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Bioassessment Tools for Stony Corals: Field Testing of Monitoring Protocols in the US Virgin Islands (St. Croix)

Final Report

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SUMMARY

The goal of this study was to field test data collection and analysis protocols for stony coral assemblages. From this study the most biologically meaningful and statistically precise methods will be selected for inclusion in a long-term reef monitoring program for the US Virgin Islands (USVI). Coral reef condition was measured at 61 reef stations in St. Croix, USVI during 2006. Three observations for stony corals were recorded: species, size, and percent live tissue. Stony corals were selected because they are primary producers of the reef environment, they provide structure and habitat for other reef organisms, and they support tourism and fisheries. Dive teams from the US Environmental Protection Agency and the USVI Division of Environmental Protection (DEP) collected physical measurements and recorded the condition of coral colonies found within a radial belt transect. Different dive teams sampling the same reef station reported very similar values indicating that the field protocol had good precision and low measurement error associated with coral measurements. Indicators of coral condition were tested against a gradient of human disturbance at three locations. Candidate metrics for assessing coral condition were derived from four categories: species abundance and composition, physical stature, biological condition, and coral community structure. Human disturbance gradients were based on visual observations and narrative descriptions of land use on shore. No quantitative or chemical measures of water quality were collected. For the most intensely disturbed area, four metrics were highly correlated with distance from an industrial point source: total surface area of coral, total live surface area, taxa richness, and average colony size. For the other two gradients, changes in indicator values were not associated with human influence, possibly because disturbance in these areas was minimal or because indicators tested here were not be capable of detecting subtle differences in reef condition. Many metrics were highly correlated with depth, even when the range was only 20–40 ft. A statistical power analysis determined that a survey area of 50 m^2 was no more precise than a survey area half that size. Coral metrics derived from this protocol had adequate precision to detect a reasonable level of change in coral reef condition that would be protective of the resource.

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INTRODUCTION

Coral reef communities surrounding the US Virgin Islands (USVI) represent a valuable economic and aesthetic resource for visitors and residents (USVI DEP & DPNR, 2004). The government of USVI recognizes their value and supports a variety of coral reef monitoring efforts (Nemeth et al., 2004). Along with rivers, streams, lakes and estuaries, the Federal Clean Water Act (CWA, 1972) provides a regulatory framework for the assessment, management and protection of near-shore water resources, including coral reefs. Both the CWA and the US Virgin Islands Territorial Water Pollution Control Act (1972) outline regulations for protection of surface waters and the biological assemblages they support. Two programs specifically rely on biological monitoring data in coastal marine areas: the 301(h) waiver program and the 403(c) ocean discharger program. The waiver program allows marine dischargers to defer secondary treatment if they can show the discharge does not affect biological communities. The ocean discharger program requires all dischargers to marine waters to provide an assessment of the biological community in the area of the discharge (Jameson et al., 1998).

The CWA authorizes the US EPA to determine appropriate minimum levels of protection and provide national oversight to State, Territorial and Tribal programs; however, considerable flexibility and discretion are left to States and Territories to design their own programs and establish levels of protection beyond any national minimums (EPA, 2005). The regulatory framework of the CWA requires States and Territories to adopt water quality standards (WQS) to protect their waters. WQS are part of State law and define the water quality goals for a water body by designating the use(s) and setting criteria necessary to protect the use(s). WQS include three parts: 1) designated uses, 2) numeric and narrative criteria that protect the uses, and 3) antidegradation policies to prevent deterioration of high-quality waters (EPA, 2006). Examples of designated uses include drinking water, navigation, and support of aquatic life. Once designated uses are described, criteria for the protection of each use must be defined. Criteria may be tied to threshold values of physical, chemical or biological measurements of aquatic condition. When criteria fail to support the designated uses, a water body is listed as impaired. States and Territories are required to assess and report whether their surface waters are supporting or failing to support designated uses. At all levels, water quality standards are much better defined for freshwater and estuarine environments than they are for coral reefs where standards and guidelines are just beginning to emerge (Fisher, in press).

For the USVI, designated uses for surface waters are described as follows (USVI DEP & DPNR, 2004; Hutchins, 2004):

Class A – Waters are for the preservation of natural phenomena requiring special conditions with existing natural conditions that shall not be changed. Class A water standards are the most stringent of the three classes because of the pristine or near pristine state of waters in this classification.
Class B – Waters are for the propagation of desirable species of marine life and for primary contact recreation.

Class C – This classification is similar to Class B, except that it has slightly less stringent water quality standards for a limited number of parameters.

Most States, Tribes, and Territories have similar types of narrative criteria that specify the protection of aquatic life as a designated use. Phrases used above such as “preservation of natural phenomena” and “propagation of desirable species” are an example of this type of narrative criteria for the support of aquatic life (a type of designated use). EPA’s Office of Water has developed guidance to help States, Territories and Tribes better characterize and more specifically define aquatic life uses as part of their water quality standards (EPA, 2005). EPA recognizes that direct measurements of the resource that is of greatest concern, e.g., coral reef communities, are more protective than surrogate measures, e.g., water chemistry.

In 2001, the National Research Council (NRC) published a report on *Assessing the TMDL Approach to Water Quality Management* in which the authors recommended *tiering* designated uses for improving the decision-making related to setting water quality standards (NRC, 2001). The NRC found the CWA’s goals to be too broad to provide the operational definition of designated uses needed to support aquatic life and recommended greater specificity in defining aquatic life uses. For example, rather than stating that a water body needs to be “fishable,” the designated use should specifically describe the expected fish assemblage (e.g., cold water fishery, warm water fishery, or salmon, trout, bass, etc.). *Tiered aquatic life uses* (TALUs) are bioassessment-based statements of expected biological condition in specific water bodies that allow more precise and measurable definitions of *designated aquatic life uses* (EPA, 2005).

Designated uses are written in qualitative, narrative terms; therefore, the challenge is to relate a water quality criterion to the designated use. Establishing this relationship is more straightforward when the water quality measure, or criterion, is closely and meaningfully related to the designated use. For this reason, the NRC recommended the use of biological information to define more appropriate aquatic life uses. Specifically, biological criteria, or biocriteria, define a desired biological condition for a water body and can be used to evaluate the biological integrity of a water body (Karr and Chu, 1999). The TALU approach provides an interpretative framework for developing a technical program that will tighten the linkage between narrative use statements and numeric biological criteria (EPA, 2005).

Individual WQS for States, Tribes, and Territories provide the foundation for the management of surface waters and pollution control programs. WQS provide the basis for determining whether a water body is impaired. Impairment triggers a process to evaluate the total maximum daily load (TMDL) of pollutants at the site and management actions are required to bring the site back into compliance with its designated use (Karr and Yoder, 2004). Historically, States, Tribes, and Territories have taken different approaches to defining their WQS. Different approaches are acceptable to EPA as long as a minimum standard is protected. In other words, States, Tribes and Territories are encouraged to be more protective than the national minimum. Once WQS are in place, States, Tribes, and Territories are authorized to implement monitoring programs that allow them to report on the attainment of those standards and to identify and prioritize waters not attaining standards for future management and abatement programs (EPA, 2005).

Project goals

The primary purpose of this project is to assist USVI in developing assessment tools, i.e., scientifically defensible protocols and a long-term monitoring program, for coral reefs. This report describes the field testing of data collection and analysis protocols derived from a coral survey conducted around St. Croix (USVI) during 2006. A companion report described the long-term monitoring approach and survey design for USVI (Fore et al., 2006b).

This report focuses on identification of biological indicators that can be used to define biological criteria for the protection of coastal resources and for managing the local human activities that threaten them. Although coral reefs are also sensitive to global disturbance (e.g., elevated seawater temperatures), USVI DEP cannot manage human disturbance at the global scale; therefore, our focus for this study was on developing tools to assist local managers.

Data collected for this study were used to 1) determine the optimum size for a field transect, 2) compare data collected by different dive teams, 3) evaluate the response of coral indicators to a gradient of human disturbance, 4) characterize coral condition in management zones expected to have different designated uses, and 5) measure the potential ability of the coral metrics to detect change in reef condition.

METHODS

Study area

Stony corals were surveyed at 61 reef stations around St. Croix, USVI, during February 2006. Reef stations were selected to satisfy two objectives: 1) test for association between coral condition and human disturbance gradients in the watershed and near-shore environment and 2) summarize coral condition in each of seven geographic areas surrounding St. Croix. The type of coral reef observed in a near-shore environment depends on geographic orientation (leeward or windward), patterns of water movement, and depth profile. Seven coastal management zones (CMZ) were defined by resource managers and scientists at the USVI Division of Environmental Protection (DEP) and Department of Planning and Natural Resources according to the type of coral habitat observed and the type of human land use within the water, along the shore, and inland (Figure 1). Six of the CMZs are under the managerial jurisdiction of USVI DEP, but the Buck Island Reef National Monument off the northeast coast of St. Croix is managed by the National Park Service.

Starting on the west side and moving in a clockwise direction: the West CMZ includes the city of Frederiksted and has the only large public dock on the island used by cruise ships (Figure 2). Although cruise ships visit infrequently, traffic is expected to increase during coming years. Recently, the area around the pier has a history of small boat and yacht use which may be associated with anchor damage to reefs and nutrient enrichment from wastewater. An earlier and more extensive history of anchorage north of the pier by much larger ships has also been documented by Toller (2005) who identified > 21 hectares north of the pier that have been impacted by large ship anchors. Also located near the pier is a small sewer overflow. The city of Frederiksted itself may be expected to contribute to general disturbance. Further north and south from the pier, human influence decreases. The Northwest CMZ has tourism associated with diving and fishing, but otherwise only minimal human influence. Recent studies indicate that the impact of recreational diving may be greater than previously expected (Barker and Roberts, 2004). In the North CMZ is the city of Christiansted (Figure 3). The harbor at Christiansted has boat traffic and 50–75 boats moored in the harbor. Potential non-point and point sources of disturbance exist at Christiansted with urban development and a large wastewater (sewage) treatment plant that discharges to the reef area.

Moving further east, Buck Island CMZ has no human development and visitors are limited to daylight hours. Nonetheless, this area still supports recreational diving and boating. The relatively low intensity of human disturbance means that Buck Island may provide reference sites for other areas on the main island. The East CMZ excludes the reef area surrounding Buck Island. Most of the East CMZ is included in the East End Marine Park, designated in 2003; the park includes “no take” zones for fishing, recreational areas, and a turtle preserve. Sources of disturbance from shore include run-off and sediment from several unpaved and steep roads in this zone. Studies in St. John and St. Thomas have shown that erosion from unpaved roads can be very high and that

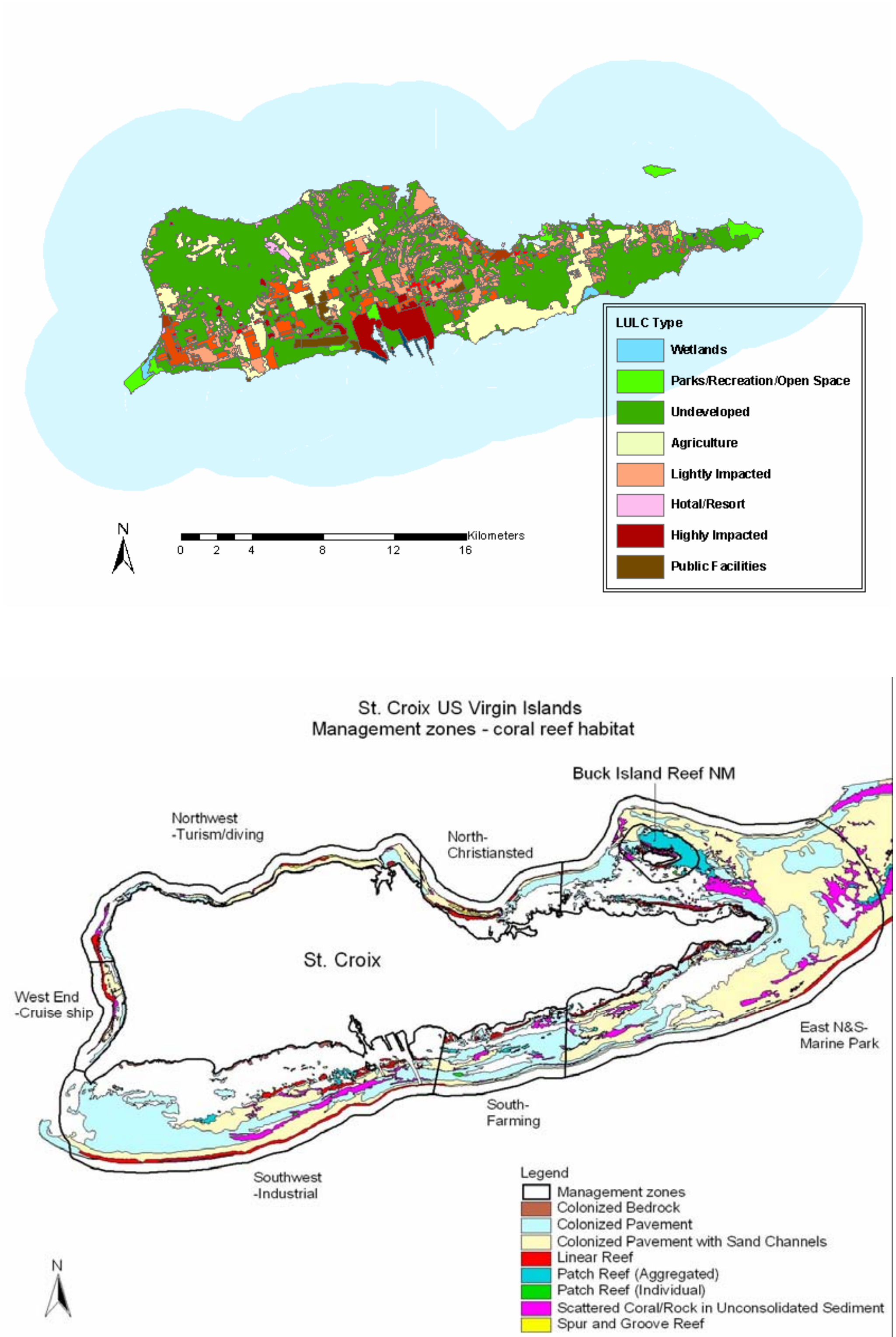


Figure 1. Land use/land cover classes (upper panel) and coastal management zones and coral reef habitat types for St. Croix (lower panel; Hutchins, 2004).

sedimentation can reduce coral cover (Nemeth and Nowlis, 2001; Ramos-Scharrón and MacDonald, 2005). The South CMZ is an agricultural area (Figure 4). Adjacent to this is the Southwest CMZ in which are located a large petroleum refinery, dredged channels for commercial docks, the airport, the land fill, and a rum distillery that has discharged effluent for >50 years. The South CMZ is nominally upstream of these disturbances because prevailing wind and current are ENE. Most of the disturbance appeared to be confined to the Southwest CMZ.

The number of reef stations surveyed varied within each CMZ (Table 1). In general, stations were selected to test specific hypotheses and to evaluate the merit of the various field sampling protocols. Our intention was not to identify locations for a long-term monitoring design and no randomization was used in station selection. Most stations were selected to provide data for the three independent tests of metric responsiveness to a human disturbance gradient. Other stations were included to characterize stony coral populations in different management zones. Three stations had duplicate samples collected, that is, different dive teams surveyed the same radial belt transect to evaluate the measurement error associated with the field sampling protocol and to determine how easily the method could be transferred to new dive teams. Within a reef area, sampling locations (stations) were selected to represent the best available habitat, that is, areas with a variety of coral colonies. Areas with sand, seagrass, or only minimal coral cover were avoided.

Table 1. Number of reef stations sampled in each CMZ.
CMZ name, number of reef stations sampled, number of stations included within a gradient of human disturbance, and whether duplicate sampling occurred in the CMZ.

		Number of stations	
CMZ	***Total***	***In Gradient***	***Duplicate sampling***
Buck Island	10	0	BI03: 6 dive teams; full transect
East	9	4 (South) + 5 (North gradient)	
North	11	11 (North gradient)	
Northwest	4	0	
South	5	5 (South gradient)	
Southwest	10	10 (South gradient)	
West	12	12 (West gradient)	WE07: 4 dive teams; ½ transect WE14: 6 dive teams; ¼ transect
Total	**61**		

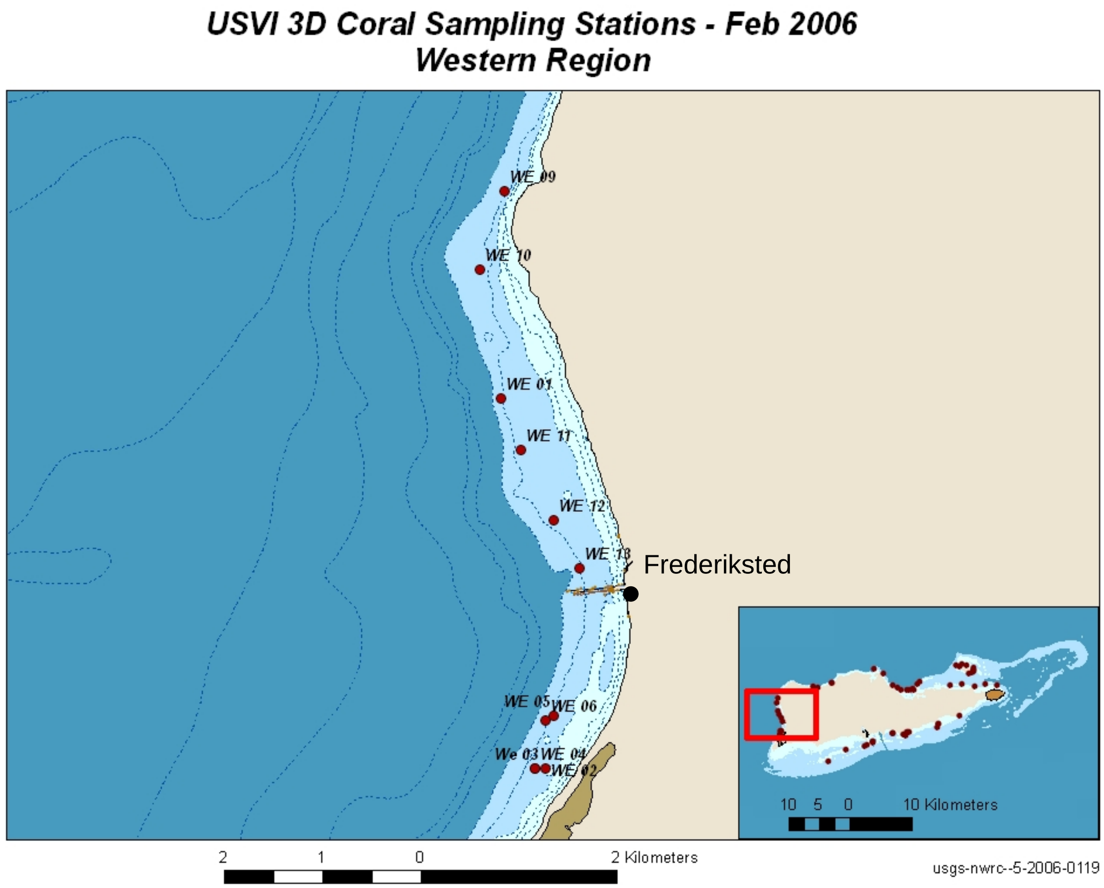


Figure 2. Reef station locations in the West CMZ (WE). The public pier is just south of station WE13.

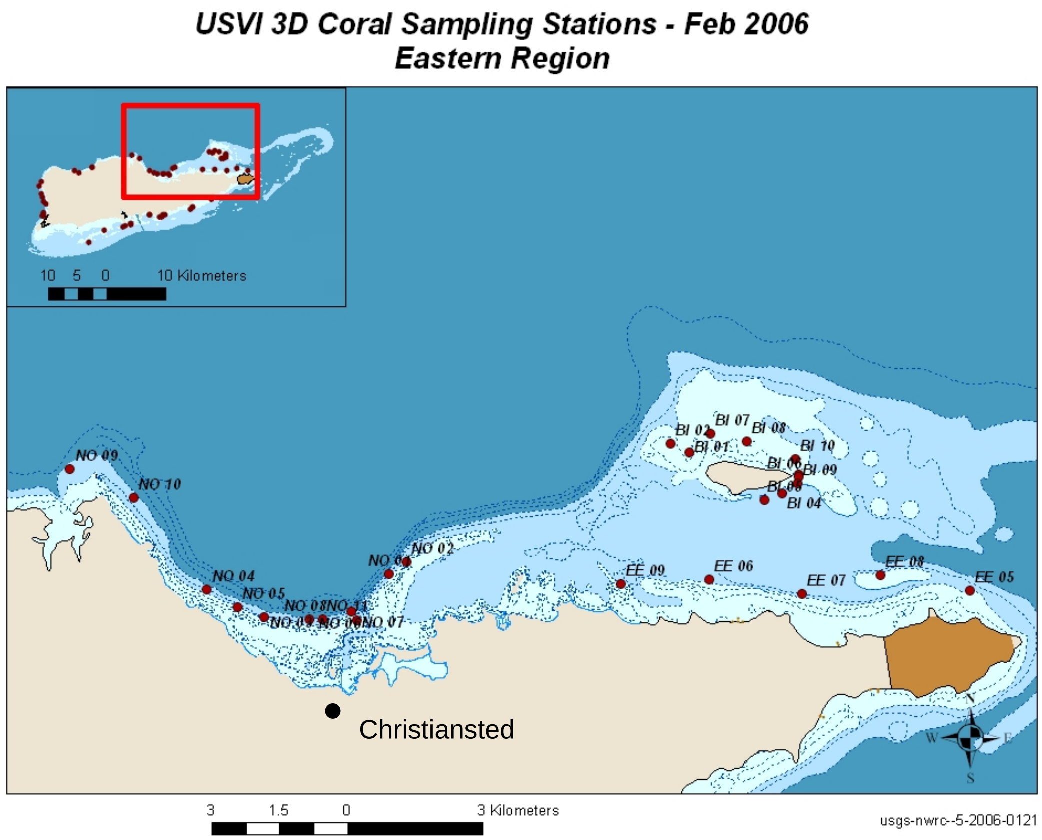


Figure 3. Reef stations located in the North (NO), East (EE), and Buck Island (BI) CMZs.

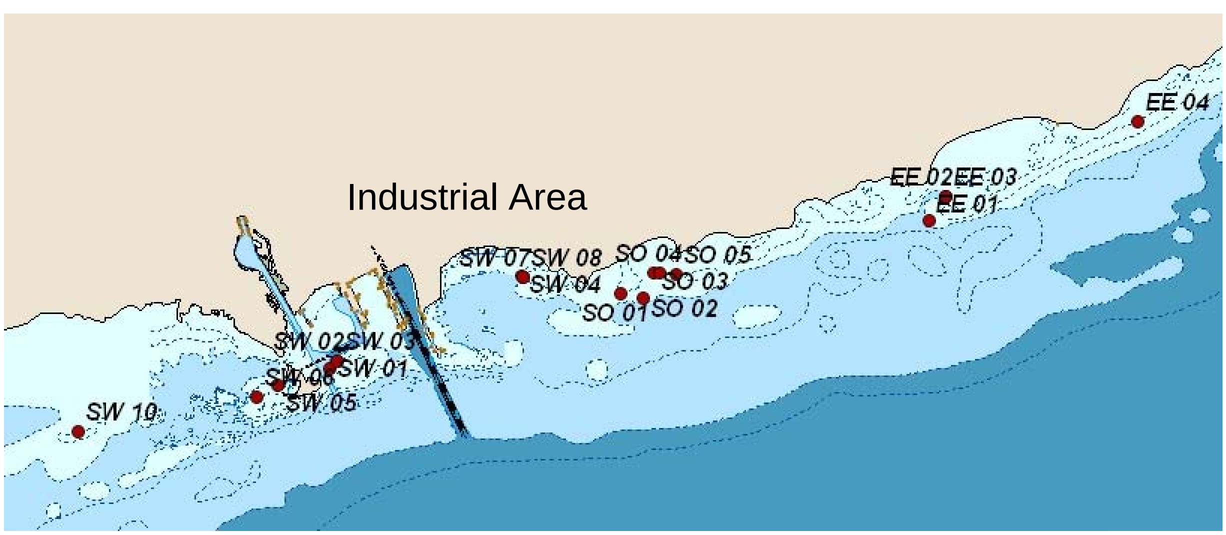


Figure 4. Reef stations along the south side of the island in the East (EE), South (SO), and Southwest (SW) CMZs.

Data collection

Each survey station was established by placing a tripod on the substrate which held an upright pole in place. A 6-m line was attached to the top of the pole. During sampling, one diver, the line tender, extended the line to its full extent and marked the spot with a start/stop flag. Markers constructed of alligator clips and beads were suspended from the line at 3- and 5-m distances from the pole so that surveyors could distinguish the 2-m band of the radial transect (Figure 5). The line tender traveled around the pole as the survey diver completed the coral measurements. At each 90^{o} increment of the belt transect, the quadrant was marked as 1 through 4. Due to the high density of coral colonies at many stations, only ½ of the radial belt was surveyed at 29 stations and the full transect was surveyed at 32 stations. At one additional station (WE14) only ¼ of the radial belt was surveyed for training purposes only. For a full radial belt, the surveyed area equaled 50.2 m^2; for a ½-transect the area equaled 25.1 m^2. For each colony found within the transect, the following data were collected: species name, maximum diameter parallel to the substrate (length), diameter perpendicular to first measurement at the center of the colony (width), maximum height from the substrate, and % of the surface area covered with living polyps. The % live tissue was recorded for each colony as 0, 0–25, 25–50, 50–75, 75–100, or 100%. For metric calculation, the middle of the range was used, e.g., for 0–25% live tissue, we used 13% for calculating sums and averages. Only corals >10 cm in their longest dimension were recorded.

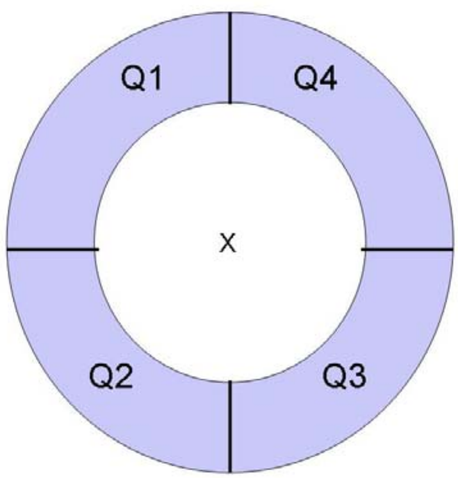


Figure 5. Schematic diagram of radial belt transect used to sample reef stations. Shaded area represents area where corals are measured. Quadrant 1 through 4 are indicated and “X” marks the location of the tripod.

Candidate metrics for stony corals
Indicators of stony coral condition related to abundance and composition, physical stature, biological condition and community structure were selected for testing (Table 2; Jameson et al., 2001; Fisher et al., 2007). Indicators that show a consistent response to different types of human disturbance in different habitat types and geographic areas are considered metrics and used to define biocriteria (Karr and Chu, 1999; Fisher, in press). The indicators described here are best qualified as "candidate" metrics because they have not been extensively tested. This study represents one such test of these candidate metrics for stony corals. Candidate metrics were calculated for each ½- transect (25 m^2 area).

Abundance and composition. The total number of colonies and the total number of unique taxa that they represent are expected to decline as human disturbance increases. For stony coral assemblages, tolerant and intolerant taxa have yet to be consistently identified although some authors recommend *Porites astreoides, P. porites, Siderastrea siderea,* and *Agaricia agaricites* as tolerant species (Tomascik and Sander, 1987). Although rare or uncommon taxa are not necessarily sensitive or intolerant, some may be. In the absence of information about which taxa are intolerant, rare taxa were simply defined as those taxa for which <20 colonies were found (out of a total of 3720 colonies for all taxa). Although the presence of dead coral may be indicative of poor reef condition, we did not quantify the abundance of dead coral heads unless they could be identified to genus. In general, coral rubble and pieces not connected to the reef could not be identified to genus; often they could not even be identified as coral.

Physical stature. An earlier study in the Florida Keys used standard-sized cubes to estimate colony size and calculated surface area by summing the areas of five sides of the cube (Fisher et al, 2007). For this study, direct measurements of each colony provided information to calculate a more exact surface area for each colony. Two equations were used to calculate the surface area depending on the ratio of the colony height to radius (measured as ½ of the maximum diameter). When the ratio is close to 1, a hemisphere is a logical choice for the geometric model of colony size ($SA_{hemi} = 2\pi r^2$). When the height is greater than the radius, a cylinder may be more appropriate ($SA_{cyl} = \pi r^2 + 2\pi rh$). For a height:radius ratio >1.3 and <5.1, a cylinder was used to calculate surface area; for other height:radius ratios, a hemisphere was used to calculate surface area. About half the colonies measured for this study were h:r <1.3; only 8 colonies were h:r >5.1.

Table 2. Description of candidate coral metrics.
Name of candidate metric, predicted response to an increase in human disturbance, and a description of how each metric was calculated. Candidate metrics were calculated for each ½- transect (25 m^2 area).

Candidate metric	Predicted response	Description
Abundance & Composition		
Number of colonies	decrease	Number of stony coral colonies >10 cm in their longest axis
Taxa richness	decrease	Number of unique taxa
% "Rare" colonies	decrease	Percent of colonies at the station that were defined as “rare” (<20 colonies found in taxon)
% SA of "rare" taxa	decrease	Percent of total surface area from “rare” taxa
Physical stature		
Total SA	decrease	Total 3D surface area of all corals found (m^2)
Average radius of all colonies	decrease	Average of the three measures of radius for each colony, then average of all colonies
Average colony SA	decrease	Average of the total 3D surface area for each colony
Biological condition		
% Live tissue	decrease	Percent live coral tissue on each colony averaged for all colonies
Live SA	decrease	Sum of live colony surface areas for all colonies
Dead SA	increase	Sum of dead (denuded) colony surface areas for all colonies
% Live SA (vitality index)	decrease	Live SA divided by Total SA
% Hermaph. colonies	increase	Percent of colonies that belong to hermaphroditic taxa
% SA of hermaph. taxa	increase	Percent of total surface area from hermaphroditic taxa
% Gonochoristic colonies	decrease	Percent of colonies that belong to gonochoristic taxa
% SA of gonochoristic taxa	decrease	Percent of total surface area from gonochoristic taxa
% Brooder colonies	decrease	Percent of colonies that belong to brooder taxa
% SA of brooder taxa	decrease	Percent of total surface area from brooder taxa
% Spawner colonies	increase	Percent of colonies that belong to spawner taxa
% SA of spawner taxa	increase	Percent of total surface area from spawner taxa
Community structure		
% SA *Diploria*	unknown	Percent of total surface area from *Diploria* spp.
% SA *Montastraea*	unknown	Percent of total surface area from *Montastraea* spp.
% SA *Porites*	unknown	Percent of total surface area from *Porites* spp.
% SA *Siderastrea*	unknown	Percent of total surface area from *Siderastrea siderea*.
Percent dominance	increase	SA of the taxon with the greatest SA divided by total SA

Total surface area (SA), which is a measure of both live and dead portions of the coral colony, is expected to decline as colonies die and are not replaced. Coral skeletons lacking live tissue are vulnerable to erosion by both biological and physical processes. Colony size measured as either average radius or as SA should also decrease with human disturbance as larger colonies are eliminated by disturbance events over time. Coral recruitment was not specifically measured for this study and only colonies >10 cm were recorded. Nonetheless, we expect a trend toward smaller colonies to indicate a change in the stony coral assemblage.

Biological condition. Coral are colonial animals that propagate somewhat like plants, thus there are several ways to quantify their abundance and relative abundance. Taxonomic groups of interest can be measured in terms of numbers of colonies or as surface area of tissue. "Percent live tissue" was calculated as the average of the amount of live coral tissue observed on each colony. Thus, a small or large colony will contribute the same amount of information to the final value. In contrast, "percent live SA" calculated the area of each coral colony that was alive, summed that area for all colonies, and divided the value by the sum of total SA for all colonies. This calculation has also been called the "vitality index" (Fisher, 2007). For this metric large colonies contributed proportionately more information to the final station value. "Live SA" is the total area of live tissue summed over all colonies. "Dead SA" was the total dead surface area summed over all colonies.

When conditions are stable, we expect taxa with separate male and female colonies (gonochoristic) to be more common than hermaphroditic taxa which may be more typical in uncertain conditions. Similarly, in more stressful conditions we expect coral colonies with a reproductive strategy designed to take advantage of changing conditions to be more common. Thus, we might expect to find more brooders than spawners in less disturbed locations and more spawners in locations with higher disturbance. Although not tested specifically for stony corals, these ideas have been applied to numerous other taxonomic groups to interpret patterns in demography and reproductive strategy across species (Reznick et al., 2002). Richmond and Hunter (1990) list reproductive characteristics for a subset of the taxa found in St. Croix (Table 3).

Community structure. Four genera contributed the greatest overall percentage of surface area to St. Croix coral reefs. *Diploria*, *Montastraea*, and *Porites* included multiple species; *Siderastrea siderea* was the only species in its genus. Expectations for these particular taxa in response to human disturbance are unknown. Dominance was measured as the taxon with the largest SA divided by the total SA for the station * 100%. Dominance quantified the relative importance of the dominant species at a station, regardless of which species it is. We expect dominance to increase with disturbance as tolerant taxa dominate the assemblage.

Table 3. Natural history information for coral species observed in 2006.
Stony coral name, the total number of colonies found, total surface area for all stations, reproductive type (hermaphroditic or gonochoristic), reproductive mode (brooder or spawner), and whether the taxon was designated as rare for this study.

Taxon name	# colonies	SA (cm2)	Repro. type	Repro. mode	Rare?
Acropora cervicornis	2	4,919	H	S	Rare
Acropora palmata	6	76,261	H	S	Rare
Agaricia agaricites	26	6,461	H	B	
Agaricia fragilis	6	1,135		B	Rare
Agaricia humilis	1	147	H	B	Rare
Agaricia larmarckii	2	339			Rare
Agaricia spp	33	14,901		B	
Agaricia tenuifolia	1	579			Rare
Colpophyllia natans	34	129,184			
Dendrogyra cylindrus	5	35,374	G	S	Rare
Dichocoenia stokesii	19	8,796			Rare
Diploria clivosa	91	99,672			
Diploria labyrinthyformis	66	75,006			
Diploria strigosa	643	668,383	H	S	
Eusmilia fastigiata	17	10,144			Rare
Isophyllia rigida	2	510	G	B	Rare
Isophyllia sinuosa	1	179	G	B	Rare
Isophyllia spp	1	101	G	B	
Madracis decactis	41	18,679			
Madracis mirabilis	17	12,995			Rare
Madracis spp	5	3,083			
Meandrina meandrites	87	53,917			
Millepora complanata	27	47,395			
Montastraea annularis	337	2,392,281	H	S	
Montastraea cavernosa	541	1,139,876	G	S	
Montastraea faveolata	227	1,270,845			
Montastraea franksii	53	181,716			
Montastraea spp	1	179			
Mycetophellia larmarckiana	1	472			Rare
Mycetophyllia spp	5	1,153			
Oculina varicosa	1	693			Rare
Porites astreoides	820	411,344	H	B	
Porites porites	226	431,571	G	B	
Siderastrea siderea	316	491,697	G	S	
Solenastrea bournoni	5	18,626			Rare
Stephanocoenia intersepts	54	13,237			

Data analysis
Different sets of stations were used to answer different questions. For metric testing, only stations located along the proposed gradients of human disturbance were used. Metrics were tested independently across all three of the gradients. For the southern gradient of human disturbance, metric response was tested using stations in three CMZs (East, South, and Southwest). For the northern gradient all stations were in the North CMZ; for the western gradient all the stations were in the West CMZ. The field protocol was evaluated using specific approaches. For example, information was needed to examine sources of variability associated with different station locations, different transect halves (microhabitat differences), and different dive teams (measurement error). Only BI03 had duplicate samples collected by different dive teams for both halves of the transect. When comparing different sources of variance, e.g., measurement error and microhabitat differences, the preferred method estimates variance components from the same set of locations rather than using different sets of locations to estimate different variance components because the results will be more reliable. The ideal design for our study to estimate variance components would have included duplicate samples by different dive teams and full transect sampling at every station; this was too time consuming and only a few stations had duplicate sampling. For this analysis, only stations in Buck Island CMZ were included; there were two reasons for this. First, inclusion of all 61 stations would have made the design even more unbalanced than it was with only a few stations having duplicate dive team samples. Second, we were interested in the relative contribution of station differences within a management zone rather than across all zones around the island.

For statistical power analysis, a third set of 16 stations was used to evaluate differences associated with the two halves of the belt transect (microhabitat differences) and differences associated with station locations in the larger reef. For this comparison we were not interested in comparing measurement error associated with dive teams. Stations in the Buck Island, East, and West CMZs were used for this analysis. Stations in the North and Northwest CMZs were not used because most stations had only ½-transects sampled. Stations in the South and Southwest CMZs were not included because coral density and surface area were much lower than for the other CMZs. Power analysis tested for the amount of change in metric values that could be detected within a CMZ.

Metric testing. Candidate metrics were tested for their correlation (Spearman's *r*) with distance from the approximate center of human disturbance in three locations: from the public dock on the west side, from the marina in Christiansted harbor, and from the commercial dock on the south side. Not all of the 61 stations were located within a gradient of human disturbance. For metric testing, 19 stations along the south side in the East, South, and Southwest CMZs, 12 stations in the West CMZ, and 16 stations in the North CMZ were used to test for metric response across a gradient of human disturbance (see Table 1). No quantitative information related to water chemistry or other measures of site condition were collected as part of this study to test metrics. All metrics were calculated for ½-transects. For stations with full transects surveyed, metric values from the two ½-transects were averaged so that each station had only a single value for each metric.

Evaluation of the field survey protocol. Coral reef communities represent a continuous resource that could be divided into discrete sampling units in a variety of ways. For this study radial belt transects were used to define the survey area at each station. Data collected were used to determine whether the entire belt must be surveyed or if a smaller area would suffice. For any monitoring study, the smallest area that will provide a reliable estimate of site condition is preferred in order to minimize the time spent at each station.

Components of variance analysis was used to evaluate the relative contribution to the overall variance of coral metrics due to differences associated with stations, transects, and measurement error. Components of variance uses an ANOVA model, one for each coral metric, to partition the different sources of variance and compare their relative contribution. Measurement error was defined as the variance associated with duplicate surveys at the same station by different dive teams. This source of variance should be small relative to the variance due to differences in stations or zones targeted in a monitoring program. If dive teams obtain similar values for the same station, we can assume that the protocol is robust and transferable to new situations. Variance associated with the two sides of the radial belt represents the natural variability in coral condition at the microhabitat level. Variance of metric values due to different station locations represents the differences associated with depth, current, substrate, or other natural features. The objective of any monitoring effort is to detect effects of human disturbances beyond the natural variability associated with different station locations.

Ten stations in the Buck Island CMZ were used to compare the different sources of variance for seven candidate coral metrics. Although duplicate samples were collected on two other stations in the West CMZ, only BI03 had full transect surveys that allowed a simultaneous evaluation of variance due to stations, transects within stations, and dive teams. The design for this analysis was unbalanced ($n = 23$). Of the 10 stations used, three had full transects surveyed while the others had only ½-transects, and all the duplicate surveys were collected at a single station. Six dive teams sampled both ½-transects on BI03.

Power analysis to detect changes in reef condition. Statistical power is the probability of detecting a change should a change truly occur. Statistical power is a function of precision: the more variable a measure is, the more difficult it will be to detect a difference between samples. Thus, a greater difference must be observed to detect change in a more variable measure of coral condition. Variance is used in statistical power equations to calculate the probability of detecting a difference for a selected statistical model and known variance.

For this study, statistical power analysis was used to answer two questions. First, what is the amount of change that we could expect to reliably detect using these candidate coral metrics? This describes how sensitive the metrics are to change. Second, are full transect samples better than ½-transect samples for detecting change? If so, it must be determined whether it is sufficiently better to offset the costs of surveying twice the area at the same location. It is possible, for example, that sampling more stations will provide greater power and a more efficient monitoring strategy.

For simplicity, a two-sample *t* test was used to compare and evaluate the relative precision of seven candidate coral metrics. To estimate the amount of change in a candidate metric that we can potentially detect, the minimum detectable difference (MDD) for a two-sample *t* test can be calculated (Zar, 1984). A two-sample *t* test evaluates the difference between two sets of samples. The samples could be from reef stations in areas with different types of human disturbance or they could be from the same reef areas sampled at different times. If the two samples are from the exact same reef stations through time, a *paired t* test should be used instead. The MDD represents the smallest difference between the mean metric values for the two sets of reef stations that would indicate a statistically significant change.

Once the variance is known (or estimated), alternative sampling designs can be compared for their relative sensitivity to detect change, either through time or between different reef areas. For example, the relative sensitivity of a design with samples from 5, 10 or 15 reef stations can be compared, even if 15 stations were not sampled in the original survey. Data from the 2006 survey in St. Croix were used to estimate the variance. Because values for the seven candidate coral metrics differed by CMZ, a one-way ANOVA design was used to estimate the variance within each CMZ. The assumption for this approach to statistical power analysis is that the two samples used in the *t* test would be from within the same CMZ. Thus, the mean squared error from the ANOVA represents the variability associated with different stations within a CMZ. This approach controls for the effect of CMZ location.

Sixteen stations in three CMZ's with full transect surveys and minimal human disturbance were used to calculate MDD: three stations in the Buck Island CMZ, six in the East CMZ, and seven in the West CMZ. Statistical power was calculated separately for seven candidate metrics using two data sets. The first data set used only data from a single ½-transect at each of the 16 stations. The second data set used the *average* value from the two ½-transects for each station. It was hypothesized that information provided by the full transect (represented as an average of the two ½-transects) would be more precise than a ½ transect, yielding a smaller MDD and a greater ability to detect change in reef condition.

MDD was calculated as:

$$\text{MDD} \geq \sqrt{\frac{2s^2}{n}}\left(t_{\alpha(1),\nu} + t_{\beta(1),\nu}\right),$$

Where s^2 = the mean squared error from ANOVA for each metric,
n = the number of stations sampled on each occasion in a CMZ,

$t_{\alpha(1), \nu}$ = the *t* value for alpha of 0.1 for a 1-sided test,
$t_{\beta(1), \nu}$ = the *t* value for beta of 0.1 for a 1-sided test, and
$\nu = 2n - 2$.

Patterns in population structure. To evaluate patterns in population structure at the species level, the seven most common species were plotted according to the number of colonies found in each size class. Size classes were defined based on the current data set and used surface area to define six bins with a fairly even distribution of colonies across bins. Bins doubled in size for each category for six species; for *Porites astreoides* the bin size increased evenly. Patterns associated with both species abundance and distribution of colonies across size classes were used to investigate possible differences in coral composition, size and health in the different CMZs.

RESULTS

A total of 4647 colonies were measured for this study; 3720 were observed on the 61 stations and an additional 927 colonies represented repeat measures by different dive teams for training and protocol testing. A total of 31 taxa were recorded. The dominant species as measured by both number of colonies and total SA were *Diploria strigosa*, *Montastraea annularis*, *M. faveolata*, *M. cavernosa*, *Porites porites*, *P. astreoides*, and *Siderastrea siderea* (see Table 3).

Sources of variance for the field survey protocol

This analysis compared the sources of variance for seven candidate coral metrics. When a dive team surveys a field station and measures coral condition, there are multiple sources of variability for the values observed. Some differences represent nuisance variance, other differences are those we wish to detect. For example, when different dive teams observe slightly different numbers of coral colonies in a transect, this represents measurement error, a nuisance variance that should be minimized. Differences associated with transect placement were captured by the different halves of the radial belt and represent another source of nuisance variance. In contrast, station differences should be relatively large compared to nuisance sources because these represent the types of differences that may have been created by anthropogenic stressors.

The metrics least affected by nuisance sources of variance were number of colonies, total SA, and average colony SA (Figure 6). For all seven coral metrics the percentage of the total variance due to differences associated with duplicate sampling by the six different dive teams was small compared to station differences. The greatest differences in dive teams were associated with % live tissue and live SA. Both these metrics rely on approximate measures of live tissue cover made by the surveyor. Differences associated with transects within stations were larger than diver differences for four of the seven metrics: # colonies, # taxa, % live tissue, and % live SA. Different dive teams obtained very similar values for the seven metrics. Microhabitat differences at the transect level were large enough for some metrics to be of concern and were evaluated separately (see “Power analysis” below).

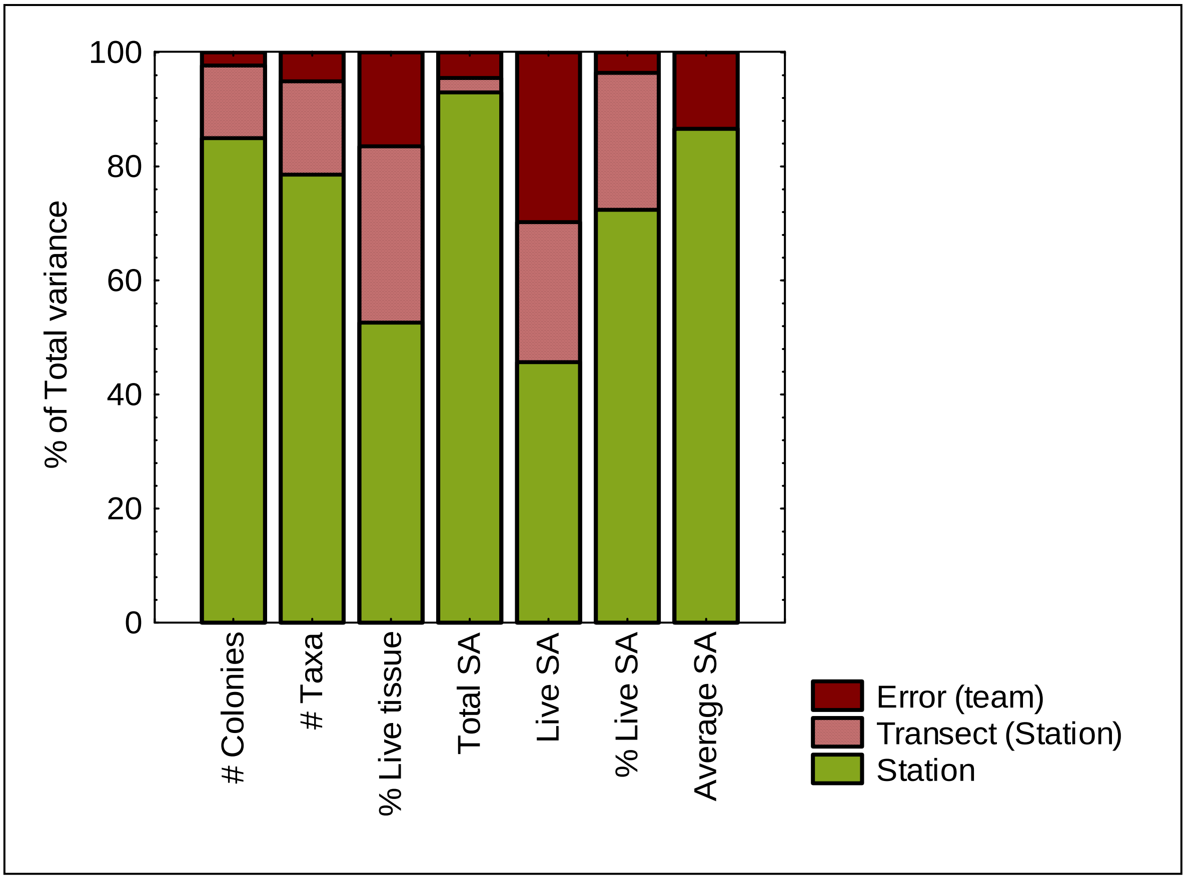


Figure 6. Variance components for candidate coral metrics. Total variance for stations in the Buck Island CMZ was partitioned according to differences associated with 10 stations, two transects within stations, and measurement error associated with six different dive teams.

Metric response to human disturbance

Changes in the coral assemblage were most obvious around the commercial docks on the south side of St. Croix. The number of taxa, total SA, and average colony size all declined at stations closest to the docks (Table 4). Live SA and dead SA both declined for stations closest to the docks (Figures 7-10). Although we expect more disturbed stations to have more dead coral, results from the south side indicate that stations further from the disturbed area had more coral overall, both live and dead. Thus, less disturbed sites had more dead coral (see parenthetic value in Table 4 for Dead SA).

Table 4. Correlation of candidate coral metrics with disturbance and depth.
Name of candidate coral metric, its correlation with distance from the center of human disturbance and correlation with depth below the surface for three gradients on the south, west, and north sides of the island (Spearman's *r*, only correlation values >0.4 or <–0.4 are shown). Correlation was calculated separately for distance and depth in each of the three areas. Metrics used in subsequent analyses are noted by an "*". Correlation for dead SA for the south gradient is noted parenthetically because correlation was in the opposite direction predicted.

Candidate metric	**Distance (South)**	**Depth (ft)**	**Distance (West)**	**Depth (ft)**	**Distance (North)**	**Depth (ft)**
N =	**19**	**19**	**12**	**12**	**16**	**16**
Abundance & Composition						
Number of colonies *						
Total number of taxa *	0.53					0.51
% "Rare" colonies	0.54	0.66				
% SA of "rare" taxa	0.52	0.69				
Physical stature						
Total SA *	0.79			0.50		
Average radius of all colonies	0.67			0.77		
Average SA of all colonies *	0.66			0.75		
Biological condition						
Average % live tissue *				-0.47		
Live SA *	0.66			0.41		
Dead SA	*(0.78)*			0.58		
% Live SA *		-0.46		-0.59		
% Hermaph. colonies			-0.54	0.53		-0.44
% SA of hermaph. taxa			-0.69	0.63	-0.46	
% Gonochoristic colonies				-0.59		
% SA of gonochoristic taxa			0.54	-0.73		
% Brooder colonies				0.72		
% SA of brooder taxa				0.47		
% Spawner colonies				-0.71		-0.54
% SA of spawner taxa						
Community structure						
% SA *Diploria*			0.45	-0.84	-0.43	-0.59
% SA *Montastraea*	0.45			0.70		0.53
% SA *Porites*			-0.54	0.42		
% SA *Siderastrea*				-0.79		
Percent dominance				0.51		

In the West CMZ, metrics were much more strongly associated with depth than with distance from the public dock even though station depth was relatively narrow (20-41 ft.). The deeper stations were nearest the dock while more distant stations were in more shallow water ($r = -0.59$). Many candidate coral metrics related to physical stature, biological condition and community structure were strongly associated with depth. The few metrics that were associated with distance from the dock were also highly correlated with depth.

For the gradient in the North CMZ, distance from Christiansted was only associated with two coral metrics, one of which (SA of *Diploria*) was also correlated with depth. A few additional metrics were also associated with depth.

Several candidate metrics were highly correlated with both distance from human disturbance and depth. For example, percent rare colonies and percent SA of rare colonies might be correlated with human disturbance if the influence of depth were controlled. Other candidate metrics such as % SA of *Diploria* were less promising given its opposite response to disturbance for gradients on the north and west sides.

Seven coral metrics were selected for additional analysis. Four metrics were selected because they were correlated with distance from the docks on the south side but not with depth: # of taxa, total SA, average SA, and live SA. Number of colonies was lower near the center of disturbance on the south side, although not significantly correlated with distance, and was also selected. Average radius of all colonies was not selected because it was highly correlated with average SA. Two other candidate metrics, although not correlated with a gradient of human disturbance, were selected for additional analysis. These two metrics were % live tissue (colony average) and percent live SA. We were interested in these two candidate metrics for their potential as indicators of change within a location compared to itself over time. These two metrics were included in the power analysis to determine if they were simply too variable to reliably detect change in coral condition.

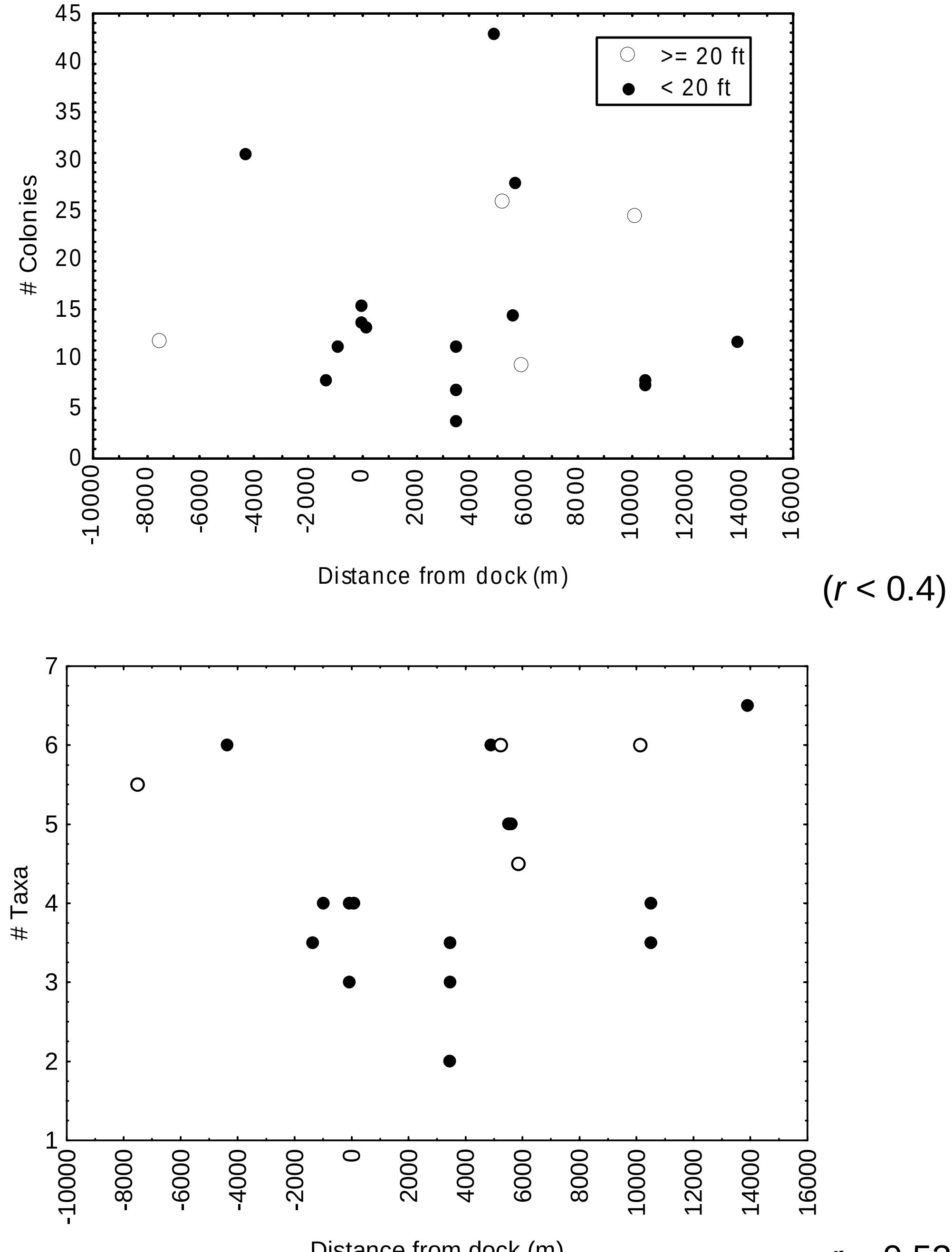
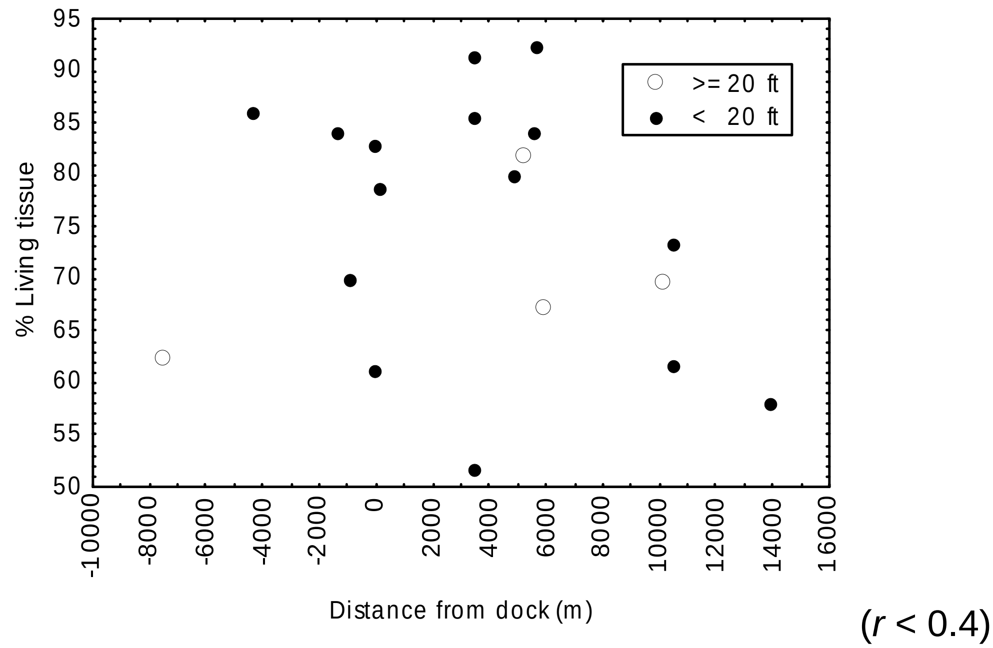


Figure 7. Number of colonies and number of taxa plotted against distance from the commercial dock on the south side of St. Croix. Negative distances were locations west of the dock, positive distances were east of the dock. Correlation coefficients were calculated for the absolute value of the distance from the dock (n = 19 stations; Spearman's *r*-values from Table 4). Correlation coefficients < 0.4 were not considered biologically significant.



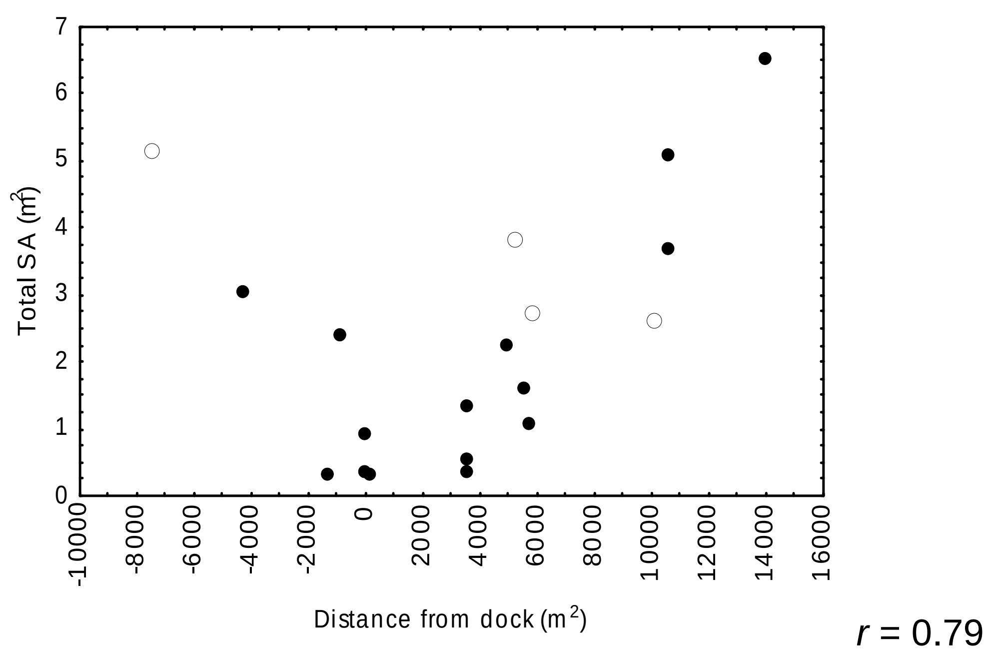
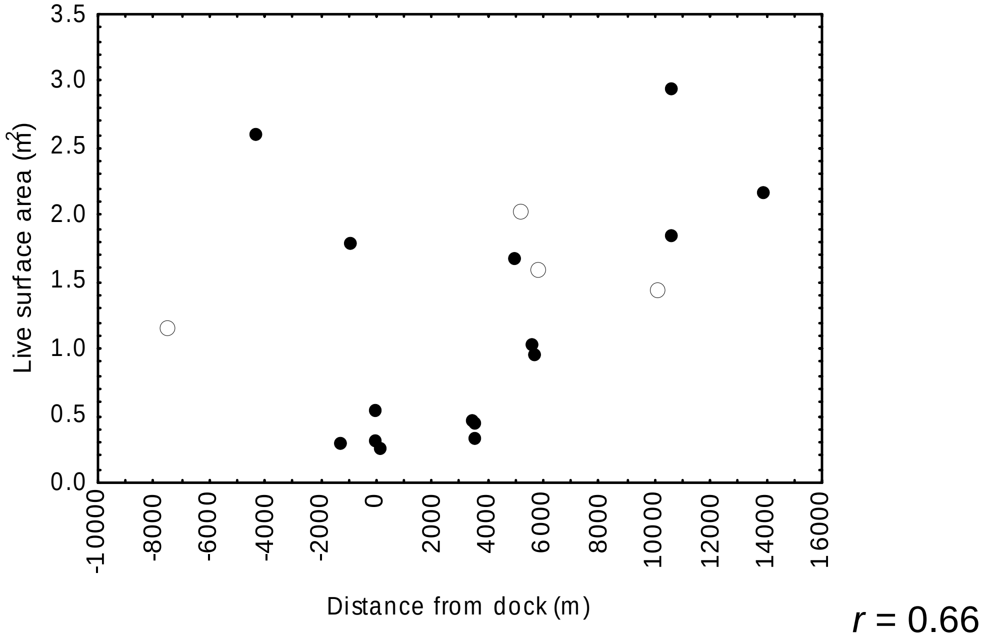


Figure 8. Percent live tissue (averaged over all colonies) and total SA plotted against distance from the commercial dock on the south side of St. Croix. Negative distances were locations west of the dock, positive distances were east of the dock. Correlation coefficients were calculated for the absolute value of the distance from the dock (n = 19 stations; Spearman's *r*-values from Table 4). Correlation coefficients < 0.4 were not considered biologically significant.



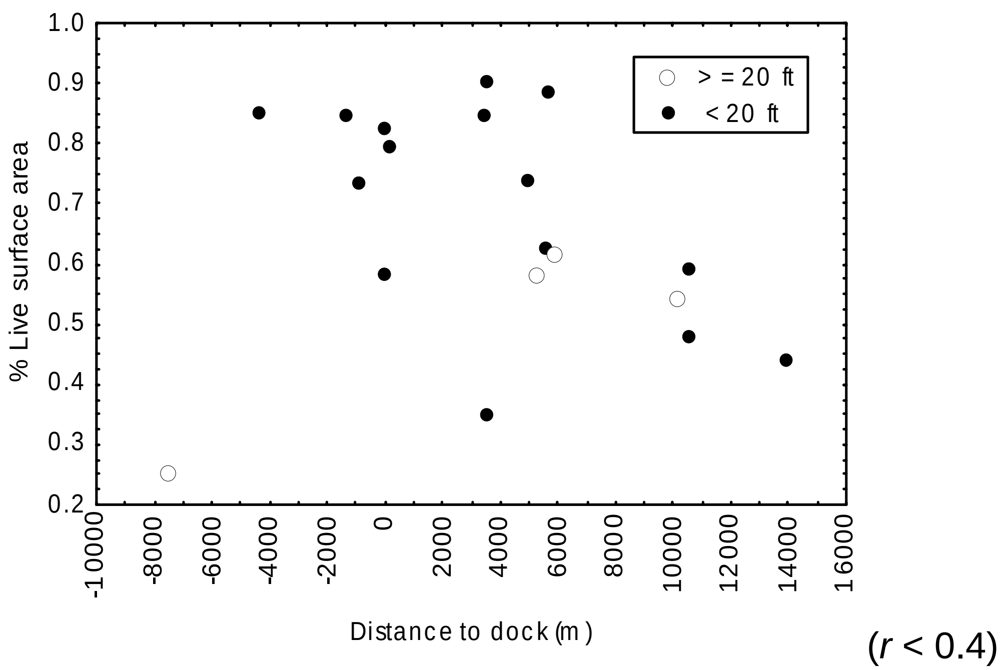


Figure 9. Live surface area and percent live surface area (shown as decimal values) plotted against distance from the commercial dock on the south side of St. Croix. Negative distances were locations west of the dock, positive distances were east of the dock. Correlation coefficients were calculated for the absolute value of the distance from the dock (n = 19 stations; Spearman's *r*-values from Table 4). Correlation coefficients < 0.4 were not considered biologically significant.

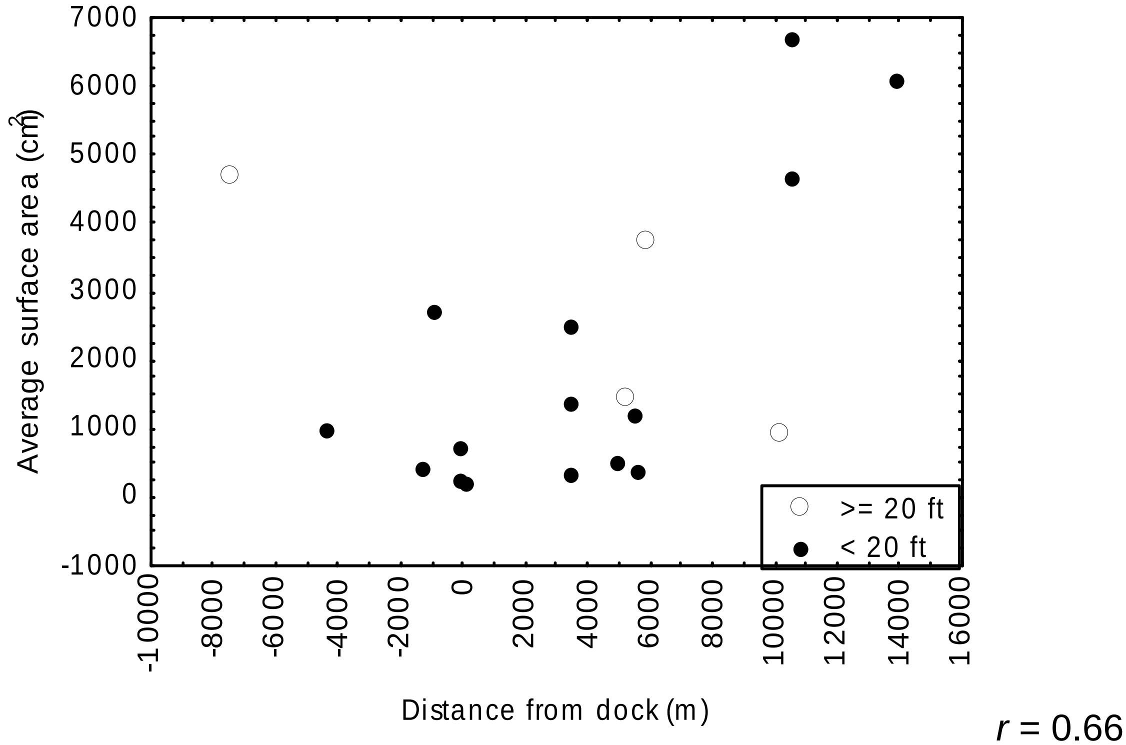


Figure 10. Average surface area (averaged for all colonies) plotted against distance from the commercial dock on the south side of St. Croix. Negative distances were locations west of the dock, positive distances were east of the dock. Correlation coefficients were calculated for the absolute value of the distance from the dock (n = 19 stations; Spearman's *r*-values from Table 4). Correlation coefficients < 0.4 were not considered biologically significant.

Natural variability associated with habitat differences

Although the coral assemblages differed visibly from one geographic area to another (see "Biological comparison of CMZs" below), distinct habitat types within a CMZ were sometimes difficult to identify in the field. In the South and Southwest CMZs, back reef, shallow fore reef, and deep fore reef habitat were observed. Fore reef along the most seaward side was too deep (>60 ft.) to sample in these CMZs. In the North, Northwest and West CMZs, most of the coral was found along a reef habitat that sloped away from shore. Back reef habitat was evident in the West, Northwest, and North CMZs, but had very little coral present. The East CMZ may include multiple habitat types and additional sampling is needed to characterize this CMZ. The Buck Island CMZ had both back reef and shallow fore reef habitat.

Differences in coral assemblages associated with depth were more obvious. For example, *Diploria* spp. declined in relative abundance with depth while *Montastraea* spp. increased. The number of colonies, the number of taxa, and total SA all increased with depth across the 61 stations sampled. Percent live tissue (averaged across colonies) and percent live SA both decreased with depth.

Biological comparison of CMZs

Stations in the Buck Island and East CMZs varied in depth from ~5–40 ft. The deepest stations were located on the north and west sides of the island. The shallowest stations were along the south side. Differences associated with depth may be driving some of the differences observed in the candidate coral metrics across zones (see Table 4 above; Figure 11). The number of colonies recorded was also a very strong predictor of the number of taxa that were found (Figures 11, lower panel and Figure 12, upper panel). For two of the least disturbed zones, Buck Island CMZ had a low number of colonies per ½-transect and fewer taxa; in contrast, the Northwest CMZ had more colonies and more taxa compared to other zones. Total SA and live SA showed similar patterns across the zones with lowest cover in the South and Southwest CMZs and higher cover in the Buck Island, North, Northwest and West CMZs (Figure 13). The largest colonies as measured by the average SA of individual colonies were found in the Buck Island and East CMZs (Figure 14, lower panel). The smallest colonies were found in the Northwest and South CMZs. The pattern for percent live SA was the opposite, with more live surface area observed in zones with smaller colonies (Figure 14, upper panel).

Percent live tissue (colony average; see Figure 12, lower panel) and percent live SA (see Figure 14, upper panel) also showed similar patterns across zones. Highest values for both metrics were observed in the South and Southwest CMZs where disturbance was highest. High values for live tissue in the most disturbed locations were the opposite of original predictions. Corals in these areas were small and sparse, but exhibited high live tissue coverage. Lower values for live tissue were observed in the Buck Island and West CMZs.

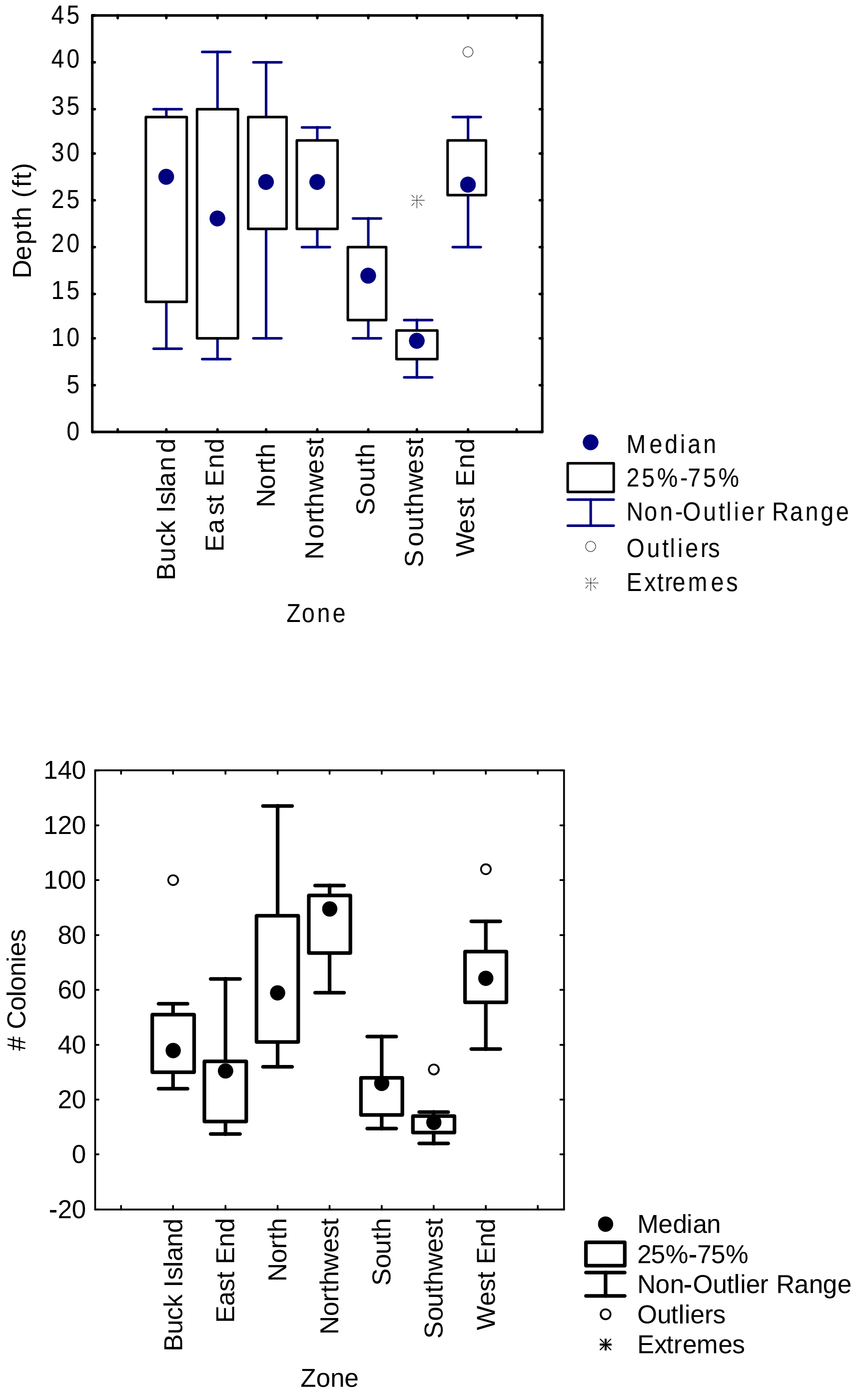
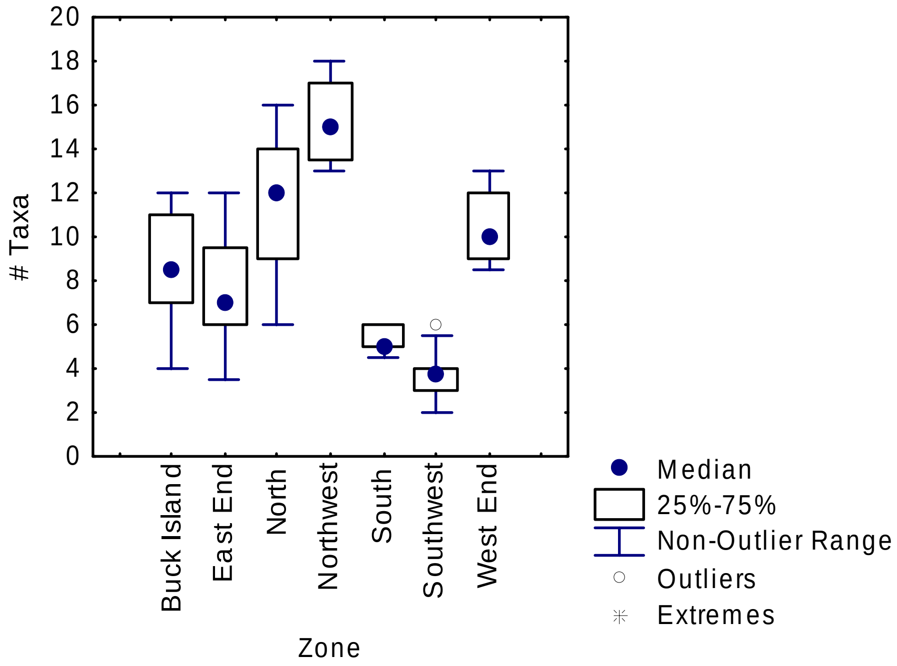


Figure 11. Depth and number of colonies for each CMZ. See Table 1 for number of stations in each CMZ.



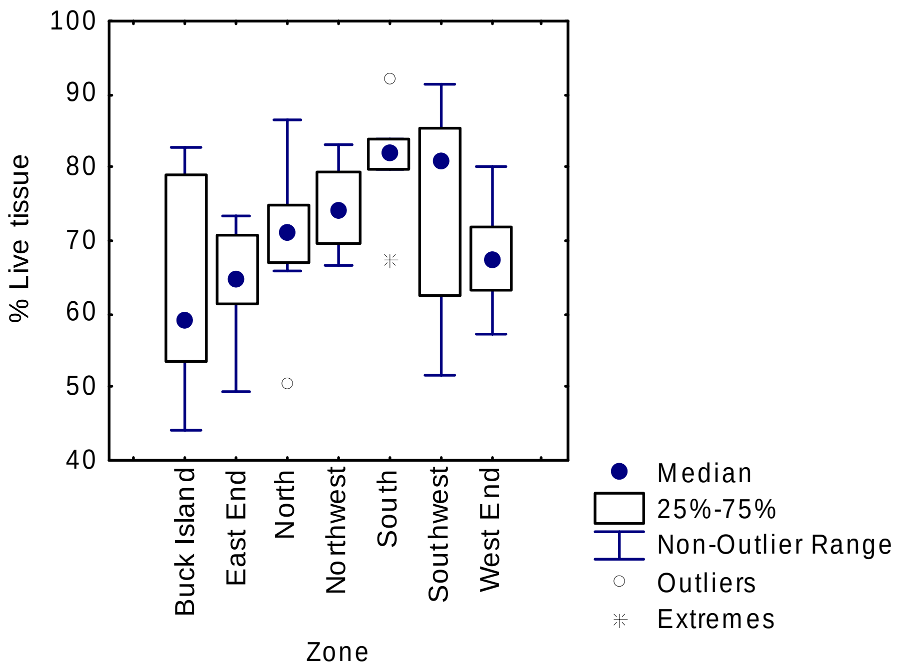
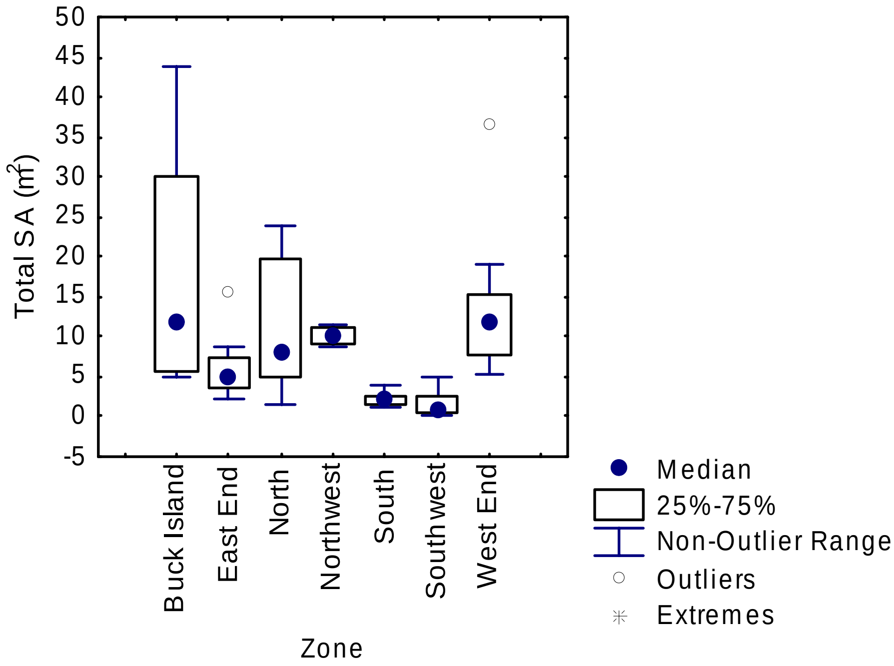


Figure 12. Number of taxa and percent live tissue (averaged for all colonies) for each CMZ. See Table 1 for number of stations in each CMZ.



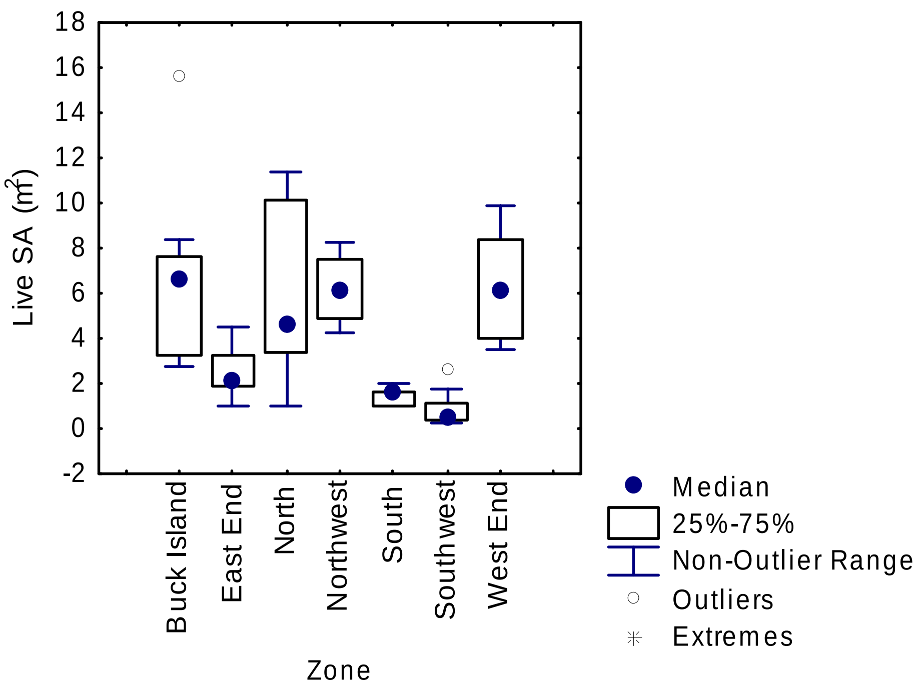


Figure 13. Total surface area and live surface area for each CMZ. See Table 1 for number of stations in each CMZ.

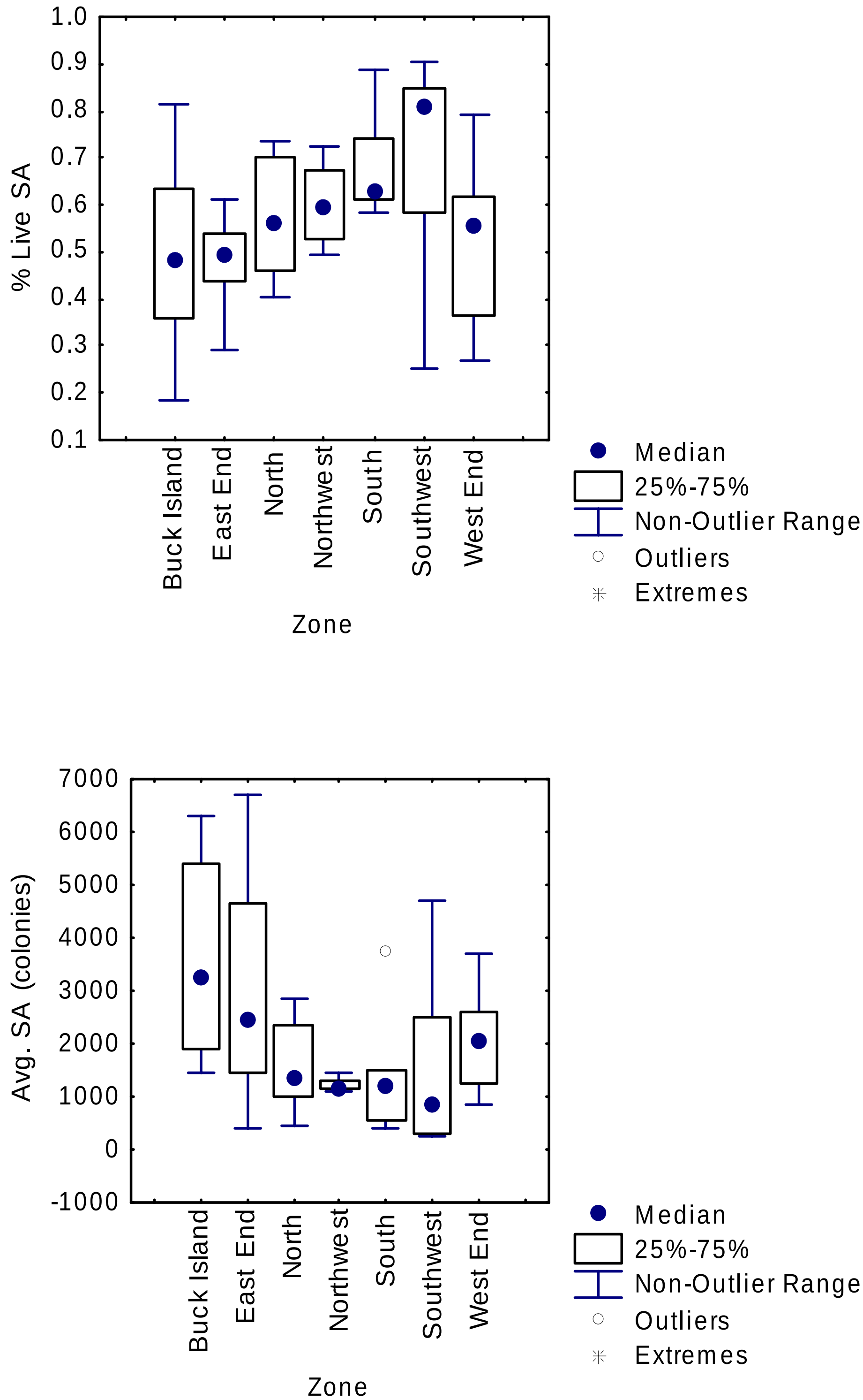


Figure 14. Percent live surface area (shown as decimal values) and average surface area (for all colonies) for each CMZ. See Table 1 for number of stations in each CMZ.

Power analysis

Although transect location within a station contributed a considerable amount to the overall variance of several coral metrics, the difference in precision associated with metrics calculated from a single ½-transect vs. metrics calculated from the average of two ½-transects (full transects) was minimal. For the 16 stations in 3 CMZs with full transect surveys, several of the seven coral metrics differed in average values by zone. The ANOVA model used to estimate variance compensated for these zonal differences and provided an estimate of the variance associated with different stations within a zone.

For a single ½-transect sampled at each station, if five stations in a CMZ are surveyed, the number of colonies would have to decline by 17 or more to represent a statistically significant change (p = 0.1 for a one-sided t test; Table 5). For 10 stations, a smaller decline in the mean number of colonies (12 colonies) would be significant. Similarly for all metrics, an increase in the number of stations surveyed corresponded to an increase in sensitivity to detect a change in coral condition (and a smaller MDD). When more information was used to calculate metrics from each of the 16 stations by averaging metric values for both ½-transects, the MDD changed little. In a few cases the MDD increased and for a few cases it declined (see parenthetic values in Table 5). For cases in which power increased for smaller sample sizes, the differences were small and can be attributed to noise in the data and should not be interpreted as meaningful differences. All the values for MDD were close for both the analyses (using one or two ½-transects). Lack of difference in MDD values for the different metrics supports the idea that no gain in precision was associated with full vs. ½-transects.

Table 5. MDD values for candidate coral metrics.
Name of candidate metrics, mean value for 16 stations (n = 3 Buck Island, n = 6 East CMZ, n = 7 West CMZ), mean squared error from a 1-way ANOVA (with CMZ as the 1 factor), and minimum detectable differences (MDD) for 5, 10 and 15 stations. The first values shown are the MDD values based on one ½-transect at each station; in parentheses are the MDD values for the average of two ½-transects for each station.

Candidate metric	Mean	MSE	MDD_5	MDD_10	MDD_15
# Colonies	38.0	96.99	17 (20)	12 (13)	9 (11)
# Taxa	7.5	2.08	3 (3)	2 (2)	1 (2)
% Live tissue (colony avg.)	69.4	51.25	13 (12)	9 (8)	7 (6)
Total SA (m^2)	8.0	5.02	4 (4)	3 (3)	2 (2)
Live SA (m^2)	4.4	5.11	4 (3)	3 (2)	2 (2)
% Live SA	0.55	0.02	0.2 (0.2)	0.2 (0.2)	0.1 (0.1)
Average SA (cm^2; colonies)	2,766	3.7×10^6	3,429 (2,907)	2,303 (1,953)	1,852 (1,570)

The relative sensitivity of each coral metric was compared by converting the MDD to a percentage of the mean. For this comparison, average SA was the least sensitive and percent live tissue could detect the smallest change relative to its mean (Table 6). For total SA, the metric most highly correlated with the disturbance gradient on the south side, a 27% decline would be detectable if 15 stations were sampled each time.

Table 6. Detectable change as a percent for candidate coral metrics.
Candidate metric name, mean value for 16 stations (n = 3 Buck Island, n = 6 East CMZ, n = 7 West CMZ), and percent change that would be significantly different for 5, 10, and 15 stations. Percentage calculated as MDD/Mean * 100%.

Candidate metric	Mean (N=16)	MDD_5	MDD_10	MDD_15
# Colonies	38.0	46%	31%	25%
# Taxa	7.5	34%	23%	18%
% Live tissue (colony avg.)	69.4	18%	12%	10%
Total SA (m^2)	8.0	49%	33%	27%
Live SA (m^2)	4.4	92%	62%	49%
% Live SA	0.55	45%	30%	24%
Average SA (cm^2;colonies)	2,766	124%	83%	67%

Population structure

The seven most abundant species differed in terms of their distribution around St. Croix. More colonies of *Diploria strigosa* were found in the North CMZ around Christiansted (Figure 15). For all three species of *Montastraea*, the greatest number of colonies was found in the West CMZ (Figure 16). *Porites astreoides* was much more common that *P. porites* in all zones and most abundant in the West CMZ while *P. porites* was more commonly found in the Buck Island and East CMZs (Figure 17). *Siderastrea siderea* was least common in the Northwest and Buck Island CMZs, the two zones with the least amount of human influence (Figure 18). For most species at most sites, a proportionately larger number of colonies were found in the smaller size classes, indicating a larger number of younger colonies. *Montastraea faveolata* and *Siderastrea siderea* showed some tendency to have a more even spread of colonies across the size classes. For four species, the most even distribution of colonies across class sizes was found in the Buck Island CMZ. For *D. strigosa, M. annularis, P. astreoides*, and *P. porites* the greatest proportion of large colonies was found in the Buck Island CMZ.

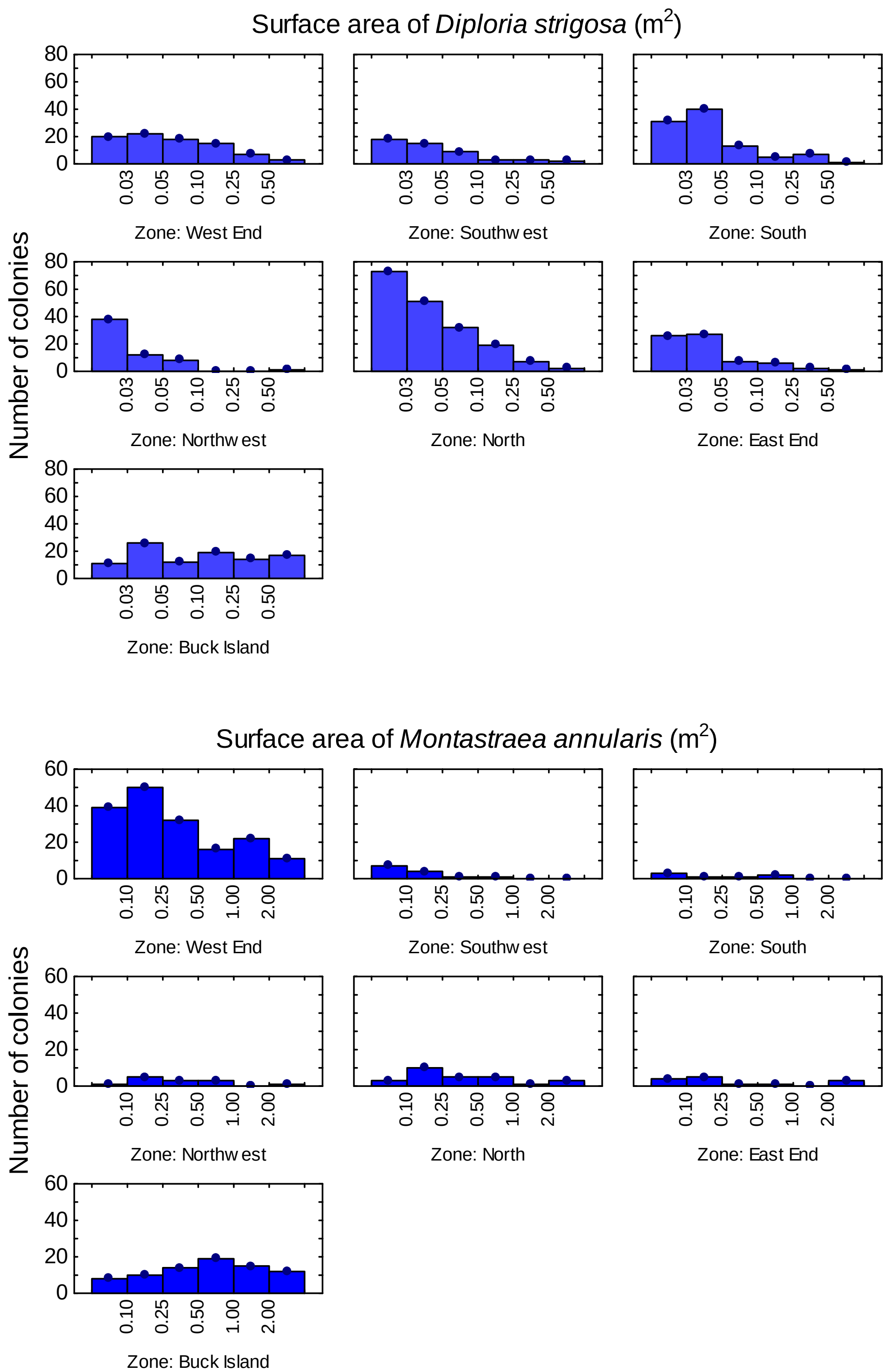


Figure 15. Number of colonies by size class for *Diploria strigosa and Montastraea annularis.* Shown are number of colonies by size for each CMZ . Note that size classes differ by species.

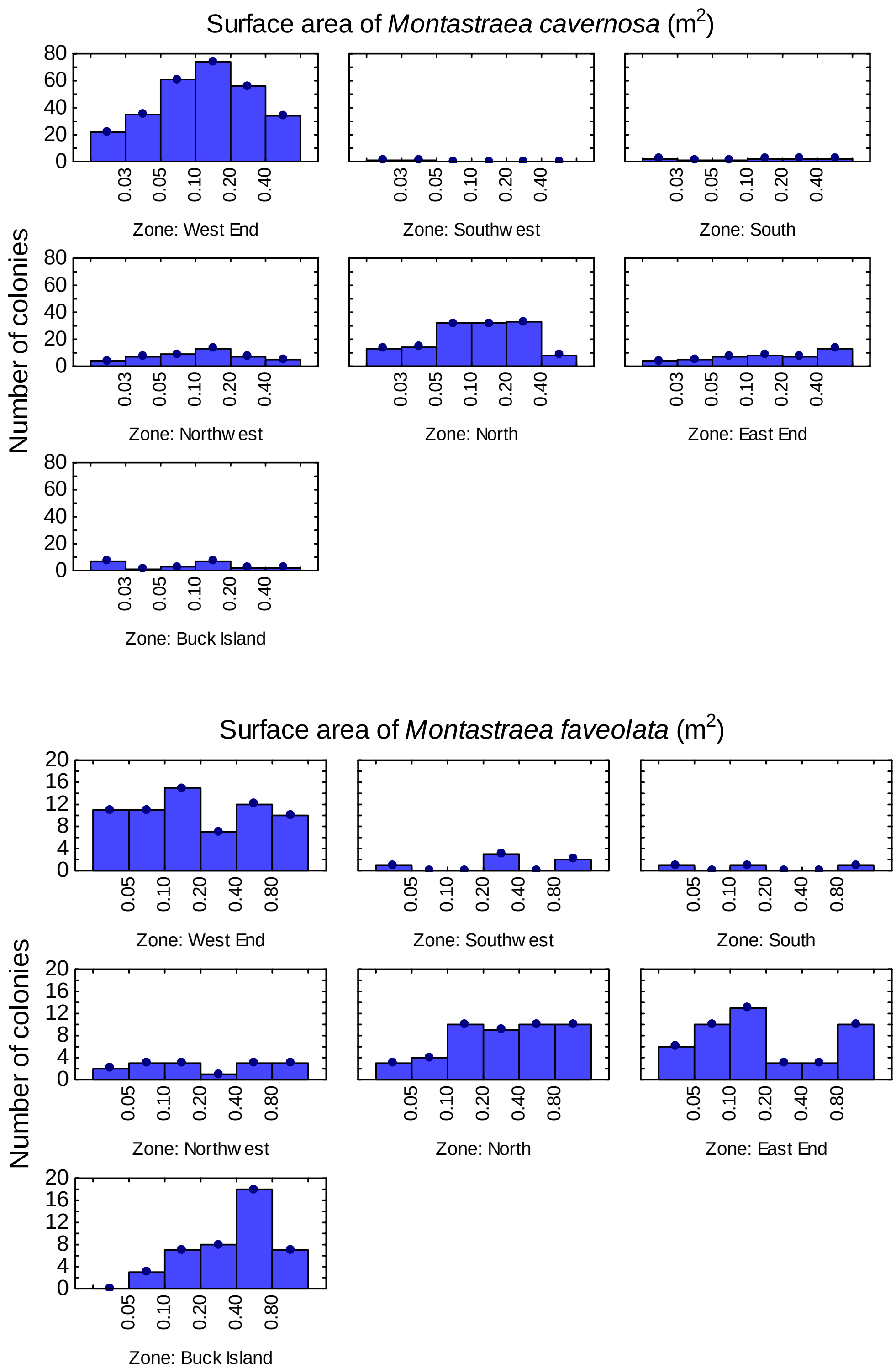


Figure 16. Number of colonies by size class for *Montastraea cavernosa* and *M. faveolata.* Shown are number of colonies by size for each CMZ. Note that size classes differ by species.

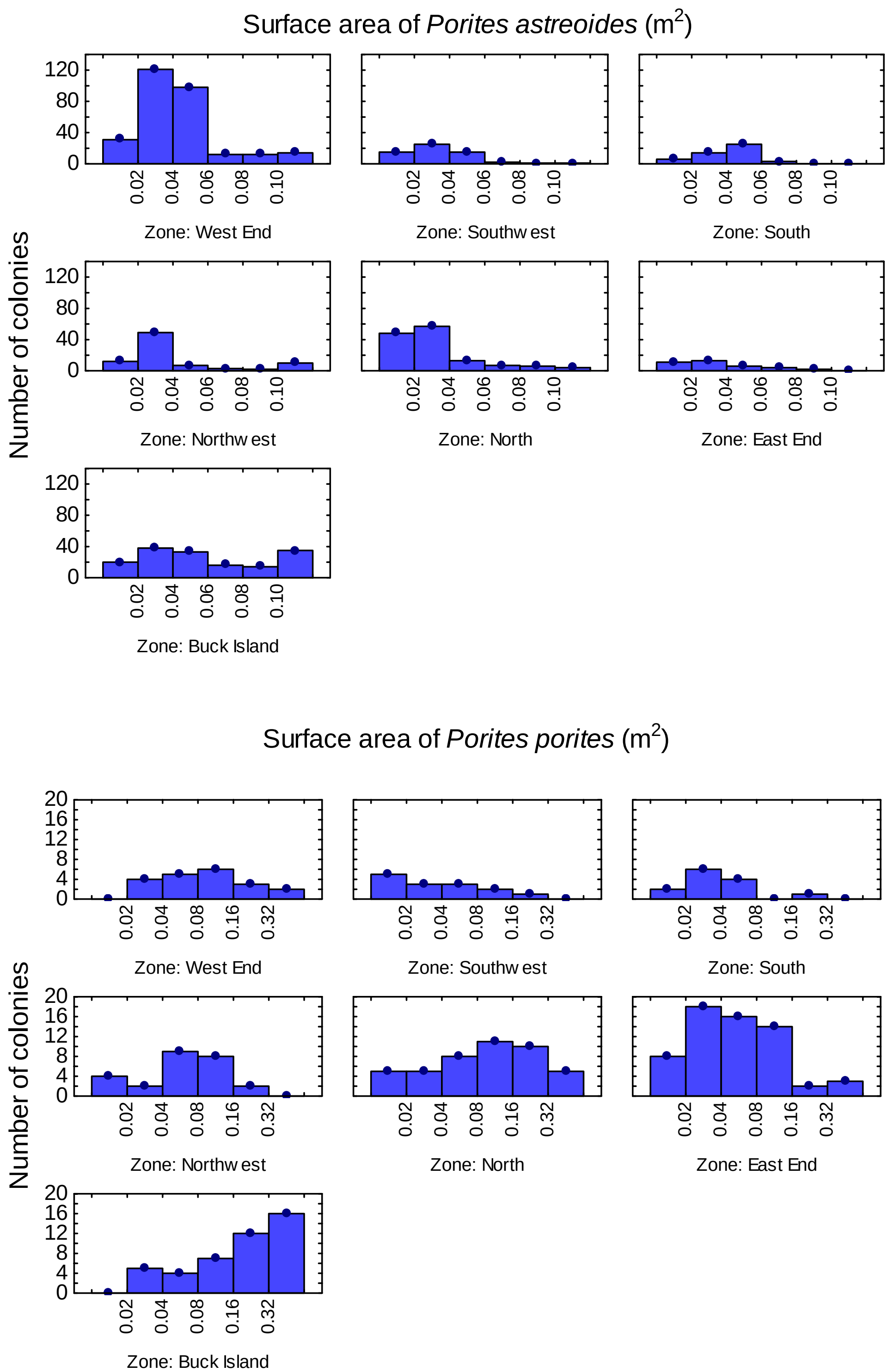


Figure 17. Number of colonies by size class for *Porites astreoides* and *P. porites.* Shown are number of colonies by size for each CMZ. Note that size classes differ by species.

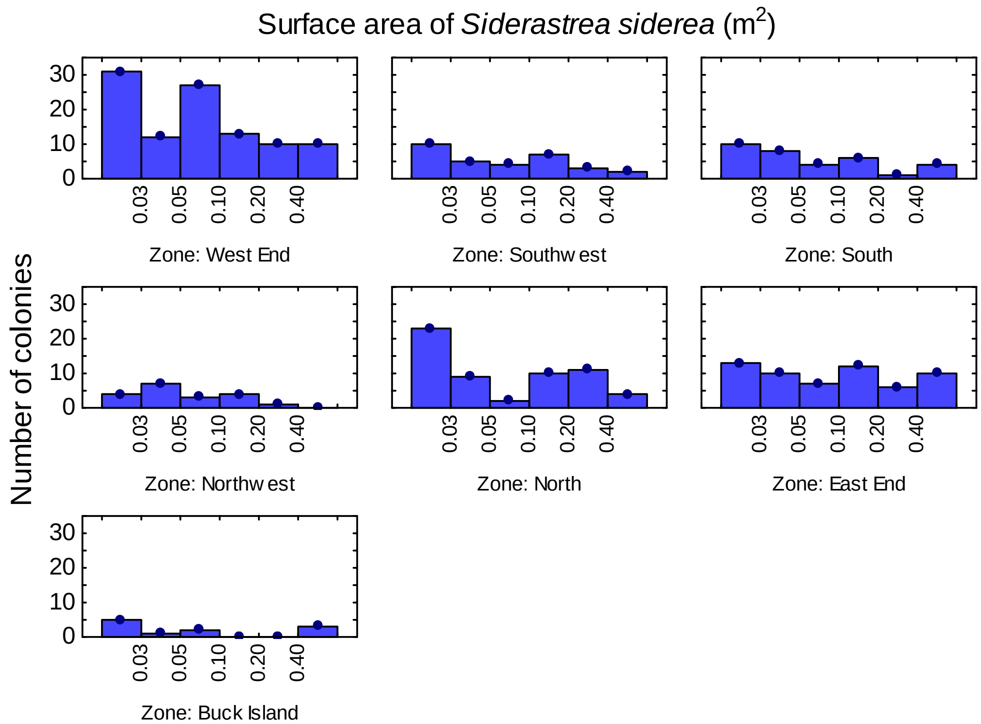


Figure 18. Number of colonies by size class for *Siderastrea siderea.* Shown are number of colonies by size for each CMZ. Note that size classes differ by species.

DISCUSSION

The focus of this study was to identify meaningful biological indicators of reef condition and to determine efficient data collection procedures to measure them. Once field tested, these indicators can be used in a probabilistic survey design to estimate and monitor reef condition throughout USVI (Fore et al., 2006b). A good bioindicator must be strongly and consistently correlated with independent measures of human disturbance in a variety of contexts, have a plausible biological connection to human-induced changes in the environment, and have adequate precision to detect a change in resource condition should a change occur (Yoder and Rankin, 1998; Fore, 2003). A good indicator should also be relatively immune to differences associated with natural conditions such as depth, seasonality, or annual variability. Biological measures that satisfy these criteria are referred to as “metrics” in the biomonitoring literature (Karr and Chu, 1999). For stony corals, metrics tested here were referred to as “candidate metrics” because they have yet to satisfy all the above criteria. Candidate metrics in four categories were tested against a gradient of human disturbance in three different areas surrounding St. Croix. A subset of those metrics was then evaluated for their statistical precision and ability to detect change over time.

Bioassessment is a relatively new endeavor for coral reef communities compared to rivers, streams, lakes, wetlands, and estuaries (Barbour et al., 1999). Thus, a short list of the best indicators, or metrics, has not been developed. Candidate metrics for stony corals could be loosely divided into three categories. The first category would include coral metrics associated with human disturbance in other locations that were also found to be associated with disturbance for this study. An example of this would be coral cover which can be measured in a variety of ways and typically declines with disturbance (Jameson et al., 2001; Sealey, 2004). The second category includes metrics derived from ecological theory and tested for this study only. Metrics may or may not have been associated with disturbance in St. Croix, but may merit testing again in new locations. Examples include metrics related to reproductive strategy such gonochoristic vs. hermaphroditic development or brooder vs. spawner. The third category includes metrics that could be derived from exploratory analysis of the current data set. For example, the percentage of colonies observed in the largest size classes could be developed as an indicator of stable environmental conditions that are adequate to support coral colonies over a long time period. Smith et al. (2005) found that *Acropora* assemblages had more adults and juveniles in reef areas with less sediment influence. Similarly, presence and absence of taxa at more disturbed and less disturbed sites could be compared to develop sensitive and tolerant taxa lists for stony corals. Because the ideas behind these types of metrics were derived from the current data set, hypothesis testing was not appropriate for the current study, but awaits data from a new location.

Efficacy of field protocols

Field assessment of stony corals is intensive because survey divers must operate underwater using SCUBA which requires a minimum of two divers, a boat, and a boat captain. Thus, if the same amount of information on biological condition is provided by a 25-m^2 area as from a 50-m^2 area, the smaller area would be preferred because it translates into less field time. The smaller the area surveyed at each station, the quicker the dive team can get to the next station, and the more stations will be visited during a field season. From the statistical perspective, measurements from more locations are preferred because as the number of survey locations (*N*) increases, so does the precision of the test (Larsen, 1997). Thus, smaller survey areas are better from both logistical and statistical viewpoints. The goal is to minimize the amount of effort required to get a reliable, and repeatable, estimate of reef condition at each station.

This study evaluated nuisance variance at two different levels. Duplicate surveys by different dive teams at the same reef station provided data to test the reliability of the field protocol used to quantify coral condition. The two halves of the radial transect provided data to assess the variability associated with microhabitat differences at a reef and test whether a half or full transect provides a more precise measure of coral condition. The analysis was complicated by the fact that at this point we do not know which coral metrics will be the best bioindicators for tracking coral condition through time. The seven metrics evaluated for their precision included four that were correlated with human disturbance on the south side of St. Croix and three others related to density and the percentage of live tissue observed.

The amount of variance associated with different dive teams was quite small for all seven candidate metrics compared to variance due to transect location, station, and zone. Teams of EPA divers with extensive experience using the field protocol in Florida recorded very similar values as teams of USVI divers new to the EPA protocol for the same reef stations. Although new to the EPA data collection protocol, USVI divers were very experienced in terms of local conditions, coral identification, and underwater data collection. The EPA field protocol used here was easily implemented by divers with scientific knowledge of stony corals.

The density of coral colonies was much higher in St. Croix compared to reef stations sampled in Florida (Fore et al., 2006a). High coral density necessitated a smaller survey area at many reef stations in order to complete data collection during a reasonable time period (i.e., one tank of air). Data from full transects were divided to provide replicate samples from the same reef area in the form of two ½-transects. Variance component analysis indicated a relatively high percentage of the overall metric variability was associated with the two different halves of the radial belt transect. Differences were likely due to microhabitat differences, such as placement of the transect in an area with a patch of sand, a spur which creates more surface area, or a large coral colony.

Statistical power analysis compared the ability of the seven candidate metrics to detect changes in a CMZ though time using a simple statistical test (the two-sample *t* test). Metric precision was compared for two sampling scenarios, the first used a single ½-transect from each station and the second used the average of two ½-transects for each station. Although the second scenario provided twice as much information about coral condition at a station, the increase in statistical power was minimal and inconsistent. In other words, the full transect did not increase our ability to detect change in these metrics over the ½-transect. The percentage of metric variability associated with transect differences was somewhat high, but station differences were greater. Thus, increasing the precision at each station did not improve our ability to detect changes in stations because station differences were greater than transect differences.

For a monitoring design that surveyed 15 stations within a CMZ either in two different areas or on two different occasions, ≥ 27% in total SA, ≥ 18% decline in taxa richness (~1.5 coral species), or ≥ 67% decline in average colony SA would represent a statistically significant change at the 90% confidence level. More reef stations in the sampling design would yield greater precision to detect smaller changes. This level of sampling effort (15 stations) provides a reasonable level of sensitivity for coral reef protection. Note that if the exact same locations were sampled, the correct statistical test would be a paired test rather than a two-sample test and a much smaller change in condition could likely be detected because site differences would be eliminated by comparing each site to itself. If only a few stations can be monitored each year (e.g., < 10), a paired test would be a better design for detecting change through time because a much larger change would have to occur to be statistically significant when sample sizes are small. For a regional comparison of stations in different areas, a paired design would not be possible and the two-sample *t* test would be one example of an appropriate test.For resource monitoring, the power to detect a change must be explicitly considered in order to be protective of natural resources. In the past, monitoring designs have too often ignored the ability of a sampling design to detect a change should it occur and instead have focused on protecting against making a Type I error, that is, concluding that a change has occurred when it has not (Dayton, 1998). In the context of resource protection, many authors agree that the probability of making either a Type I (false positive) or a Type II (false negative) error should be equal (Peterman, 1990; Steidl et al., 1997; Yoccoz et al., 2001). The two types of error are mathematically related and should be considered together. Although a 5% Type I error rate is more typically associated with hypothesis testing, for power analysis a value of 5% for both types of error can be too restrictive. For this study, we followed recommended guidelines and balanced both types of error at 10% for power analysis calculations.

Coral response to human disturbance

Reef stations were selected to follow potential gradients of human disturbance. Differences along the south side associated with commercial and industrial land use centered at the docks was reflected in dramatic differences in coral condition. Human disturbance was intense and associated with multiple land uses. Many of the disturbances have also occurred over a long time period, e.g., the rum distillery has discharged effluent to the near-shore environment for ~80 years. The coral metrics quantified the changes in the amount of coral surface cover, average size of coral colonies, and the number of coral colonies. The number of coral species also increased for stations located further from the dock; however, this could either be due to loss of taxa due to human influence or a spurious correlation with the number of colonies found. The total number of taxa was highly correlated with the number of colonies measured across all stations. A comparison of reefs near developed and undeveloped areas in the Bahamas found that taxa richness of coral *increased* for developed areas, the opposite of what was found for St. Croix. For the same study coral surface area declined with disturbance, which agreed with our results (Sealey, 2004). A much larger scale study conducted across 135 reefs in the Great Barrier Reef found a decline in species richness associated with agricultural run-off (DeVantier et al., 2006). In contrast, a smaller scale study conducted in the area of agricultural run-off failed to detect a difference in species richness for stony coral, although a decline in both hard coral cover and richness of soft corals was observed for sites with greater agricultural run-off (Fabricius and De'ath, 2004). Species richness of hard corals was also shown to decline in Barbados across a eutrophication gradient as measured by water quality samples (Tomascik and Sander, 1987).

For the other two gradients, distance from the Christiansted harbor and from the public dock on the west side failed to correlate with the same metrics. Several candidate metrics were correlated with distance in the West CMZ, but were also correlated, and typically more strongly correlated, with depth. The deepest sites in the West CMZ were nearest the dock and moving away from the dock the sampling stations were in more shallow water. At the time of the survey, the 20 ft. difference in depth across these stations was not considered as a potentially confounding factor because it represented such a narrow range. Metrics calculated from samples collected at the same depth might show a more direct correlation with disturbance. Based on the current analysis, the sensitivity of many of the coral metrics to depth may represent an important consideration when designing monitoring programs. Nonetheless, lack of consistent correlation between candidate coral metrics and disturbance gradients in the North and West CMZs was not surprising because the coral communities at all locations appeared healthy.

Several reasons could explain the lack of correlation between many candidate coral metrics and the gradients of human disturbance. First, the human disturbances in the North CMZ (Christiansted) and West CMZ (Frederiksted) could have been too small to cause differences in the coral assemblage; there may have been no gradient to detect. In contrast, the high intensity of human disturbance along the south side may have overwhelmed more subtle measures of coral condition, such as those related to reproductive strategy. It is also possible that we have yet to discover the coral metrics that will quantify subtle changes in coral condition. An alternative explanation is that the scale of disturbance may be larger than our survey design can detect. Given the potentially complex mixing patterns associated with ocean currents, we do not know the spatial scale at which corals respond to disturbance. For example, Edmunds (2002) compared coral cover at two long-term monitoring stations (12 years). Both sites were located in a marine park in St. John, USVI with minimal human disturbance, but one site showed a dramatic increase in coral cover while the other declined just as dramatically. Random sampling around these long-term stations suggested that coral change may be occurring at larger spatial scales and over longer time scales than can be captured by a typical survey.

For our study, rather than comparing stations along the northern gradient according to their distance away from Christiansted harbor, stations should perhaps be compared with more distant pristine areas. The original sampling design was developed with this approach in mind. Stations located around Buck Island were selected as potential reference sites for the larger island of St. Croix. Unfortunately, the differences between Buck Island stations and other stations around St. Croix were large enough in terms of both summary metric values and species composition, that natural differences, such as depth, and differences associated with human influence, such as proximity to a developed area, could not be distinguished.

Another somewhat surprising result was the high positive correlation between the amount of surface area that was live and the amount that was dead. High values of both live and dead surface area were observed together. The original prediction was that live coral would be replaced by dead coral as human disturbance increased. A study in the Great Barrier Reef found a higher percentage of dead coral in more disturbed areas (Fabricius and De'ath, 2004). Oddly, the most disturbed areas on the south side of St. Croix had the highest values for percent live surface area and among the highest for percent live tissue (averaged across all colonies). This result supports the value of calculating surface area. At the disturbed areas along the south shore there were a few, small colonies with high tissue survival; thus, high tissue survival alone would have led to an erroneous conclusion regarding the health of the coral community. This result further suggests that the presence of dead coral depends on live tissue and that once a colony dies, erosion may happen very quickly, eliminating dead coral from the reef. Dead coral was only recorded if it could be identified to at least the genus level. Physical structure that could not be identified to genus was also difficult to identify as coral rather than rock substrate. In addition, coral rubble was also difficult to distinguish from rock rubble and, therefore, was not recorded as dead coral. The inability to account for all dead coral must be considered in any interpretation of these results.

Influence of habitat on stony coral assemblages

The original sampling design for this study was to survey coral stations across a gradient of human disturbance in the different habitat types found in that area. Although NOAA maps indicated different types of benthic habitat within survey areas, in many cases the differences were not visibly obvious (Kendall, 2001; NOAA, 2001). For example, spur and groove, linear reef and colonized hard-bottom were difficult to distinguish in the North CMZ. Larger differences between fore and back reef habitat types were easier to recognize, but in many cases, e.g., the fore reef in the South, Southwest, and West CMZs, the reef was too deep (>50 ft.) for efficient sampling. In the North CMZ, there were too few corals in back reef areas to survey.

The high correlation between depth and many of the candidate coral metrics was somewhat surprising, particularly in the West CMZ where the difference was only 20 ft. across all stations. Given the additional differences associated with amount of coral cover, average colony size, and species composition observed for different CMZs around St. Croix, comparisons within similar geographic areas may be the best approach to monitoring. Yet, even within a particular CMZ, the influence of depth should be carefully considered.

CONCLUSIONS

The EPA protocol for stony corals records three observations for each coral colony within a transect: species, size, and tissue condition. Four coral metrics derived from these measures were highly correlated with proximity to disturbance along the south side of St. Croix. Candidate metrics related to taxa richness, total coral surface area, live surface area, and average colony size all declined for stations closest to the disturbed area. A similar response was not seen for coral metrics and the proposed gradients of human disturbance in the West and North CMZs. The lack of correlation in these areas was not too surprising because the corals at these stations all appeared healthy and diverse. More subtle changes in coral condition may perhaps be present, but the current candidate metrics did not detect them. Ben-Tzvi et al. (2004) failed to find differences in taxa richness when comparing reefs with different levels of human disturbance but they did document more subtle differences associated with coral recruitment and mortality.

The influence of depth on many of the candidate coral metrics was much greater than anticipated. Although differences according to habitat type were expected, such strong associations with metric values over only a 20 ft. range of depth were noteworthy. Depth may covary with ocean currents or water chemistries that also influence stony corals.

Although the best coral metrics to use as biological indicators of reef condition are not yet certain, the candidate metrics that correlated with human disturbance along the south side of the island had adequate statistical precision to detect a level of change that would provide reasonable protection of coral reef resources and could be used to monitor for change in coral condition. Data from this type of field survey could also be used to test additional candidate coral metrics not considered here but that may be more sensitive to smaller changes in coral condition.

Four results from this study support the use of the EPA field protocol for the assessment of stony corals. First, four candidate metrics were highly correlated with distance from a known area of disturbance. Second, divers new to the method obtained nearly identical results as experienced divers for the same survey area. Third, the metrics derived from the field protocol were sensitive enough to document coral loss. Fourth, the method is efficient because an area of only 25 m^2 was needed to characterize a reef station. Although additional testing in other coral reef areas both in the USVI and in other geographic areas remains, the results for St. Croix provide a solid start toward the development of biocriteria for the protection of USVI’s coral resources.

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