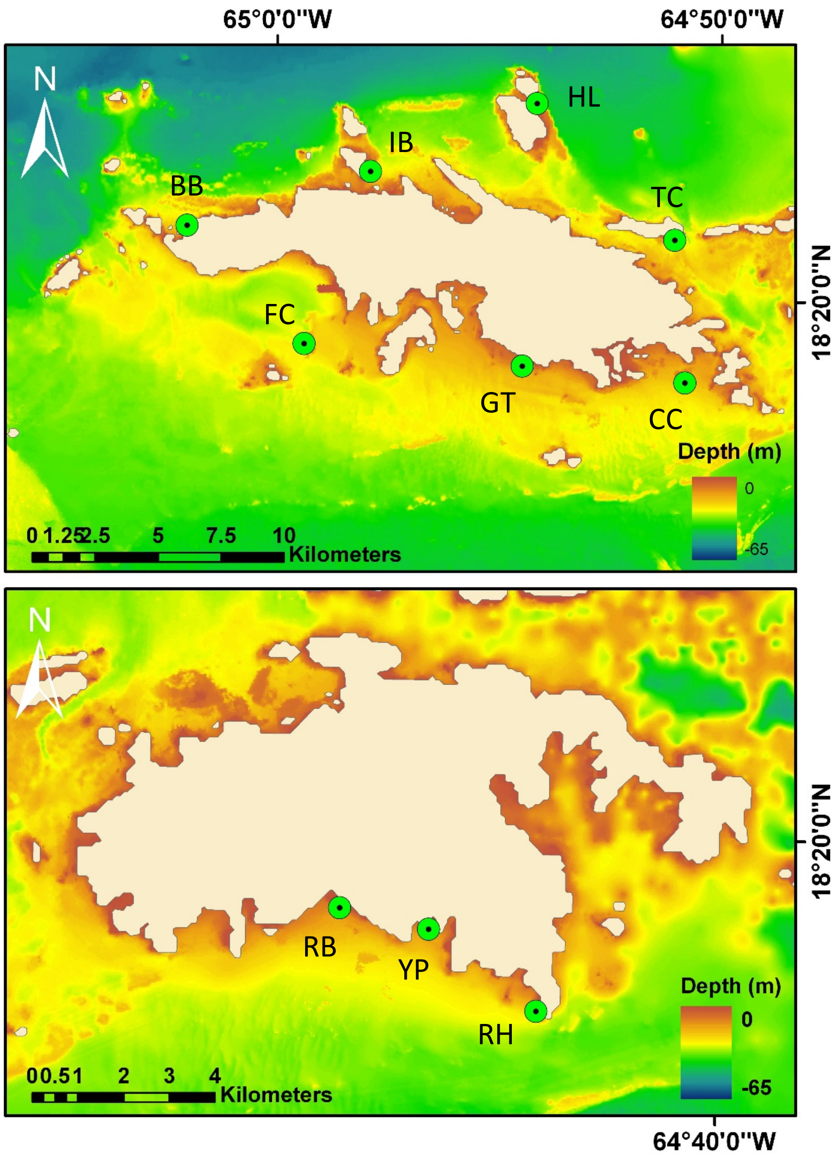


Figure 2. Map of *Acropora palmata* monitoring sites around the northern US Virgin Islands. Sites indicated by green markers: BB – Botany Bay, IB – Inner Brass, HL – Hans Lolick, TC – Thatch Cay, CC – Cow and Calf, GT – Green Cay-St. Thomas, FC – Flat Cay, RB – Reef Bay, YP – Yawzi Point, RH – Rams Head.

Results

Live Tissue Area, Density, and Size Structure

Live tissue area of *Acropora palmata* in the northern USVI increased during the survey period. The Live Area Index (m^2) was used to assess changes in live tissue area. Live Area Index (LAI) = the average dimension of a colony squared, then multiplied by the percent live tissue. Initial estimates of live tissue varied by almost an order of magnitude, from a low of 2.0 m^2 at Cow and Calf to 15.4 m^2 at Flat Cay (Table 1). Over all locations, LAI increased significantly from 49.3 m^2 at initial mapping (March – September 2012) to 55.3 m^2 during annual mapping (October – December 2013), a 12.2% gain (two-tailed t-test comparing total mean percent change to 0; df = 28, t = 2.74, p = 0.011). Total change in live tissue was variable and not significantly different among sites when comparing mean change in percent area from plots (df = 19, F = 1.76, p = 0.144); however, there was a trend of great increase in LAI at the eastern Thatch Cay and St. John sites (Reef Bay, Yawzi Point, and Rams Head) and great decrease in LAI at Botany Bay (Fig. 3). Thatch Cay's highly positive change in LAI made total LAI for St. Thomas positive, outweighing the site with highly negative change in LAI, Botany Bay (Table 1). Thatch Cay's large increase in LAI can be attributed to plot 1 increasing by 25 colonies (mostly attached or encrusting remnants of fragments; Table 1) and plot 3 hosting two highly branched, mostly live colonies which increased their respective average dimension (cm) from 104 to 142 and 118 to 140. All other St. Thomas sites had weak LAI trends in either direction (Table 1; Fig. 3).

Permanently marked colonies in plots showed a similar trend in LAI to overall plot trends, suggesting that some of the increase in LAI was due to growth of extant colonies rather than de novo recruitment to plots. The percent change in LAI was compared among the permanently marked colonies at sites with a nested ANOVA using plot as a nested factor and colony as the level of replication. There was a significant effect of site (df = 9/385, F = 3.4, p = 0.0005) and plot nested within site (df = 20/385, F = 1.8, p = 0.018), with Thatch Cay showing a significant increase in LAI compared with Cow and Calf, Hans Lolick, Inner Brass, Flat Cay, and Botany Bay, which were not significantly different from each other (Fig. 4). Overall, the fact that seven of ten sites increased in overall LAI (Table 1), 54% of colonies present in initial surveys increased in LAI, and percent change of live tissue per marked colony being positive at nine of ten sites (Fig. 4) indicate a general trend of increasing LAI in the area.

The change in the density of colonies in plots (total area 154 m^2) tended to follow trends in total LAI, but the response was not as strong (Table 1; Fig. 3). Similar to total LAI, there was an overall increase in the total number of colonies (significant for total number of colonies, but not total LAI), from 445 to 506 between March 2012 and December 2013, a 13.7% increase (two-tailed t-test comparing total mean percent change in colony number to 0; df = 28, t = 2.27, p = 0.031). The mean percentage change in colony density was variable and not significantly different among sites (df = 19, F = 1.42, p = 0.250); however, Thatch Cay stood out as having a large increase in the total number of colonies in plots, from 41 to 71. This was partly explained by an increase of 25 colonies in plot 1 (also responsible for much of the overall increase in LAI for this location). Most other sites had a small increase in the number of colonies (mean = 3.4), with the exception of Botany Bay, which lost 4 colonies from an initial 50 (Table 1).

Analysis of the size structure of colonies across northern USVI sites revealed that stands selected for monitoring were not dominated by large colonies at most sites (Fig. 5). A caveat to the area index size structure as presented is that plots were selected for criteria to favor the logistics of longitudinal monitoring and the plots were not randomized to be unbiased representations of the acroporid stands in an area. Size structure bins were assigned to mirror the approximate mean distribution of colony sizes across quartiles for all sites combined across the USVI (0.0-0.005 m^2 = 0-10%, 0.006-0.015 = 11-25%, 0.016-0.050 = 26-50%, 0.051-0.200 = 51-75%, 0.201+ = 75%+). Thus, deviations from an even distribution within size classes indicate processes that are changing size structure at a given site, relative to the mean across sites. Most sites had fairly even size distributions, with increases or deficits in a few size classes. Botany Bay, Flat Cay, Rams Head, and Thatch Cay all had right skewed distributions, indicating a preponderance of colonies in the largest size classes. This size distribution suggests a mature stand; however, increasing portions of the colonies that were dead also showed an increasing accumulation of disturbance on larger colonies. Sites such as Cow and Calf, Hans Lolick, Reef Bay and Yawzi Point had deficits in the largest colony size classes, suggesting increasing disturbance at these sites that limits the upper sizes of colonies. However, Reef Bay and Yawzi Point had greater proportions of larger colonies live, suggesting that chronic disturbances that generate partial mortality may be less of a problem at these sites. Conversely, Hans Lolick, Cow and Calf, and Green Cay, St. Thomas, all show large proportions of colonies with partial mortality that may represent the effect of chronic disturbance across size classes.

Processes that generated differences in the growth of colonies among sites may be related to the frequency of physical disturbance at sites. There may be a survival and growth advantage for coral colonies on both the east side and north side of St. Thomas. Corals at east side sites such as Thatch Cay may generally benefit from being upstream from the many stressful anthropogenic processes (especially terrestrial input) originating from the St. Thomas coastline while sites such as Botany Bay and Flat Cay may be negatively impacted by being downstream from most commercial coastline activity. Additionally, both Botany Bay and Flat Cay experienced significant losses of large colonies between mapping surveys due to turbulence/storm surge (Botany Bay between quarterly surveys: October 2012-March 2013; Flat Cay between Initial and first quarterly surveys: May-October 2012). Smaller attached and stable fragments replaced these colonies. Strong winter storms off the U.S. mainland can produce large swells that hit northern USVI reefs, such as Botany Bay, and cause considerable breakage and fragmentation of acroporids (Bright et al. in review). During the summer months, the plots on the acroporid reef at Flat Cay face directly into intense swell created by passing tropical storms in the Caribbean Sea. The impacts of watershed development and effluent, in addition to exposure to annual stochastic weather events, may make Botany Bay and Flat Cay more vulnerable to live tissue loss than other northern USVI sites.

Table 1. Change in LAI (m^2) and colony number (N) between Initial and Final mapping surveys (March 2012 – Sep 2012). Initial LAI and Change LAI are the sum of all three plots at a site (154 m^2) (two plots at Green Cay-St. Thomas).

Variable	BB	IB	HL	TC	CC	GT	FC	RB	YP	RH	Total
Initial LAI	5.3	2.8	4.1	5.3	2.0	1.9	15.4	2.7	3.4	6.3	49.3
Change LAI	-1.82	0.09	-0.11	3.82	0.09	0.30	-0.25	0.98	0.92	1.95	5.96
Initial Site N	50	48	59	41	43	26	55	39	45	36	445
Change Site N	-4	8	2	30	2	5	4	3	8	3	61

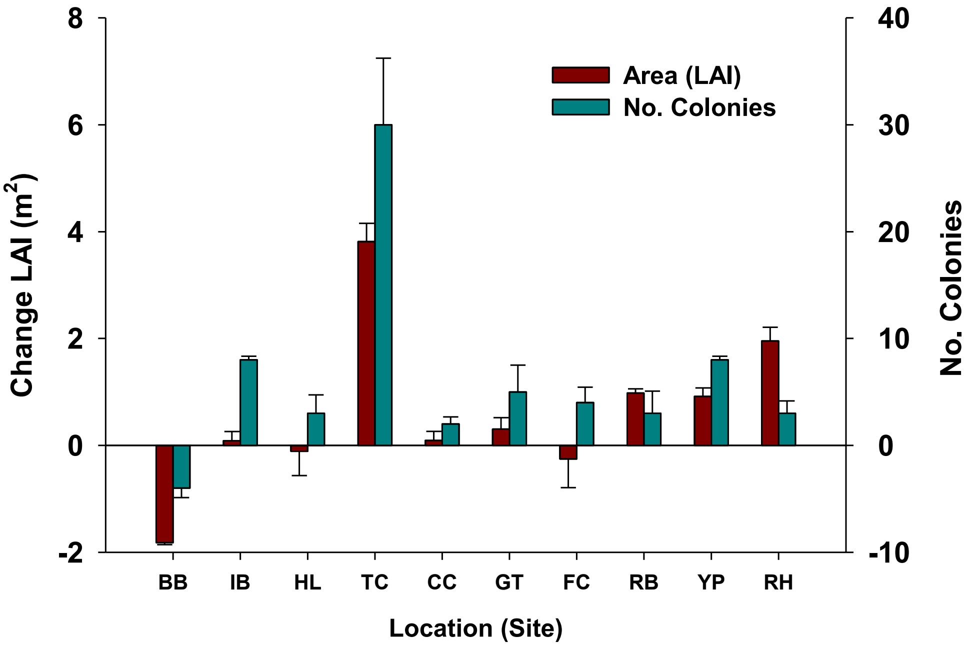


Figure 3. Actual change in Live Area Index (m^2) and in colony number (+/- SE) across plots at each northern USVI site between mapping surveys (March 2012 – October 2013).

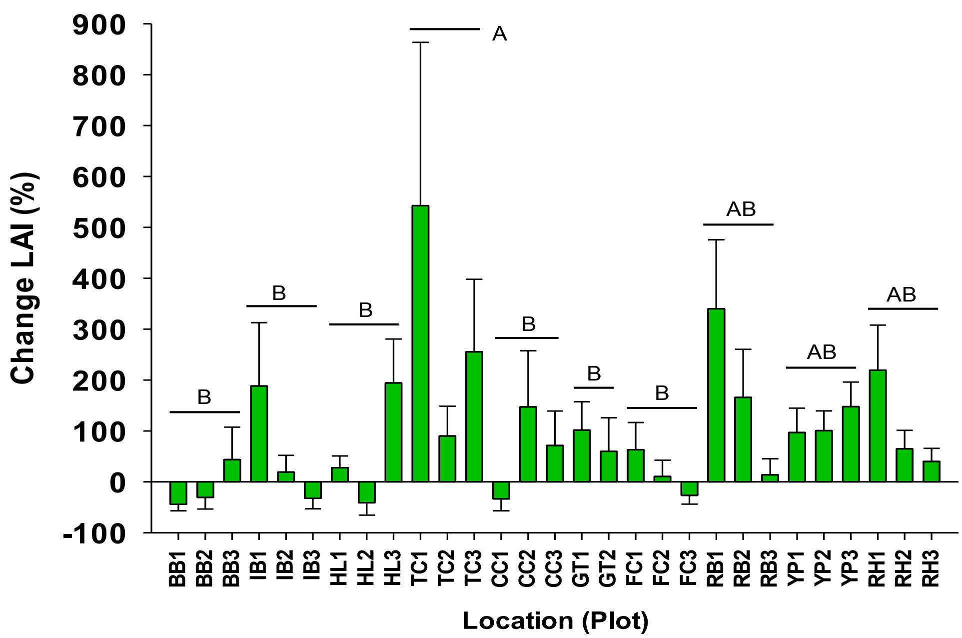


Figure 4. Percentage change in Live Area Index (m^2) *per marked colony* (mean ± SE) for individual plots at each site between mapping surveys (March 2012 –October 2013).
Letters above bars indicate comparison between sites with a Tukey's HSD post hoc test.

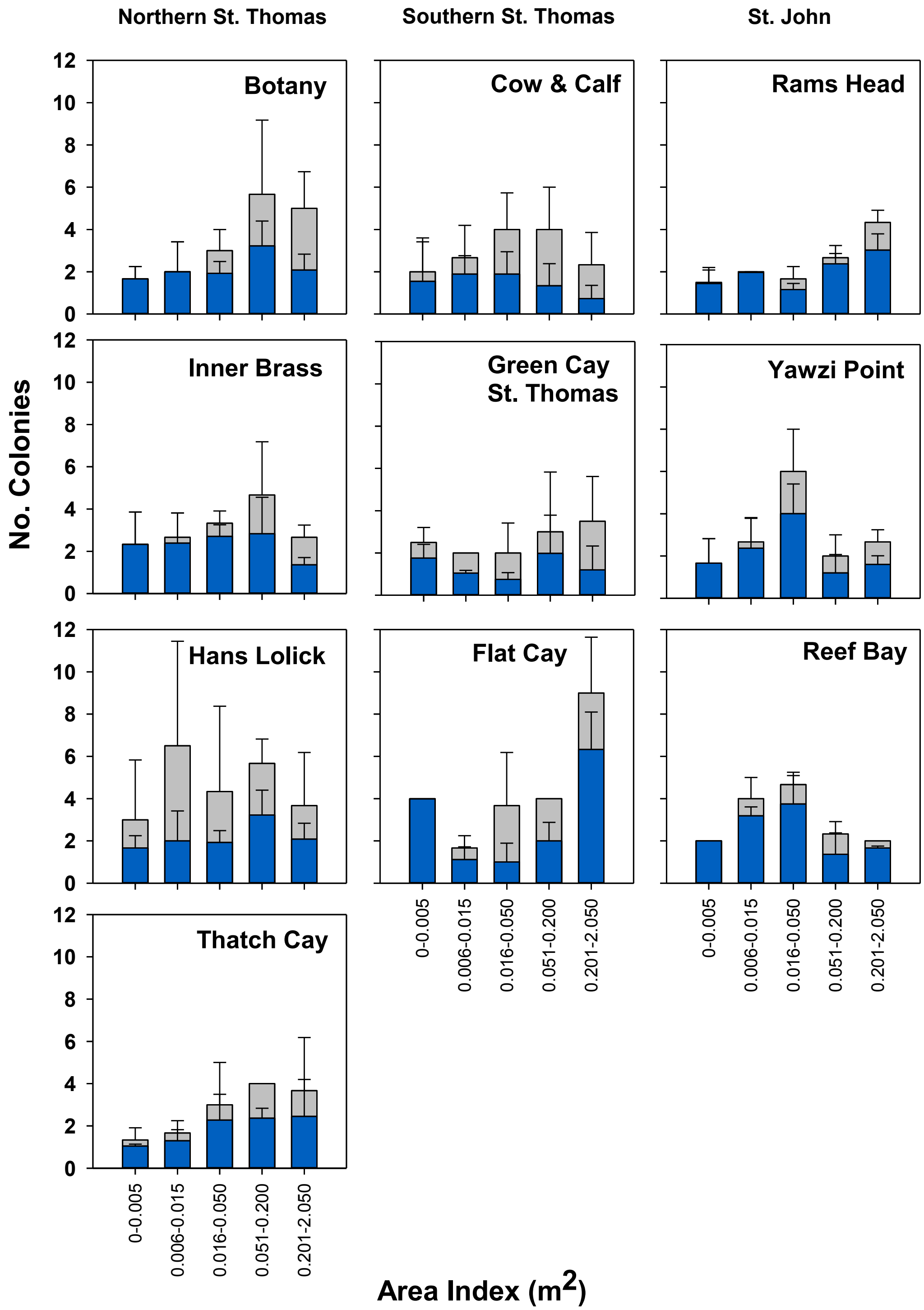


Figure 5. The size structure of *A. palmata* populations by total colony area index (full bar; $m^2 \pm$ SD) and the proportion of colony area consisting of live tissue (proportional size of the blue bar relative to the total bar ± SD) across study sites in the northern US Virgin Islands.
Example: Botany Bay 0.201-2.050 m^2 area index was a mean of 5 colonies across plots and these colonies had an average of 42% living tissue and 58% dead tissue by area index.

Coral Colony Health

Permanently marked colonies of *A. palmata* showed factors negatively impacting health at nearly all monitoring sites. Coral bleaching indicates a loss of symbiotic dinoflagellates (*Symbiodinium*) in host tissue and may or may not result in tissue mortality. Coral bleaching of *A. palmata* occurs at a lower frequency and intensity than most other Caribbean scleractinian corals, likely due to evolutionary acclimation to shallow water habitat (reviewed in ARBT, 2005). A relatively consistent number of colonies bleached across sites over time (Fig. 5 – 167 total, n = 1548), indicating that there was no bleaching peak tied to the annual shallow water thermal maximum temperatures in the USVI (September to October). Most bleaching occurrences were small wedges (<1% LAI) on the sides of colonies that were associated with turf or macroalgae tactile interactions. Some causes of spotty bleaching were not readily identifiable in the field.

Recent mortality was most commonly the result of five factors (ranked high to low): feeding scars, disease, abrasions, parrotfish bites, and boring clionid sponges (Fig. 6). These factors accounted for 35.4% of partial mortality cases. Across all colonies with mortality (n = 1548), there were 242 recorded signs of recent *Coralliophila* spp. (snail) feeding mortality, 159 incidents of tissue eroding diseases (White Pox Disease - 133, White Band Disease - 24, and Rapid Tissue Loss - 2), 65 incidents of abrasions, 50 incidents of parrotfish bites (thought to be primarily caused by *Sparisoma viride*), and 33 incidents of boring clionid sponge lesions. Snails and disease were the greatest causes of mortality on corals by prevalence and effect. Snail feeding scars and/or recognizable diseases were present on a combined 59% of all colonies exhibiting recent mortality (n = 606). For colonies experiencing 10% or greater mortality (n=114) and 50% or greater mortality (n=13) during a given survey, feeding scars and/or diseases were present on 85% and 100% of these colonies respectively. Abrasions tended to occur commonly in areas where colonies were associated with high abundance of sessile macrophytes that could brush edges (Fig. 7); however, abrasions may also have been attributed to unrecognized feeding scars. Colonies were occasionally impacted by more than one factor concurrently; however, visual inspection of the data suggested that there was no apparent pattern of co-occurrence between factors.

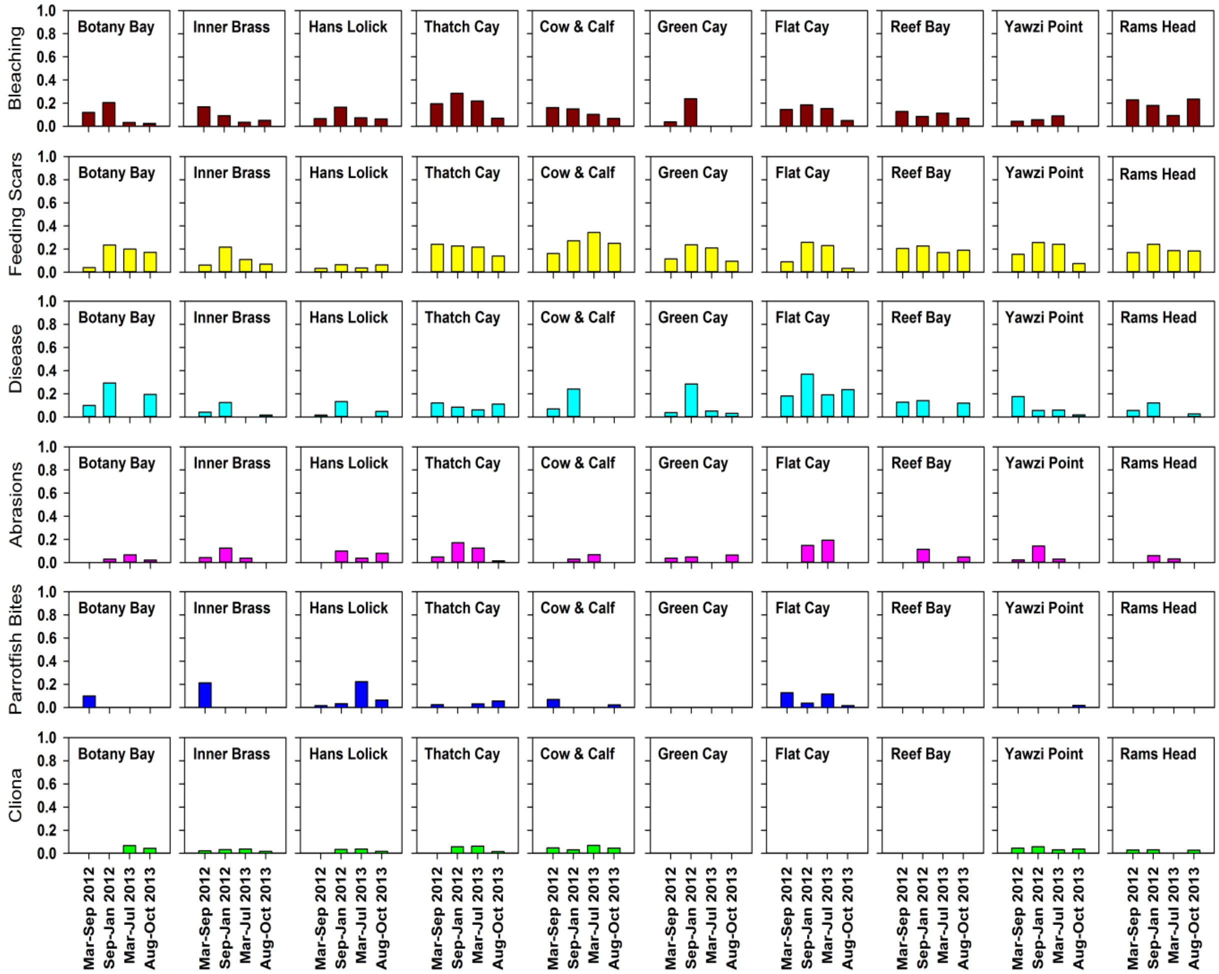


Figure 6. Prevalence of tagged colonies across all four surveys at each site that experienced coral bleaching or the sources of recent mortality: feeding scars, disease, abrasions, parrotfish bites, and clionid sponge borings (in decreasing order of prevalence).

Multiple colonies experienced two or more of the five most prevalent types of mortality during a survey. “Feeding Scars” shows the proportion of colonies suffering from *Coralliophila abbreviata* and/or *Coralliophila caribaea* predation; “Disease” shows the combined number of colonies affected by white band disease, white pox disease, and rapid tissue loss.

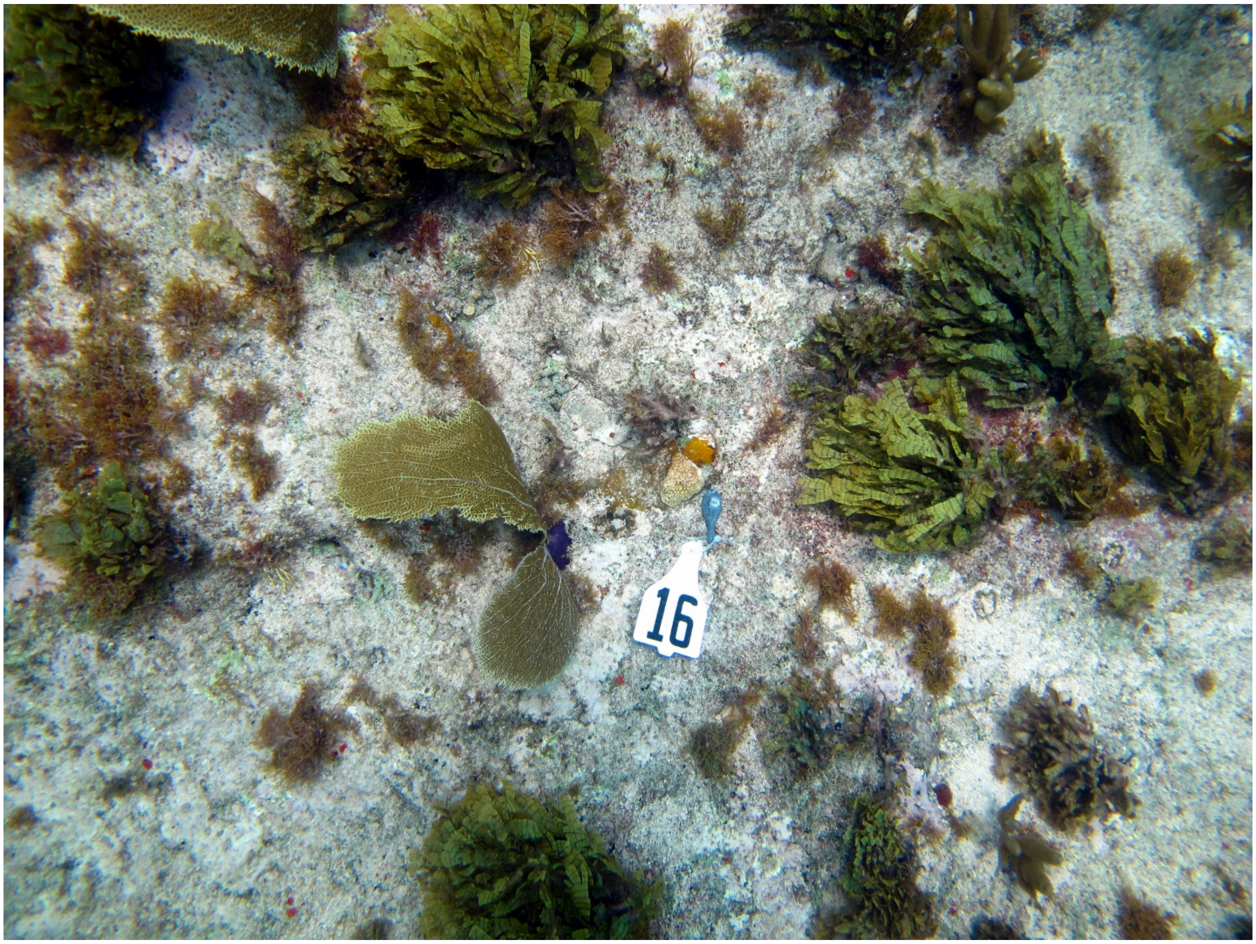


Figure 7. A small colony of *A. palmata* susceptible to interactions with other sessile macrophytes. Colony recorded at Inner Brass during initial surveys (April 2012). This reef scape at 4.5-5.5 m depth can experience heavy outbreaks of *Stypopodium zonale*, which can shade and constantly “brush” over *A. palmata* colonies, causing disease and/or bleaching. (Photo credit – Alexis Sabine)

Corallivorous snails were the most common causes of partial mortality (Fig. 6, Fig. 8). Visual inspection of the data suggested that the prevalence of *Coralliophila* spp. predation did not follow any particular geographic trend, occur more frequently on particular type of reef, or correspond to changes in total site LAI. There appeared to be differences in the impact between the two native snail species present, but the differences were not easily quantified with the methods used in this study. The species *C. abbreviata* had a greater impact than *C. caribaea*, as it caused the greatest partial and whole colony mortality shown by the presence of snails and their crescent-shaped feeding scars. The species *C. caribaea* tended to cluster in higher numbers near the leading edge of colonies but did not feed as heavily as *C. abbreviata*. On colonies where both species occurred, it was sometimes difficult to ascertain whether only one or both species contributed to areas of mortality on colony edges, thus necessitating grouping species in feeding scar analyses.

Figure 8. A colony of *A. palmata* at Reef Bay with 30+ *Coralliophila abbreviata* causing severe mortality, indicated by dead colony portions on the left branches (July 2013).
(Photo credit – Alexis Sabine)

In contrast to snail predation, sites with a higher prevalence of disease across all surveys (Botany Bay, Flat Cay) did experience the two greatest decreases in total LAI between mapping periods (Fig. 3 and Fig. 4). There was also a trend of disease increasing to a greater extent on the south side of St. Thomas compared to the north side during warmer water months (All St. Thomas sites during this survey period were completed in Sep. – Nov. 2012, Fig. 6). This may be related to human land and water usage patterns across St. Thomas, with higher impacts on the western sites that are downstream from much of the island due to a consistent westerly surface current. The south side of St. Thomas has two large commercial harbors (Crown Bay and Charlotte Amalie Harbor), boatyards and chandleries, resident and temporary live aboard boat moorings, the island's solid waste facility (Bovoni Landfill), sewage treatment and release facilities, and the island's main power plant, whereas the north side has very little commercial activity or boat traffic. Anthropogenic activities concentrated on the south side of St. Thomas may reduce disease resistance at south side sites (Smith et al. 2008). Development in the watershed above Botany Bay may have the same effect, despite various run-off mitigation practices employed by developers (Rothenberger et al. 2008). Verification of these impacts may require more direct diagnostic methods, such as cellular indices and contaminants testing.

Mortality of tissue on growing edges of colonies in contact with the substrate was a common sign on monitored colonies. Some of this attrition was associated with turf algae or cyanobacteria, but rarely occurred with common macroalgal species, such as *Dictyota* spp. or *Halimeda* spp. Of note, a number of shallow water reefs of western St. Thomas containing robust populations of both *A. palmata* and *Acropora cervicornis* were experiencing rapid overgrowth by an encrusting form of *Lobophora variegata*, including the monitored population at Flat Cay. Throughout our surveys, *L. variegata* was occasionally seen overgrowing *A. palmata* edges (Fig. 9), but the impacts at affected locations were more severe on stony coral species with massive morphologies and hydrocorals. *A. palmata* and *A. cervicornis* seem to have minimal problem expanding their leading edge over substrate containing normal, relatively thin layers of this algae. However, when disease afflicts the edges of either *Acropora* species, *L. variegata* rapidly moves into the weakened space (R. Brewer, pers. obs.). For other colonies experiencing mortality on growing edges where algae were absent, no telltale signs of cause existed, i.e., no relationship with bleaching or disease or recent fragmentation was found.

The site-attached damselfish *Stegastes planifrons*, which is sometimes associated with tissue death due to algal farming, was virtually non-existent around surveyed colonies. Only 23 total *S. planifrons* were seen during all surveys and most damselfish predation impacts recorded were small, healthy and readily healing chimneys (number of damselfish predation was observed to affect 389 colonies with only three colonies experiencing more than 10% LAI impact, n = 1548). It is unknown what species of damselfish or other biota may be causing what looks like damselfish predation. Other biota known to cause mortality such as ciliate bands, non-clionid sponges (overgrowth), *Hermodice* spp. (annelid predation), and *Diadema antillarum* (urchin predation) were rare.

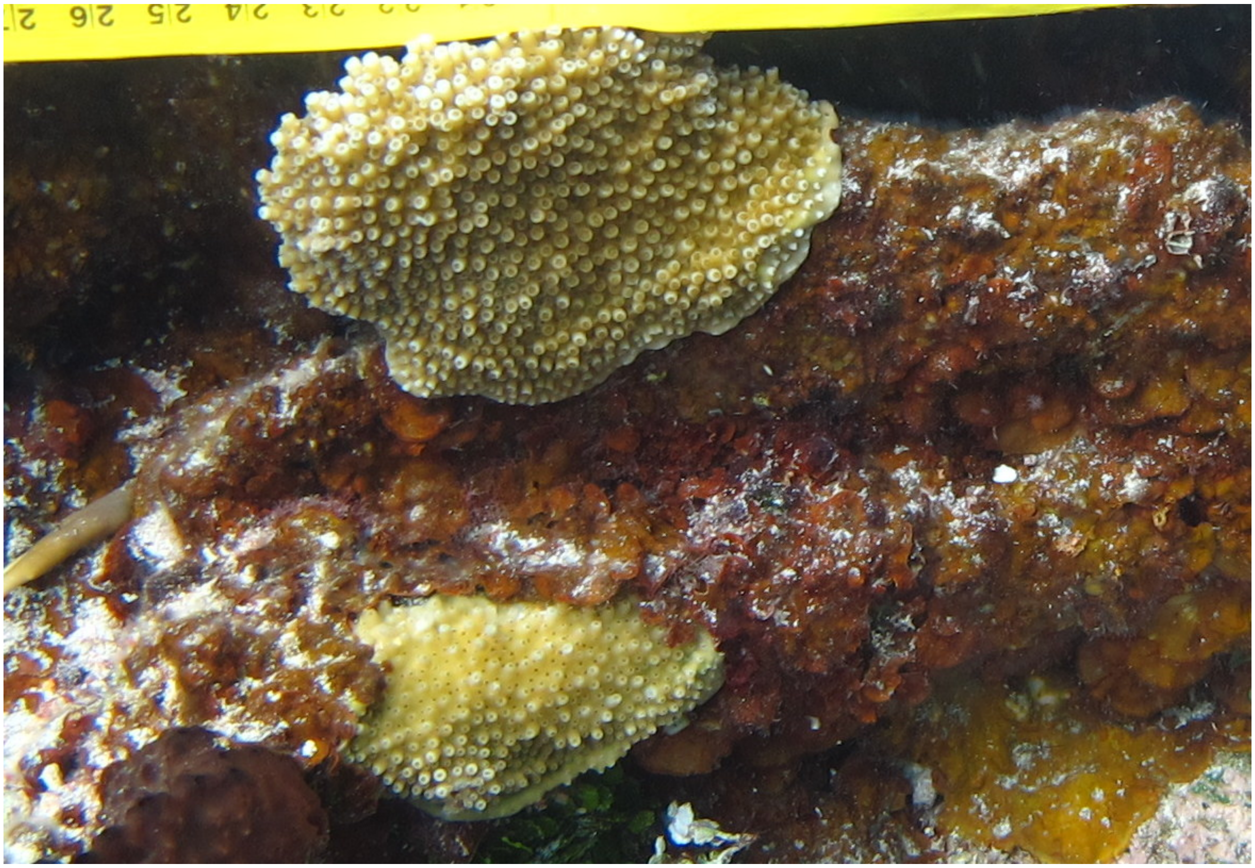


Figure 9. An example of two *A. palmata* tissue isolates, presumably of the same genotype, demonstrating the potential to readily overgrow encrusting *Lobophora variegata* (top isolate) and to also be overgrown by this macroalgae.
The top isolate is exhibiting a healthy, accreting leading edge while growing over *L. variegata*. The bottom isolate is being overgrown/sheeted over by an encrusting plate of *L. variegata* from the top and left, typical of how this algae sheets over other mound/boulder corals on shallow reefs. Picture from Flat Cay during Annual surveys (Sep 2013). (Photo credit – Robert Brewer)

Facilitating sexual recruitment is a management priority for *Acropora palmata*. Based on Baums et al (2006), Williams et al (2008), and Rogers and Muller (2012), the potential for sexual recruitment in the USVI may be higher relative to the Florida Keys. However, confirming sexual recruitment can only be done via genetics, and identifying recruits to species *in situ* is a virtual impossibility (Miller et al, 2007). Our Annual mapping did not give any indication that a major recruitment event occurred after the 2012 spawning event, either from recorded data or anecdotal observations and currently, genetic analysis of potential recruits has not been performed.

Conclusions and Recommendations

Our 19-month survey period is only a snapshot of USVI *Acropora palmata* population demographics, but an overall 12% increase in live tissue area and a 14% increase in number of colonies is an encouraging sign for this threatened species. A steady increase in St. John *A. palmata* live tissue despite a relatively similar profile in coral bleaching, snail predation and disease occurrence with St. Thomas sites may indicate that the national park's undeveloped, intact watershed and restricted public use of reef areas produce an overall positive effect on coral health. Other recent studies have also indicated that the *A. palmata* population on St. John is recovering as a whole (Muller et al, 2013). Over time, it will be interesting to see if our St. John sites and east and north side St. Thomas sites maintain a positive LAI trend relative to south and west side St. Thomas sites.

It is readily apparent that corallivorous gastropods and disease (primarily White Pox, which recently was shown to be the most prevalent disease afflicting *A. palmata* across St. John as a whole – Rogers and Muller, 2012) are the two main drivers of severe recent mortality seen in the northern USVI. Based on our data, *C. abbreviata* may be a heavy, chronic, ubiquitous contributor to *A. palmata* mortality around St. Thomas and St. John. Colonies that experience both disease and snail predation may be the colonies most susceptible to large LAI losses. It is suggested that limiting human impact from runoff and non-point sources of pollution on the south side of St. Thomas would be the best course of action to take to positively influence the health of negatively impacted or struggling acroporid reefs. A management strategy that targets the removal of *C. abbreviata* may help maintain positive LAI changes in localized areas (Williams et al. 2011). However, because these gastropods can prey an alternate coral species, but show a preference for acroporids, they will likely migrate back into areas with concentrations of acroporid corals and would need long-term removal. Overall, more monitoring periods are needed to produce a clearer picture of site-specific demographic trends and how any changes to human behavior may influence *A. palmata* populations in the future.

Suggestions for future *A. palmata* demographic monitoring in the USVI:

1. Permanent transects running through or near plots to assess benthic cover would be ideal. Assessing potential settlement habitat and identifying changing trends in cover that may impact *A. palmata* populations would add another layer to our understanding of the ecology of acroporid reefs.

2. Most northern USVI plots also contain either *Acropora cervicornis* or the hybrid *Acropora prolifera*; tracking these species' numbers and general colony condition will undoubtedly inform on *A. palmata* ecology as well.
3. Pointedly assess the threat encrusting *Lobophora variegata* may pose to *A. palmata* and other acroporids in plots.
4. Continue to describe in detail and attempt to find causality for the different types of unhealthy *A. palmata* leading edges.

St. Croix Demographic Monitoring

Summary of Methods

St. Croix demographic sites were established and monitored with methods as described in the section on St. Thomas monitoring. Because of the time it took to establish and train new personnel on St. Croix and inability of one key monitoring researcher to dive due to medical reasons, plots were established but not re-monitored or remapped. Thus, this section will report on initial site characteristics with the hope that future funding can be directed at monitoring and maintaining these established sites.

Sites were selected after *in situ* inspection on the northern and eastern sites of St. Croix (Fig. 10). These coasts of St. Croix had adequate populations to allow the establishment of monitoring plots (see St. Croix Synoptic Monitoring section). Selected areas also included important historically assessed populations near Teague Bay and the Buck Island (e.g., the first descriptions of white band disease in the Caribbean associated with the closed West Indies Laboratory; Gladfelter 1982). Sites were also established within notable management units, including the St. Croix East End Marine Park (Green Cay-St. Croix, Teague Bay-West, Teague Bay-East, Channel Rock, Turner Hole), Buck Island National Monument (Buck Island), and the Salt River National Park (Whitehorse Reef). Three plots were established in each location between August 2012 and March 2013

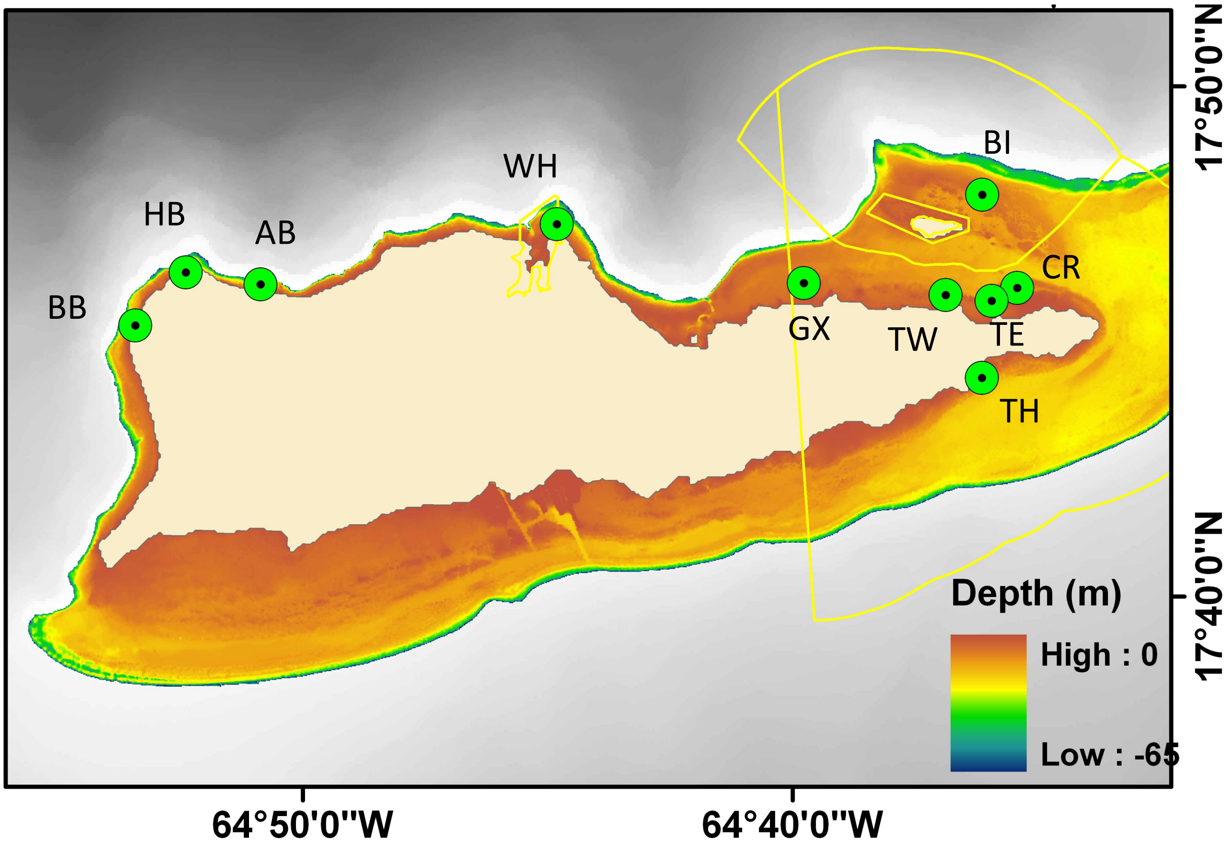


Figure 10. Map of *Acropora palmata* monitoring sites around St. Croix.
BB – Bulter Bay, HB – Ham's Bluff, AB – Annaly Bay, WH – Whitehorse Reef/Salt River, GX – Green Cay-St. Croix, TW – Teague Bay-West, TE – Teague Bay-East, CR – Channel Rock, BI – Buck Island, TH – Turner Hole.

Results

Live Tissue Area, Density, and Size Structure

Live tissue areas (LAI) of *Acropora palmata* in St. Croix during site establishment locations were variable (Table 2), but many locations had large values relative to sites in the northern USVI (Table 1). In some cases this was due to a large number of colonies in plots (>20), such as at Whitehorse Reef, Green Cay, Teague Bay-West, Channel Rock, and Buck Islands. In other cases this was due to an abundance of large colonies with live tissues (Fig. 11), such as at Annaly Bay, Buck Islands, and Teague Bay-East. In general, the proportion of colonies that was live tissue seemed to be higher than in the northern USVI. Yet, recent mortality prevalence was high in many locations, such as all northwest sites (Butler Bay, Ham's Bluff, Annaly Bay), Whitehorse Reef, and Teague Bay-East, suggesting chronic impacts are also important to demographic processes in St. Croix.

Table 2. Demographics of St. Croix sites during Initial mapping surveys (June 2012-March 2013).

Site (month/year)	Date Est.	# of colonies	Average dimension of colonies (cm)	Sum of LAI (m^2)	% of colonies with mortality
Bulter Bay (8/'12)	2012-08-28	37	36.5	3.3	54.2%
Ham's Bluff (6/'12)	2012-08-28	23	74.0	6.4	46.4%
Annaly Bay (3/'13)	2013-03-17	36	55.3	10.6	51.3%
Whitehorse (3/'13)	2013-03-17	62	38.9	13.4	44.4%
Green Cay (6,9/'12)	2012-10-22	85	25.1	6.4	16.7%
Teague Bay-West (6/'12)	2012-09-10	81	45.7	14.5	21.1%
Teague Bay-East (6/'12)	2012-09-14	49	51.7	20.5	38.9%
Channel Rock (7/'12)	2012-09-12	78	38.4	16.5	22.2%
Buck Island (9,10/'12)	2012-10-18	66	49.7	17.5	30.6%
Turner Hole (3/'13)	2013-03-15	49	20.9	3.3	27.8%

Conclusions and Recommendations

Conclusions from St. Croix demographic sites are preliminary, since this monitoring is designed to be longitudinal and with sampling periodicity at a frequency sufficient to capture changes in *A. palmata* populations and the major drivers of change. Thus, the major recommendation is that this program should be continued to begin an earnest long-term assessment of the populations around St. Croix. These acroporids have a rich scientific history and are interspersed inside and outside of important territorial and federal management entities. A long-term assessment of these populations would help to connect historical data with modern processes, including the positive or negative influence of marine protected areas on acroporid demographics.

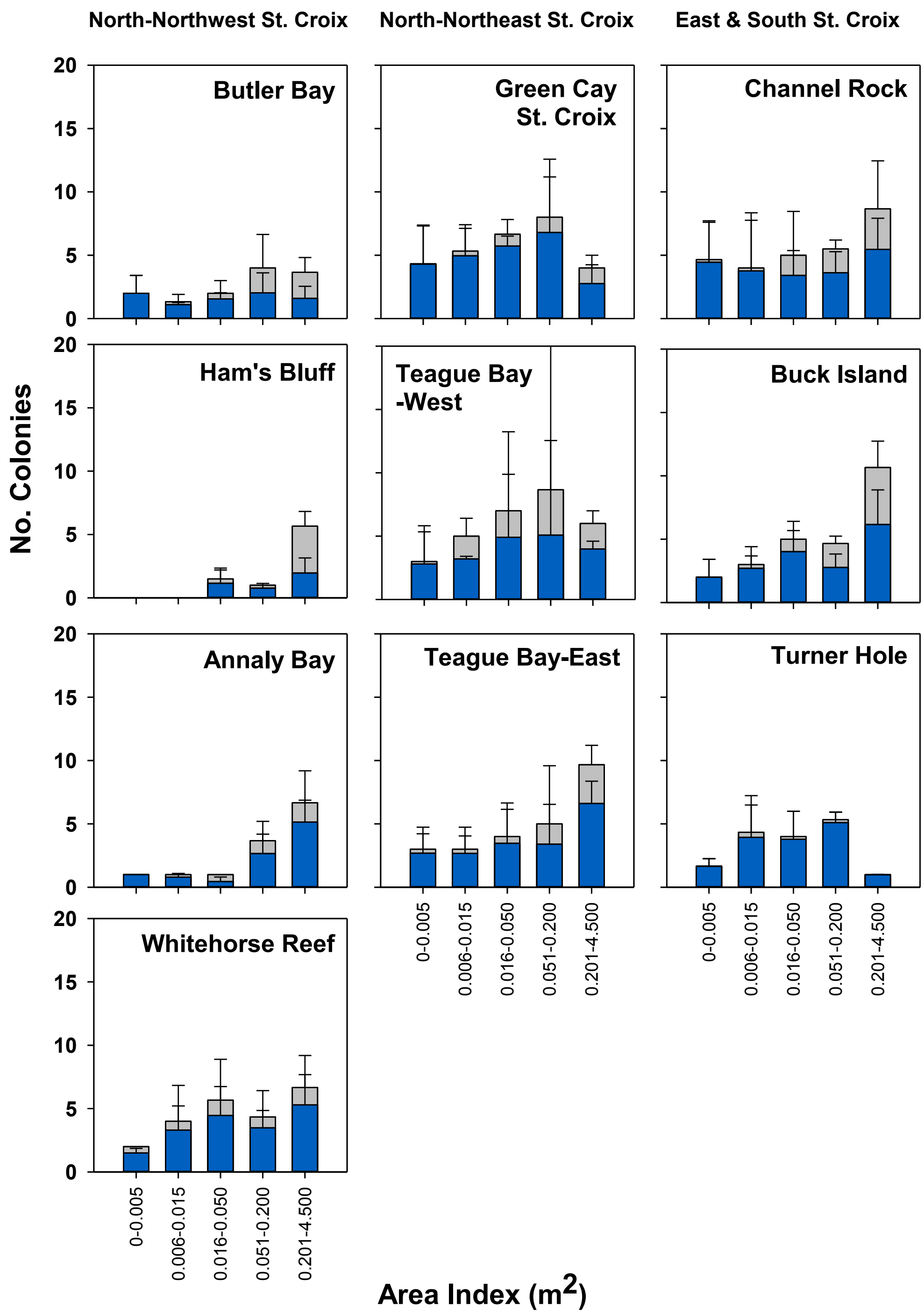


Figure 11. Area index size structure of *A. palmata* populations across study sites in St. Croix. Area index is shown for overall colony sizes (total bar ± SD) and for the mean proportion of the colonies in each size class with live tissue (blue bar portion ± SD).

St. Croix Synoptic Assessment

Summary of Methods

Synoptic surveys were designed to allow robust population estimates of acroporid corals by employing a spatially-stratified random approach (Miller et al. 2011). Between Summer 2012 and Winter 2014, surveys of Acroporid populations were completed at 261 randomly selected sites around the island of St. Croix. Sites were allocated within four sampling regions: the northshore, the southshore, the west end, and offshore to the east, on the Lang Bank platform (Fig. 12, Table 3). The trade winds blow east to west across the island, making the East, North, and South sampling regions relatively high energy environments, while the West is generally calmer. Allocated sites were randomly selected in each region from 50x50 m grid squares across a depth range of 0 -18 m, in five hardbottom habitats: bedrock, linear reef, patch reef, pavement, and scattered coral (Figs. 13-17).

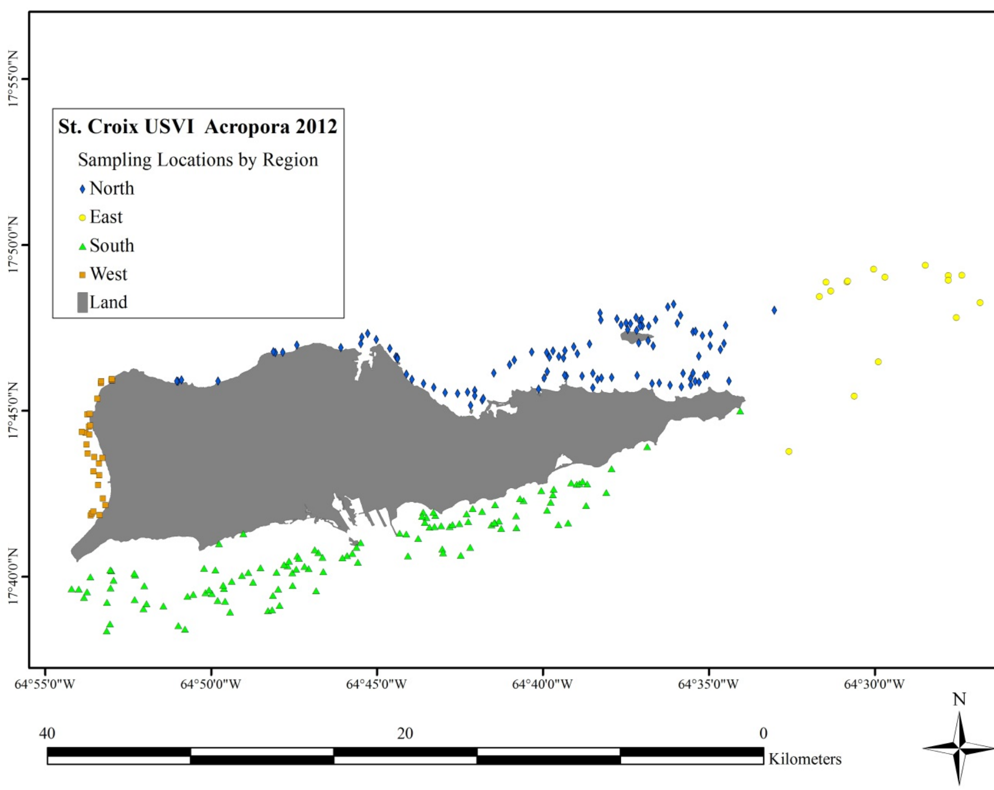


Figure 12. The location of the 261 sites surveyed around St. Croix, with the four sampling regions, North, East, South and West indicated by color.

Figure 13. Examples of two patch reef habitats on St. Croix sampled during 2013.
The high relief "haystack" is typical of the northern side of Buck Island, formations composed from dead *Acropora palmata* skeletons. Left panel: High-relief "Haystack" Patch, North, Buck Island, 3-10 m (17.79387°, -64.62273°). Right panel: Low-relief patch reef, South, West of Hovensa, 8.5-9.1 m (17.68011°, -64.78121°).

Figure 14. Examples of two linear reef habitats sampled during 2013. The low-relief linear reef is typical of the shallow reef formation that runs along the northeastern coastline.
Left panel: Deep, rugose linear reef. West, North of Pier, 13.7-14.6 m (17.72862°, -64.89528°). Right panel: Shallow, low-relief linear reef, North, East End, 0.9-1.2 m (17.76668°, -64.63211°).

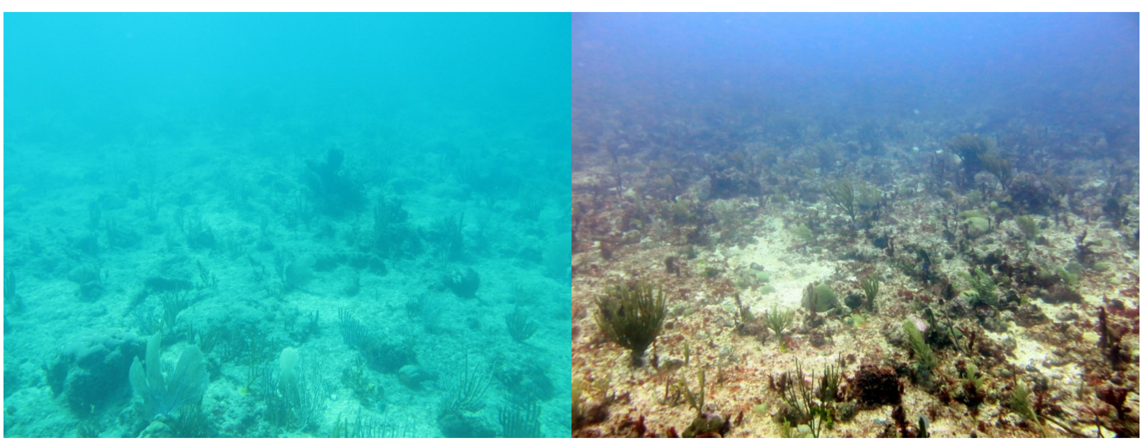


Figure 15. Examples of two pavement habitats sampled during 2013.
Left panel: Shallow low relief pavement, North, Salt River, 6.0-6.0 m (17.78371°, -64.7582°). Right panel: Deep low relief pavement, East, Lang Bank, 17.9-18.2 m(17.79678°, -64.45902°).

Figure 16. Examples of two scattered coral sites sampled during 2013.
Left panel: Shallow scattered coral, West, South of Frederiksted, 5.8-6.0 m (17.70607°, -64.88756°).
Right panel: Shallow scattered coral, North, Buck Island, 2.4-3.0 m (17.7841°, -64.61849°).

Figure 17. Example of one bedrock site sampled during 2013.
These sites were typically very difficult to photograph, due to the characteristically low visibility and high surge. Shallow bedrock**,** West, Hams Bluff, 3.6-3.9 m (17.76545°, -64.88335°)**.**

Sites were surveyed by a team of two divers, according to the protocol of Miller *et al* (2011). At each site, divers first assessed the habitat and depth to determine if it was suitable to be surveyed. Sites that were deeper than 18 m, or located in sand or seagrass were not surveyed. At suitable sites, each diver laid a 15x1 m belt transect. The orientation of transects was determined by the physical features of the site and the predominant current direction. Transects were surveyed for acroporid corals, the black spiny sea urchin (*Diadema antillarum*), and Queen Conch (*Strombus gigas*). Acroporid corals within the transect were measured for length width and height. The dimensions of the entire skeleton (skeletal unit) was recorded, as well as those of each individual patch of live tissue (physiological units). For each skeletal and physiological unit, the percentage of the colony that was long dead or recently dead was estimated. Observations of bleaching, disease, and predation were made, and the area affected by each was estimated. For each acroporid colony the presence of damselfish (*Stegastes* spp. and *Microspathodon chrysurus*) was recorded to estimate the potential impacts of these site-attached fishes on tissue loss. In addition, regardless of whether they were present in the surveyed transect at each site, the presence or absence of acroporids was noted. Data was also collected on the physical features of the survey site, such as depth and vertical relief.

For many sites, the habitat and depth defined in the allocation was inconsistent with what was found in-situ. This made it necessary to discard many of the sites in favor of predetermined alternate sites. The most common issue was with primary sites exceeding the maximum depth of 18 m for surveys. Along St. Croix's northern coastline the reef drops off very steeply to form 'the wall'. Many of the northern sites that were intended to be in only a few feet of water were actually off the drop in waters much greater than 18m, a likely consequence of modeled bathymetry features from sparse soundings data on a narrow and precipitous coastal margin. In most cases if a site fell into one of the five habitat types (bedrock, linear reef, patch reef, pavement, and scattered coral) the surveys were completed regardless of whether the site matched the description of the original allocation. Sites were later substituted within each study region, to ensure that the resulting data set matched the original allocation as closely as possible.

Effort. The 261 sites were sampled over 45 field days, for an average of six sites per day. A summary of the field sampling effort is presented in Table 4. The vast majority of surveys (38 of 45 field days, and 237 sites) were completed between Summer 2013 and Winter 2014. Shallow sites were often surveyed on snorkel where practical.

Table 3. Sampling Effort for *Acropora* corals, *Diadema antillarum*, and *Strombus gigas* around St. Croix during June 2012 – February 2014.
At each site, two replicate 15x1 m transects were surveyed for all variables. Available sites: the total number of mapped 50x50 m grid cells in the habitat/depth stratum. Percent Domain: the percentage of the entire domain that the stratum occupies. Percent stratum mapped: percent of mapped stratum cells that were included in the allocation. Percent allocated sites sampled: the percentage of allocated sites in the stratum which were sampled. Table continued over the following pages for each region.

Region/Habitat	Depth Range (m)	No. Sites Sampled	Available Sites (% Domain)	% Stratum Mapped	% Allocated Sites Sampled	No. transects (area, m2)
North St Croix						
Bedrock	0-6	2	438 (0.82)	0.46	100.00	4 (60)
	6-12	0	4 (0)	0.00	0.00	0 (0)
	12-18	0	0 (0)	0.00	0.00	0 (0)
	Total	2	442 (0.82)	0.45	100.00	4 (60)
Linear reef	0-6	16	1900 (3.56)	0.95	88.89	32 (480)
	6-12	5	193 (0.36)	1.04	250.00	10 (150)
	12-18	2	118 (0.22)	1.69	100.00	4 (60)
	Total	23	2211 (4.14)	1.00	104.55	46 (690)
Patch reef	0-6	10	502 (0.94)	2.19	90.91	20 (300)
	6-12	5	908 (1.7)	0.44	125.00	10 (150)
	12-18	1	724 (1.35)	0.28	50.00	2 (30)
	Total	16	2134 (3.99)	0.80	94.12	32 (480)
Pavement	0-6	21	3857 (7.22)	0.62	87.50	42 (630)
	6-12	24	4785 (8.96)	0.42	120.00	48 (720)
	12-18	6	1426 (2.67)	0.21	200.00	12 (180)
	Total	51	10068 (18.86)	0.47	108.51	102 (1530)
Scattered coral	0-6	1	297 (0.55)	0.67	50.00	2 (30)
	6-12	4	382 (0.71)	0.52	200.00	8 (120)
	12-18	2	275 (0.51)	0.73	100.00	4 (60)
	Total	7	954 (1.78)	0.63	116.67	14 (210)
North Total		99	15809 (29.62)	0.59	105.32	198 (2970)

Table 3. (con't)

Region/Habitat	Depth Range (m)	No. Sites Sampled	Available Sites (% Domain)	% Stratum Mapped	% Allocated Sites Sampled	No. transects (area, m2)
East St Croix						
Bedrock	0-6	0	0 (0)	0.00	0.00	0 (0)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	0	0 (0)	0.00	0.00	0 (0)
	Total	0	0 (0)	0.00	0.00	0 (0)
Linear reef	0-6	0	0 (0)	0.00	0.00	0 (0)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	0	0 (0)	0.00	0.00	0 (0)
	Total	0	0 (0)	0.00	0.00	0 (0)
Patch reef	0-6	0	0 (0)	0.00	0.00	0 (0)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	2	16 (0.02)	12.50	100.00	4 (60)
	Total	2	16 (0.02)	12.50	100.00	4 (60)
Pavement	0-6	0	0 (0)	0.00	0.00	0 (0)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	12	6540 (12.25)	0.18	100.00	24 (360)
	Total	12	6540 (12.25)	0.18	100.00	24 (360)
Scattered coral	0-6	0	0 (0)	0.00	0.00	0 (0)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	2	628 (1.17)	0.48	66.67	4 (60)
	Total	2	628 (1.17)	0.48	66.67	4 (60)
East Total		16	7184 (13.46)	0.24	94.12	32 (480)

Table 3. (con't)

Region/Habitat	Depth Range (m)	No. Sites Sampled	Available Sites (% Domain)	% Stratum Mapped	% Allocated Sites Sampled	No. transects (area, m2)
South St Croix						
Bedrock	0-6	2	517 (0.96)	0.39	100.00	4 (60)
	6-12	0	4 (0)	0.00	0.00	0 (0)
	12-18	0	0 (0)	0.00	0.00	0 (0)
	Total	2	521 (0.97)	0.38	100.00	4 (60)
Linear reef	0-6	13	1418 (2.65)	0.99	92.86	26 (390)
	6-12	3	254 (0.47)	0.79	150.00	6 (90)
	12-18	8	166 (0.31)	1.20	400.00	16 (240)
	Total	24	1838 (3.44)	0.98	133.33	48 (720)
Patch reef	0-6	6	375 (0.7)	2.40	66.67	12 (180)
	6-12	9	425 (0.79)	0.47	450.00	18 (270)
	12-18	0	86 (0.16)	2.33	0.00	0 (0)
	Total	15	886 (1.66)	1.47	115.38	30 (450)
Pavement	0-6	20	4682 (8.77)	0.64	66.66	40 (600)
	6-12	33	4871 (9.12)	0.41	165.00	66 (990)
	12-18	15	13353 (25.02)	0.16	68.18	30 (450)
	Total	68	22906 (42.93)	0.31	94.44	136 (2040)
Scattered coral	0-6	0	417 (0.78)	0.48	0.00	0 (0)
	6-12	4	156 (0.29)	1.28	200.00	8 (120)
	12-18	5	1456 (2.72)	0.41	83.33	10 (150)
	Total	9	2029 (3.8)	0.49	90.00	18 (270)
South Total		118	28180 (52.81)	0.41	102.61	236 (3540)

Table 3. (con't)

Region/Habitat	Depth Range (m)	No. Sites Sampled	Available Sites (% Domain)	% Stratum Mapped	% Allocated Sites Sampled	No. transects (area, m2)
West St Croix						
Bedrock	0-6	3	65 (0.12)	3.08	150.00	6 (90)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	0	0 (0)	0.00	0.00	0 (0)
	Total	3	65 (0.12)	3.08	150.00	6 (90)
Linear reef	0-6	0	93 (0.17)	3.23	0.00	0 (0)
	6-12	5	227 (0.42)	0.88	250.00	10 (150)
	12-18	3	104 (0.19)	1.92	150.00	6 (90)
	Total	8	424 (0.79)	1.65	114.29	16 (240)
Patch reef	0-6	0	0 (0)	0.00	0.00	0 (0)
	6-12	0	0 (0)	0.00	0.00	0 (0)
	12-18	0	0 (0)	0.00	0.00	0 (0)
	Total	0	0 (0)	0.00	0.00	0 (0)
Pavement	0-6	6	941 (1.76)	0.64	100.00	12 (180)
	6-12	3	464 (0.86)	0.43	150.00	6 (90)
	12-18	2	50 (0.09)	6.00	66.67	4 (60)
	Total	11	1455 (2.72)	0.76	100.00	22 (330)
Scattered coral	0-6	2	55 (0.1)	3.64	100.00	4 (60)
	6-12	3	176 (0.32)	1.14	150.00	6 (90)
	12-18	1	7 (0.01)	0.00	0.00	2 (30)
	Total	6	238 (0.44)	1.68	150.00	12 (180)
West Total		28	2182 (4.08)	1.10	116.67	56 (840)
All regions/habitats		261	53355 (100)	0.47	104.4	522 (7830)

Table 4. SCUBA diving and snorkeling effort for benthic coral reef surveys around St Croix, US Virgin Islands during June 2012 – February 2014.
All divers are affiliated with the University of the Virgin Islands.

Scientific Diver	No. of dives	Dive depth range (ft.)	Bottom time (hrs.)	No. of Snorkels	Snork. depth range (ft.)	Snork. time (hrs.)
Ashley Ruffo	181	2 to 65	41.12	58	3 to 26	11.78
Emily Weston	24	3 to 54	6.75	0	-	0.00
Liz Whitcher	152	2 to 64	35.32	62	3 to 26	11.30
Rob Brewer	27	6 to 57	6.38	0	-	0.00
Ron Sjoken	23	6 to 51	6.35	1	3	0.28
Total all divers	407	2 to 65	96	121	3 to 26	23.37

Results

Of the 261 sites surveyed, acroporids were present inside or outside transects at 49 sites (19%) (Fig. 18). The Elkhorn coral *A. palmata* was present at 45 sites, while the staghorn coral *A. cervicornis* was present at only seven sites. Out of the 49 sites where acroporids were present, 40 (82%) were located in the North study region. Within surveyed transects, acroporid corals were recorded within transects at 20 sites, 18 (90%) of which were located in the North region. Colony density for both species was greatest in the northeast of St. Croix, with high concentrations around Buck Island and along the coastline north of Christiansted (Fig. 19). Both corals were absent from all survey sites in the West study region, and were rare at survey sites in the South study region.

The Elkhorn coral *A. palmata* was only present in shallow (0-6 m) to medium depths (0-12 m), while *A. cervicornis* was present across all depth ranges (Fig. 20). Out of the 45 sites where *A. palmata* was present, 40 were in pavement and linear reef habitats. Pavement also accounted for five of the seven sites where *A. cervicornis* was present.

Over the course of the study, a total of 86 *A. palmata* colonies and 12 *A. cervicornis* colonies were found within transects and surveyed. Scaling of habitat area estimates and colony densities resulted in an estimate of the population of *A. palmata* on St. Croix at 83,321 (± 23,591 SE) colonies, while the *A. cervicornis* population was estimated to be 21,439 (± 14,409 SE) colonies. A vast majority of the estimated *A. palmata* population was confined to the North study region (Fig. 21). The estimated *A. palmata* population was approximately evenly between linear reef and pavement habitats, with patch reefs accounting for a much smaller portion of the island's population (Fig. 21).

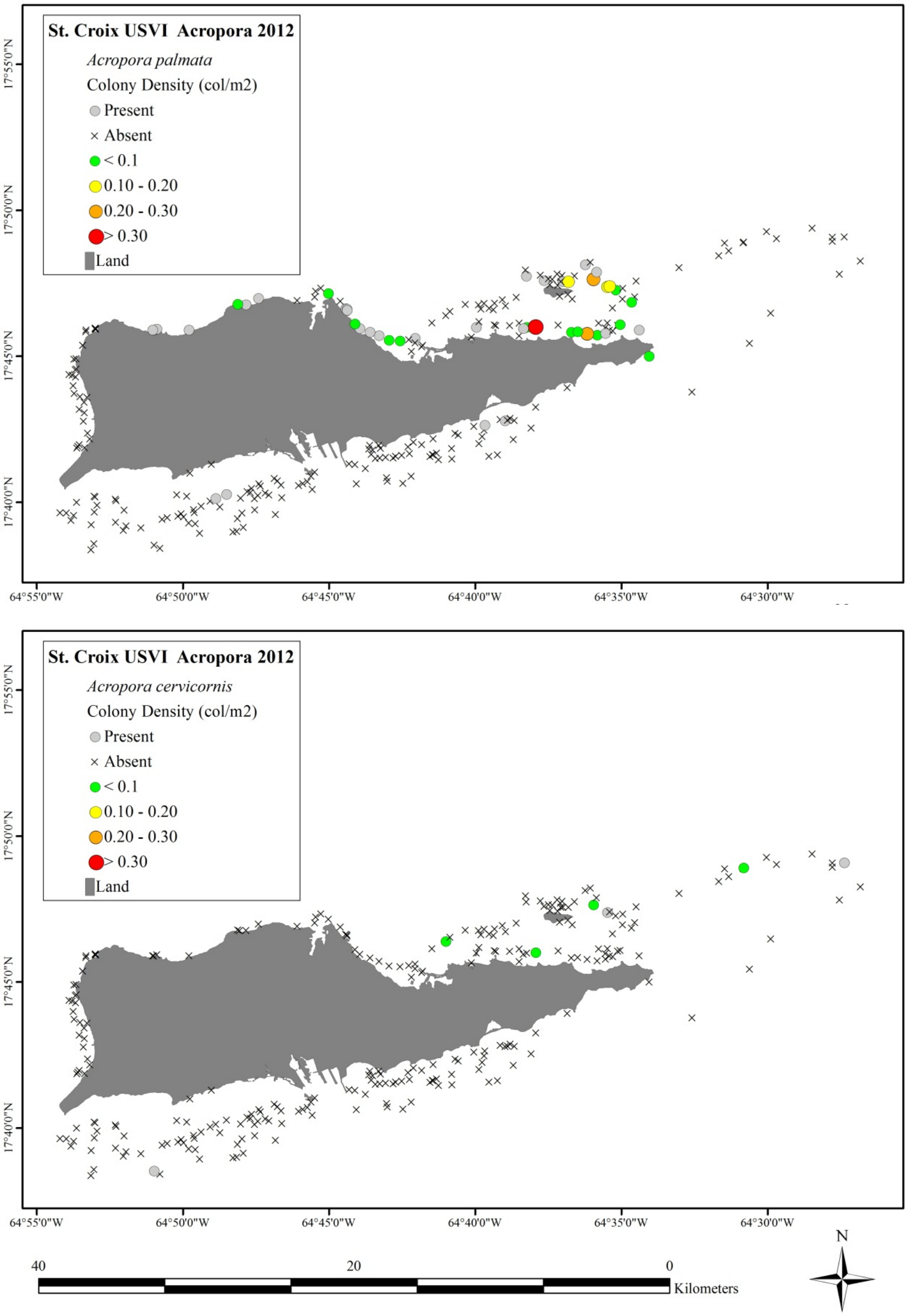


Figure 18. Density maps for *A. palmata* (top panel) and *A. cervicornis* (bottom panel) expressed as colonies per square meter from transects or present/absent from overall site surveys.

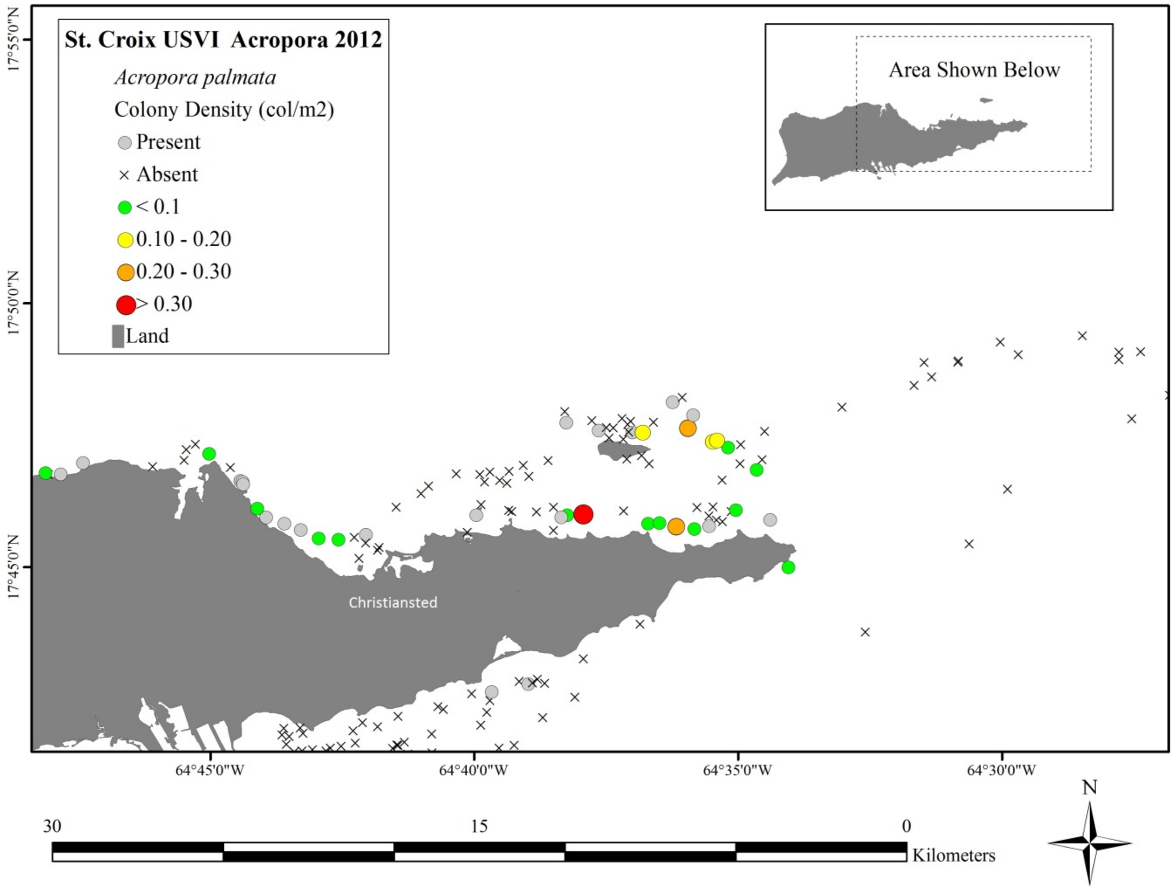
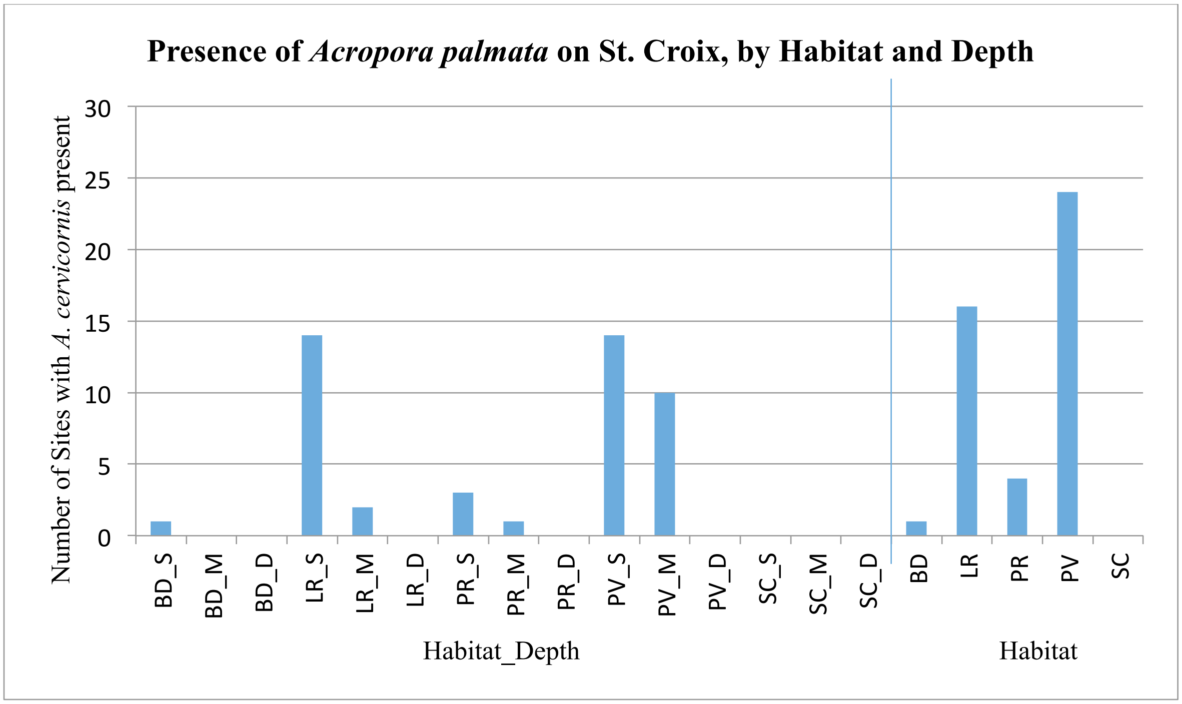


Figure 19. Close up of northeast St. Croix density maps for *A. palmata* expressed as colonies per square meter from transects or present/absent from overall site surveys.



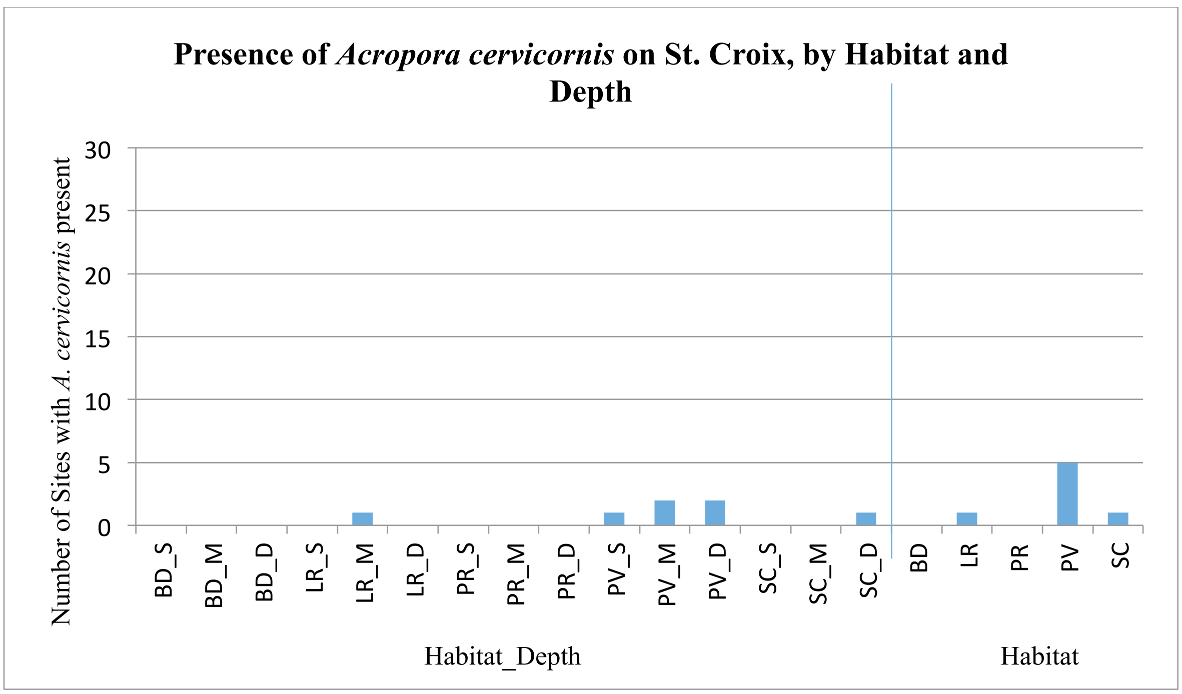
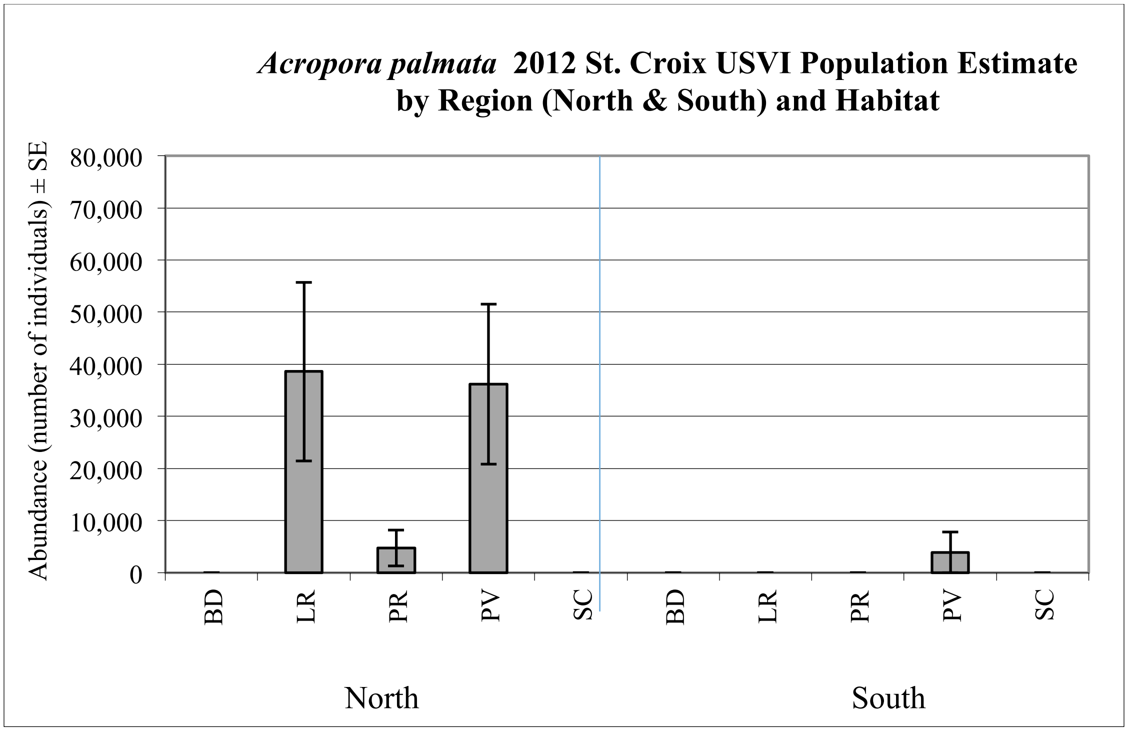


Figure 20. The distribution of sites where acroporids were present (at the site or in the surveyed transect) across habitat and depth ranges.
Habitats are denoted as BD (bedrock), LR (linear reef), PR (patch reef), PV (pavement) and SC (scattered coral). Depths are denoted as S (shallow, 0-6 m), M (medium, 6-12 m) and D (deep, 12-18 m).



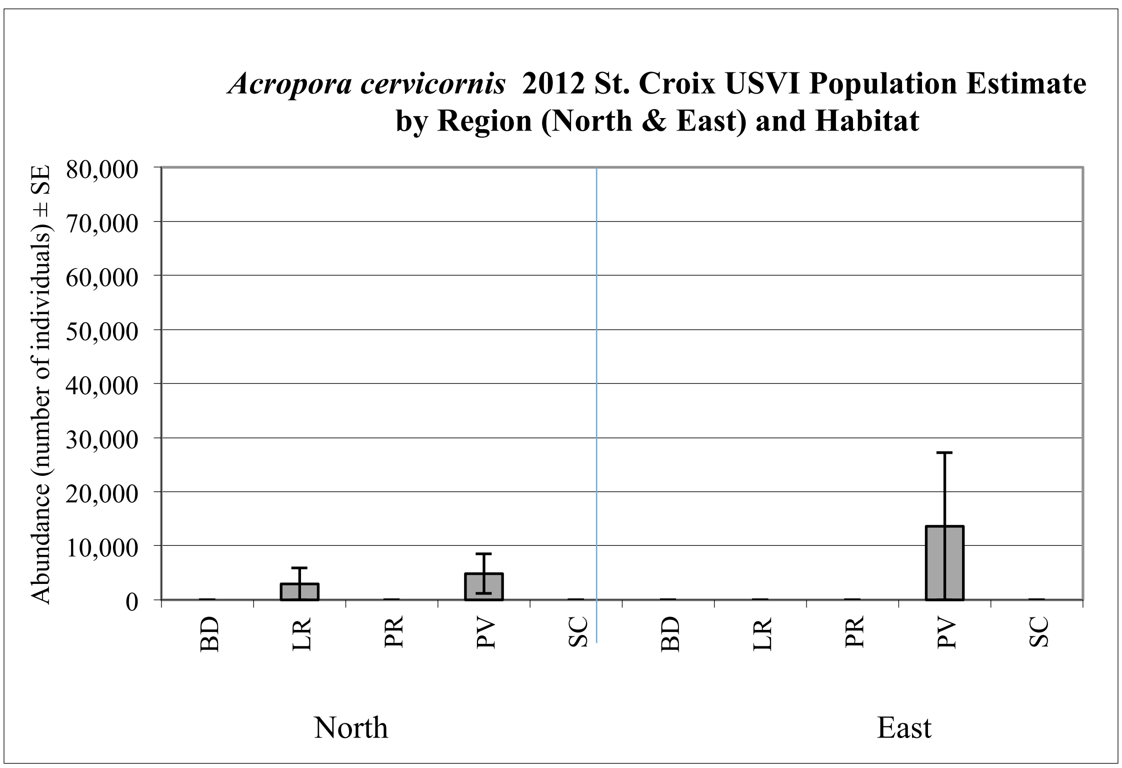


Figure 21. Estimated population sizes for *A. palmata* and *A. cervicornis* throughout study regions by habitat type in regions where colonies were located in transects.
A. palmata = North and South [not found east on Lang Bank (East) and West]. *A. cervicornis* = North and East (not found South and West). BD = Bedrock, LR = Linear reef, PR = patch reef, PV = Pavement, SCRB = Scattered coral and rock.

Conclusions and Recommendations

This program had the opportunity to document additional populations of acroporids in a wider range of locales than are traditionally surveyed since surveys were spatially randomized (unbiased). The results of this study improve our understanding of the spatial distribution and abundance of *Acropora palmata* and *Acropora cervicornis* in the insular and federal waters surrounding St. Croix. In particular, this study improves our understanding of the *A. palmata* population, which is estimated to be much larger than that of *A. cervicornis*. Acroporids were present in the North, South and East regions of St. Croix. Shallow linear reef and shallow to medium pavement habitats were most important for *A. palmata*.

The North study region emerged as exceptionally important for acroporids. The north, particularly the northeast barrier reef and the shallow waters around Buck Island, contains the most important habitat for both acroporid species, but is particularly critical for *A. palmata*. Clearly these are important areas for this coral, an observation that has been documented by many previous studies (Gladfelter & Gladfelter, 1978; Gladfelter, 1982; Mayor, 2006). This region is a high-energy environment, with relatively little impact from land-based sources of pollution (Smith et al. 2012). Because it is located upwind from Christiansted, the nearest densely populated area, it likely receives little land-based pollution. In addition, the designation of the Buck Island National Monument protects corals in this region from direct impacts, such as damage from fishing gear and anchoring, and indirect impacts, such as reductions of herbivorous fishes due to fishing.

High densities of *A. palmata* along the coastline west of Christiansted may be particularly vulnerable to mortality. High land use intensity around Christiansted, activities associated with one of the island's main channels, and the presence of the Water and Power Authority (WAPA) just west of town all could impact corals in this region. Additional resources may be considered to protect these populations from decline.

The West and South study regions had low or undetected populations of acroporids. The West St. Croix region may be naturally depauperate of acroporids, particularly *A. palmata*. While acroporids may exist in the West, shallow bedrock habitat that would support *A. palmata* is relatively rare we did not locate any colonies during our surveys of that area. Acroporids were present in low densities in the southwest of St. Croix, suggesting that the overall St. Croix population may be less vulnerable to changes due to industrial activity in this sector. Anthropogenic activities is this sector include high watershed development, agricultural land-use, and industrial plants, such as the Hovensa Oil Refinery and the

Diageo Distillery. Nonetheless, scarcity of acroporids in this region may also be a result of mortality and erosion of colonies that was caused by anthropogenic activities in the decades before monitoring. The suitability of this habitat for future populations of acroporids still needs assessment.

In St. Croix, populations in *A. cervicornis* were rarer than *A. palmata*; however, this program did not survey the entire habitat of this species. In the northern USVI, widespread populations of *A. cervicornis* are known from 18-30m depths (Smith et al. 2012). Although locating colonies at these depths is more logistically challenging due to diving considerations, they could easily be included in future surveys, particularly if done by technical diving researchers such as are trained at the University of the Virgin Islands. This would provide a more complete view of the population, particularly if deeper populations are buffered from localized stressors and global stressors, such as sea surface warming. Observations by authors suggest that *A. cervicornis* colonies near 30m depth are large (>1m) and often have thickened branches, suggesting that they are older and less prone to disturbance.

The data collected in this synoptic assessment is an important first step to assessing the status of populations in the USVI. Within St. Croix, this data can be used to refine the stratification of sampling among habitats and depths to improve population estimates. Additional extant data sources, such as National Park surveys, NOAA Biogeography Program surveys, and the National Coral Reef Ecosystem Monitoring Surveys (St. Croix, 2012), may also be used to supplement the information from this program. This strategy could be used to document “hot-spots”, where acroporids are abundant and healthy, and also “trouble-spots”, where current populations of acroporids are under threat and may need additional management intervention. Furthermore, in the northern USVI large populations of acroporids are still under-documented. Spatial surveys in the northern USVI are also critical in assessing acroporid populations, and are a natural compliment to temporal demographic monitoring.

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