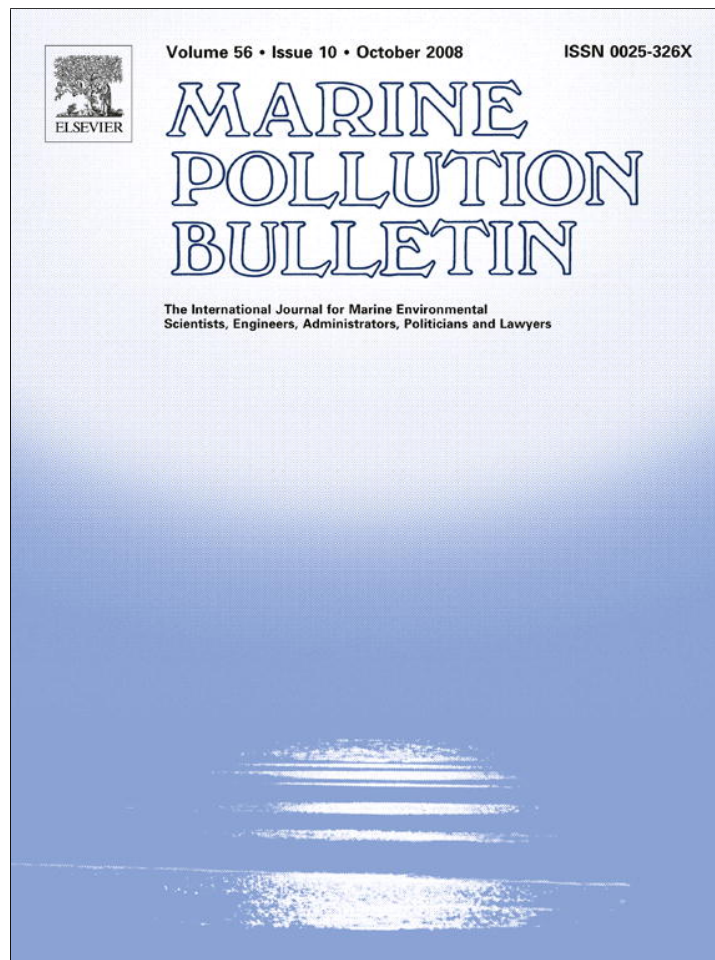


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Evaluation of stony coral indicators for coral reef management

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ABSTRACT

Colonies of reef-building stony corals at 57 stations around St. Croix, US Virgin Islands were characterized by species, size and percentage of living tissue. Taxonomic, biological and physical indicators of coral condition were derived from these measurements and assessed for their response to gradients of human disturbance—a requirement for indicators used in regulatory assessments under authority of the Clean Water Act. At the most intensely disturbed location, five of eight primary indicators were highly correlated with distance from the source of disturbance: Coral taxa richness, average colony size, the coefficient of variation of colony size, total topographic coral surface area, and live coral surface area. An additional set of exploratory indicators related to rarity, reproductive and spawning mode and taxonomic identity were also screened. The primary indicators demonstrated sufficient precision to detect levels of change that would be applicable in a regional-scale regulatory program.

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1. Introduction

Coral reef ecosystems are valuable economic, ecological, and aesthetic resources that have been declining worldwide from interactive effects of climate change and human activities in the coastal zone and terrestrial watershed (Hoegh-Guldberg, 1999; Gardner et al., 2003). The US Federal Clean Water Act (CWA, 1988) provides a regulatory framework to protect coral reefs and other near-shore resources against adverse effects of anthropogenic activities, including physical damage and diminished water quality from terrestrial efflux of sediments, contaminants, nutrients, or microorganisms. The US Virgin Islands (USVI) has recognized the value of coral reefs for its residents and visitors (Nemeth et al., 2004; USVI, 2004) and embarked on a collaborative program with the US Environmental Protection Agency (EPA) to extend coral reef protection through the development of biological water quality standards (EPA, 2000, 2005; Jameson et al., 1998, 2001; Fisher, 2007).

The regulatory framework of the CWA requires that States, Tribes, and Territories adopt water quality standards to protect their navigable waters. These jurisdictions have authority to define water quality goals expressed as designated use(s) of a water body and to set criteria necessary to protect those uses (EPA, 2005).

Examples of designated uses include drinking water, navigation, and protection of aquatic life. Criteria are established as threshold values of physical, chemical, or biological measurements of aquatic condition. Biological criteria (biocriteria) are based on expectations of biological integrity and can include condition of living resources (e.g., coral reefs). A water body may be listed as impaired when measured values do not meet a particular criterion. This 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).

Adverse environmental conditions are caused by both natural and human factors, but biological assessments (bioassessments) and monitoring programs are primarily intended to characterize only anthropogenic effects. These are, by definition, any “man-made or man-induced alteration of the physical, chemical, biological or radiological integrity of water” (CWA, 1988). Because of this focus, an effective bioindicator must be consistently correlated with independent measures of human disturbance, have a plausible biological connection to human-induced changes, and exhibit sufficient precision to detect a change in resource condition should a change occur (Yoder and Rankin, 1998; Karr and Chu, 1999; Jameson et al., 2001; Fore, 2003). Bioindicators used in regulatory monitoring should be relatively insensitive to natural variability associated with local (small-scale) habitat variation, depth,

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seasonal or annual variability. Bioindicators that meet these requirements (“metrics”) can be used to define expectations for biological condition and implemented as criteria for water quality standards.

Stony corals are a dominating influence in the reef ecosystem because they build and maintain the physical infrastructure that supports all other organisms in the community. They are often considered the primary indicator organisms for reef communities (Loya, 1972; Brown, 1988; Done, 1997). In this study, EPA’s rapid bioassessment protocol for stony corals (Fisher, 2007) was applied at stations along gradients of human disturbance located along three sides of St. Croix, US Virgin Islands (USVI). The sides (North, South and West) differ primarily in exposure to prevailing currents (from ESE) and shelf slope. Each side also experiences unique human activities in the near-coastal area. Descriptive coral characteristics such as abundance, physical status, biological condition and community composition were documented for reefs along each side, and assessment indicators derived from these characteristics were compared in relation to distance of the sampling location from the center of human activity (disturbance gradient). Selected indicators were then evaluated for statistical precision and potential application to regulatory monitoring.

2. Methods

2.1. Sampling locations

Stony corals were surveyed at 57 reef stations in four coastal zones around St. Croix, USVI, during February 2006 (Fig. 1). Each zone exhibited a unique hydrogeography and land use pattern. Three of the zones (North, South and West) were included because of visible human activity on the adjacent land and near-shore environment; the fourth zone had minimal human influence and was used to evaluate measurement error of the data collection protocol. A human disturbance gradient was selected *a priori* for the three zones. Benthic habitat maps (NOAA, 2008) were used to identify hardbottom substrate where corals would likely be located. Sampling locations (stations) were selected as the best available reef, by visual judgment, located on hardbottom substrate at intermittent distances from the approximate center of the human disturbance zone.

The West Gradient (WG) included 12 stations located along the western shore of St. Croix near the city of Frederiksted. The city generates a variety of potential stresses from human activity, including a sewage overflow line, small boat traffic and a long pier

used intermittently by cruise ships. The WG is leeward of prevailing winds, water current at WG is generally north to south and shelf slope is steep.

The North Gradient (NG) included 16 stations located around the Christiansted boat channel, which has small boat traffic and 50–75 boats moored in the nearby harbor. Other disturbances, both point and non-point, included urban development (Christiansted), an oil-fired power and water desalination plant, and a large combined sewage pump station with an emergency bypass discharge line terminating just seaward of the reef area. Water current at NG is generally east to west; shelf slope is steep in the northwest but gentle in the northeast.

The South (SG) included 19 stations located around a dredged commercial ship channel and piers where large tankers and work boats serve a petroleum refinery and other industrial enterprises. The St. Croix airport, a landfill, a former alumina factory, a coal-fired power plant, the island’s main sewage treatment plant and a rum distillery are all adjacent to or within the industrial area near the channel. Water current at SG is generally east to west and shelf slope is gentle.

A fourth coastal zone, Buck Island National Monument (10 stations), was used to test precision and accuracy of the protocol in the relative absence of direct human disturbance. Stations from around Buck Island were selected for this purpose because the high density and diversity of corals provided a rigorous comparison of surveyors.

2.2. Rapid bioassessment protocol

A previously described protocol was adapted for this survey (Fisher, 2007; Fisher et al., 2007). Survey transects were established by placing a tripod on the substrate which held an upright pole in place and a 2 m wide annulus (radial belt) was surveyed 3–5 m from the pole. Data were recorded from either a full-annulus (360°; 50.2 m²) or a half-annulus (180°; 25.1 m²) if colony density was very high. Data for full-annulus transects were collected in half-annulus segments and averaged to obtain a single station value. All stony corals (Order Scleractinia) described by Humann and Deloach (2002) and one reef-building hydrocoral (*Millepora complanata*) were included in the survey. All surveyors, including those new to the protocol, were experienced in stony coral identification.

Each coral colony that occurred within the transect perimeter was identified by genus and species, morphological dimensions were measured, and the amount (%) of live tissue on the colony

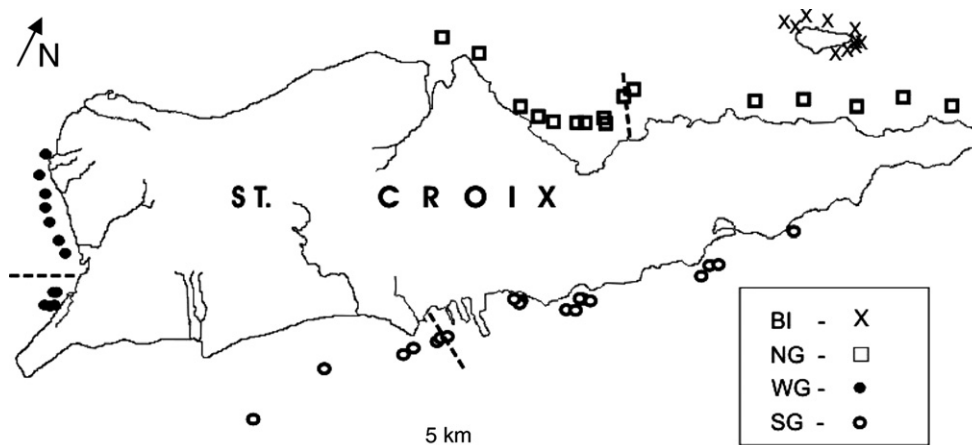


Fig. 1. Coral surveys were performed along three human disturbance gradients, including 16 stations on the northern portion (NG), 19 stations on the southern portion (SG) and 12 stations on the western portion (WG) of St. Croix. Dotted lines show approximate center of human disturbance for each gradient. Ten additional stations were sampled at Buck Island National Monument (BI) to assess precision and accuracy in a location undisturbed by human activity. Prevailing current is from east to west.

was estimated visually. Any stony coral (Scleractinia) or the hydrocoral *M. complanata* that was >10 cm at any dimension was included in the survey (Fisher et al., 2007). Colony dimensions were measured as height (greatest distance from substrate), maximum diameter (greatest distance parallel to the substrate) and width (distance orthogonal to the maximum diameter measured at the approximate center of the colony). The three colony dimensions were combined to generate an average radius for the colony, which was entered into the geometric formula for a bottomless hemisphere ($2\pi r^2$) to calculate three-dimensional (3D) colony surface area (CSA; Courtney et al., 2007).

Percent live tissue (%LT) on each colony was estimated using six categories. If the colony was completely covered with live coral tissue, %LT was reported as 100%; if completely dead, %LT was reported as 0%. Otherwise, %LT was approximated by quartiles (1–25%, 26–50%, 51–75%, or 76–99%) and the middle value was assigned (e.g., 13%LT for the 1–25% quartile). Completely dead colonies (0%LT) had to be identifiable to genus to be included in the survey, a convention also used by the Atlantic and Gulf Rapid Reef Assessment Program (Lang, 2003).

2.3. Indicator testing

All indicators were derived from the three core observations made on each colony within the sampling transect. Two categories of indicators were tested in this study: eight primary indicators (Table 1) and an additional set of 17 secondary (exploratory) indicators related to rarity, reproductive strategy, and specific taxonomic groups. Primary indicators have been previously described (Table 1; Fisher, 2007) and characteristics for secondary indicators are described below. For rarity, an arbitrary decision was made to designate uncommon (rare) species as those with <15 colonies documented across the entire gradient. For reproductive strategy, characteristics of different taxa were identified according to Richmond and Hunter (1990). Of the most abundant corals documented at SG, brooding species included *Porites astreoides* and *Porites porites*; spawning species included *Diploria strigosa*, *Montastraea annularis*, *Montastraea cavernosa*, and *Siderastrea siderea*; gonochoristic species included *M. cavernosa*, *P. porites*, *S. siderea*; and hermaphroditic species included *D. strigosa*, *M. annularis*, and *P. astreoides*. Species were also grouped according to genera for additional testing of the most common genera.

2.4. Data analysis

The eight primary indicators (Table 1) were tested individually for association with each of the three human disturbance gradients. These included taxa richness, colony density, average colony

surface area (AvCSA), coefficient of variation of CSA (CSA-CV), total coral cover (TC), average percent live tissue (Av%LT), live coral cover (LC), and percent live surface area (%LSA). The primary indicators were calculated from all colonies documented at each station. Correlation (Spearman's r) was tested between each indicator value and distance of the station from the approximate center of the zone of human disturbance: from the Frederiksted pier at WG, from the Christiansted harbor channel at NG, and from the commercial pier at SG (see Fig. 1). Indicators were also tested for correlation with water depth.

Analysis for secondary indicators was more exploratory in nature because these indicators have not been widely tested or reported in the literature. For this second group, each indicator was summarized in eight different ways (e.g., relative abundance, relative surface area, total cover). Seventeen taxonomic sub-groups were tested for correlation at SG. These included rare species (arbitrarily set at <15 occurrences), brooders, spawners, gonochoristic, hermaphroditic, the three most abundant genera and the nine most abundant species. Eight different calculations were used to summarize these taxonomic sub-groups: density, relative abundance (number of colonies/total colonies), AvCSA, relative surface area (sum of CSA/total surface area), TC, Av%LT, LC, and %LSA. Taxa richness and CSA-CV were not calculated. In total, 136 values (17 taxonomic sub-groups \times 8 calculations) were explored for correlation with distance from disturbance at SG.

Statistical precision of the eight assemblage level indicators was examined using components of variance analysis and power analysis. Components of variance analysis was used to compare the proportion of the total variance observed for indicators due to different survey teams on the same transect, different transects within a station, and different stations within the reef. Data collected from ten stations at Buck Island were used to estimate mean squared error for each component from an ANOVA model with station as the main factor and transects nested within stations. Only two transects (at one station) had replicate data for six survey teams. Three of the stations had two transects to evaluate variance associated with microhabitat differences within a station. Components of variance were calculated separately for each of the eight indicators.

Statistical power is defined as the probability of detecting a change should a change truly occur. Power can be summarized as the minimum detectable difference (MDD) that can be discriminated for a given statistical test, an estimate of variance, and specified number of replicates. MDD was calculated for a two-sample t test with variance estimates derived from the 28 stations at NG and WG for 10, 20, and 30 reef stations. Stations in SG were not included due to the range of coral condition associated with human disturbance. The MDD represents the smallest difference between

Table 1
Stony coral indicators adapted from Fisher (2007)

Definitions
Colony surface area (CSA): derived for each colony using a 3D hemispheric surrogate (m^2)
Percent live tissue (%LT): estimated for each colony
Total surface area (TSA) = Σ CSA
Live surface area (LSA) = $CSA \times (\%LT/100)$
Primary Stony Coral Indicators
Species (taxa) richness: number of species occurring at a station or location
Colony density: number of colonies/ m^2 sea floor
Average colony surface area (AvCSA) = Σ CSA/# colonies
Colony size coefficient of variation (CSA-CV) = standard deviation CSA/mean CSA
Total Coral Cover (TC) = TSA/m^2 sea floor
Average Percent Live Tissue (Av%LT) = $\Sigma\%LT/\#$ colonies
Live Coral Cover (LC) = Σ LSA/ m^2 sea floor
Percent live surface area ³ (%LSA) = $[LSA/TSA] \times 100$

Indicators were calculated for each station and combined or compared for each disturbance gradient. Colony surface area (m^2) was determined by 3D geometric surrogate (hemisphere) using average colony dimensions to represent radius.

the mean indicator values for two sets of reef stations that would indicate a statistically significant change. For each of the eight indicators, MDD was calculated as (Zar, 1999):

$$MDD \leq \sqrt{\frac{2s^2}{n}}(t_{\alpha(1),v} + t_{\beta(1),v}),$$

where s^2 = the mean squared error from ANOVA for each indicator, n = the number of stations sampled, $t_{\alpha(1),v}$ = the t value for alpha of 0.1 for a 1-sided test, $t_{\beta(1),v}$ = the t value for beta of 0.1 for a 1-sided test, and $v = 2n - 2$.

3. Results

A total of 2794 colonies were recorded on 47 reef stations surveyed along three gradients of human disturbance. An additional 536 colonies were recorded at 10 stations in Buck Island National Monument. Thirty species were identified at the three gradient locations and one additional species at Buck Island. Physical, biological, and taxonomic composition of corals varied among the three disturbance gradients (Table 2). Most conspicuous was the low number of taxa, low colony density, and low TC and LC at SG. All three of the most abundant genera were lower in density and TC at SG (Table 3). At the species level, *Montastraea* species were much lower in density and TC at SG. Taxonomic composition at stations along WG and NG differed despite similarities in overall density (see Table 2). In particular, *Diploria* species were relatively more abundant at NG stations and *Montastraea* species, particularly *M. annularis*, were relatively more abundant at WG stations.

3.1. Indicator response to human disturbance

The strongest relationships between coral indicators and human disturbance were found at SG. Of the eight primary indicators, five were positively correlated with distance from the center of disturbance: taxa richness, AvCSA, CSA-CV, TC, and LC significantly increased at stations further from the commercial docks (Spearman's r ; Table 4, Fig. 2). In contrast to expectations, %LSA showed a significant negative correlation with distance, declining at stations further from the docks.

At NG and WG, none of the indicators were significantly correlated with distance from the center of human disturbance. At WG, several indicators were significantly correlated with depth, even though the range of depths sampled was relatively small (6–12.5 m). Depth and distance from disturbance were highly correlated ($r = -0.59$) and deeper stations were located near the dock. Taxonomic composition also changed: *M. annularis* and *P. astreoides* increased with depth (both in number and surface area) whereas *D. strigosa*, *D. labyrinthiformis*, *M. cavernosa* and *S. siderea* declined with depth.

Of the 17 additional indicators derived from taxonomic subgroups and tested at SG, rare taxa increased with distance from

Table 3

Colony density (colonies/m²) and total coral cover (TC = cm² 3D colony surface area per m² 2D sea floor) for the nine most common species and groupings of three of the most common genera (2–4 species each)

Taxonomic group	NG (n = 16)		SG (n = 19)		WG (n = 12)	
	Density	TC	Density	TC	Density	TC
<i>Diploria</i> (3 spp.)	0.55	281.2	0.26	150.7	0.30	247.1
<i>Montastraea</i> (4 spp.)	0.67	1931.1	0.07	245.4	1.18	3205.6
<i>Porites</i> (2 spp.)	0.57	301.3	0.18	111.0	0.69	282.8
<i>D. clivosa</i>	0.02	5.6	0.06	21.7	0.00	0.8
<i>D. labyrinthiformis</i>	0.02	16.4	0.00	0.4	0.09	87.1
<i>D. strigosa</i>	0.50	259.2	0.20	128.6	0.20	159.2
<i>M. annularis</i>	0.08	325.0	0.03	98.4	0.37	1667.7
<i>M. cavernosa</i>	0.40	664.9	0.02	42.1	0.58	887.3
<i>M. faveolata</i>	0.18	927.9	0.02	104.8	0.16	499.1
<i>P. astreoides</i>	0.38	109.9	0.13	34.5	0.64	228.4
<i>P. porites</i>	0.19	191.4	0.05	76.4	0.05	54.4
<i>Siderastrea siderea</i>	0.21	249.6	0.09	126.3	0.22	232.0

Values shown represent averages for all stations (n) within each gradient location (NG, SG and WG).

the docks for all eight calculations of coral cover and abundance (Table 4). Some indicators for reproductive type and strategy (AvCSA, TC and LC) were positively correlated with distance. Also, *Montastraea* species and *S. siderea* declined consistently with disturbance for many of the calculations.

3.2. Statistical precision of coral indicators

Components of variance analysis compared the relative contribution of different sources of variance to the overall variance of each of the eight primary indicators. In general, coral indicator values were more similar for transects within stations than for the 10 different stations within Buck Island National Monument, indicating that the transect area was a sufficient subsample to represent coral condition (Fig. 3). For six of the indicators, the variance associated with different survey teams measuring the same transect was much lower than the variance associated with different stations, indicating that the measurements were repeatable, independent of survey team. Exceptions to this were AvCSA and LC which had a higher proportion of variance associated with differences in survey teams (less precise). CV of SA and Av%LT showed the highest proportion of variance due to transect differences.

3.3. Statistical power analysis

Statistical power analysis calculated the minimum detectable differences separately for each of the eight primary indicators. For taxa richness, a decline of at least 28% (~3 taxa) for a comparison of 10 stations would represent a statistically significant change (Table 5). For larger numbers of stations, a smaller decline would be significant, e.g., 19% (2 taxa) for 20 stations and 16% (1.7

Table 2

Mean and standard deviation for indicator values for all stations within each gradient, including number of different taxa, colony density, average colony surface area (AvCSA), coefficient of variation for CSA (CSA-CV), total cover (TC = 3D colony surface area/2D substrate surface area), average percent live tissue (Av%LT), live cover (LC = live 3D colony surface area/2D substrate surface area) and percent live surface area (%LSA)

	NG (n = 16)		SG (n = 19)		WG (n = 12)	
	Mean	SD	Mean	SD	Mean	SD
# Taxa	10.7	2.99	4.5	1.27	10.4	1.73
Density (col/m ²)	2.34	1.07	0.63	0.40	2.62	0.70
AvCSA (m ² /col)	0.13	0.06	0.16	0.17	0.16	0.07
CSA-CV (%)	174		119		156	
TC (m ² /m ²)	0.31	0.21	0.07	0.06	0.41	0.24
Av%LT	68.6	9.37	74.8	11.94	67.7	6.39
LC (m ² /m ²)	0.16	0.10	0.04	0.03	0.19	0.07
%LSA	54.3	13.02	65.9	18.87	51.5	15.62

Table 4

Correlation coefficients for indicators in relation to distance from the center of human disturbance at SG (Spearman's r , only significant values are shown, $p < 0.05$, one-sided test for indicators)

Group	Indicator	r -value	Group	Indicator	r -value	Group	Indicator	r -value
All	# Taxa	0.53	Brood	AvCSA	0.43 [*]	Mann	Density	0.40
	CVCSA	0.65		Spawn	AvCSA		0.68	Rel Ab
	AvCSA	0.67	Mont spp.	TC	0.66		AvCSA	0.47
	TC	0.80		LC	0.42		Rel SA	0.47
	LC	0.67		Density	0.53		TC	0.47
	%LSA	(-0.47)**		Rel Ab	0.49		Av%LT	0.43
Rare	Dens	0.53 [*]	Por spp.	AvCSA	0.61	Past	LC	0.44
	Rel Ab	0.54 [*]		Rel SA	0.45		Rel Ab	(-0.40)
	AvCSA	0.54 [*]		TC	0.56		Rel SA	(-0.46)
	Rel SA	0.52 [*]		LC	0.54		AvCSA	0.48
	TC	0.54 [*]	Mfav	AvCSA	0.45 [*]	Ssid	AvCSA	0.48
	Av%LT	0.44 [*]		Density	0.48		TC	0.44
	LC	0.46 [*]		Rel Ab	0.40		Av%LT	0.44
	%LSA	0.44 [*]		AvCSA	0.49		LC	0.51
Gono	AvCSA	0.40		Rel SA	0.40		%LSA	0.51
	TC	0.46		TC	0.48			
	LC	0.48		Av%LT	0.46			
				LC	0.44			
Herm	AvCSA	0.61		LC	0.44			
	TC	0.47		%LSA	0.44			

Various taxonomic groupings were compared, including all species, rare species, gonochoristic (gono), hermaphroditic (herm), brooding (brood), spawning (spawn) dominant genera (*Montastraea* spp. and *Porites* spp.), and dominant species (*M. faveolata*, *M. annularis*, *P. astreoides* and *Siderastrea siderea*). Indicator abbreviations are noted in Table 1 except for relative abundance (Rel Ab) and relative surface area (Rel SA). Some correlations were also positively correlated with depth and some correlations were negatively correlated with depth (Spearman's r , $p < 0.1$, 2-sided test for depth). Correlations that were opposite of expected responses are noted parenthetically. These data represent only the significant correlations from 148 tests (9 community level + 136 exploratory indicators).

taxa) for 30 stations. A 14% change in Av%LT would be significant when comparing the means for 10 stations. In contrast, a 75% decline would be needed for TC. All seven indicators could detect 8–42% change in coral condition with a sampling design of 30 stations.

4. Discussion

The regulatory framework of the Clean Water Act provides a potential regulatory role for bioassessments within the context of water resources management (Adler, 1995; Ransel, 1995). Yet, compared to freshwater and estuarine ecosystems (Davis and Simon, 1995; Karr and Chu, 1999; Simon, 2002), regulatory bioassessment is relatively new for near-shore marine waters and effective bioindicators have not been developed for coral reefs, mangroves or sea grass beds. The goal of this study was to formally test measures of stony coral condition that have been proposed or tested in other locations. Indicators that reflect change in reef condition associated with human disturbance can be used to support development of USVI water quality standards to manage and protect coral reefs.

Two categories of indicators were tested in this study, eight primary indicators and 17 additional taxonomic indicators. The primary indicators were more typical, having been measured in previous studies and representing data from all species encountered. The secondary indicators were more exploratory and focused on data from taxonomic subsets. Primary indicators were tested for association across all three gradients of human disturbance, but only one (SG) showed effects of human influence on stony coral assemblages. These effects included change in taxa richness, AvCSA, CSA-CV, TC and LC. Responses at NG and WG did not vary with the disturbance gradient, a result that verified diver observations of apparently healthy stony corals at those locations. For this reason, secondary indicators were only tested at SG.

Several of the primary indicators have been previously associated with human disturbances (Gardner et al., 2003; Fabricius and De'ath, 2004; Sealey 2004; DeVantier et al., 2006; Edmunds and Elahi, 2007). Results from SG confirmed this association, showing a significant loss of total and live coral cover at stations closest to the center of shipping, industrial, and commercial activity. Sim-

ilarly, the decline in coral taxa richness at SG near the center of human disturbance has been previously noted at other locations (Tomasick and Sander, 1987; DeVantier et al., 2006), presumably a consequence of intolerant species that are less likely to survive stressful conditions. Some studies, however, have shown no change and others have actually shown an increase in taxa richness with disturbance (Ben-Tzvi et al., 2004; Fabricius and De'ath, 2004; Sealey, 2004).

Recent studies in the Great Barrier Reef indicate that when stressed by human disturbance, intolerant fish and algal taxa tend to be replaced by those with greater tolerance. The same studies, in contrast, found that stressed coral assemblages tend to simply lose rather than replace taxa (Fabricius et al., 2005; DeVantier et al., 2006). Despite the decline in taxa richness near human disturbance at SG (Fig. 2), two species persisted. *D. strigosa* was the dominant species in both abundance and surface area at SG and did not decline closer to the center of disturbance. *P. astreoides* had higher relative abundance and relative surface area closer to the disturbance, indicating a unique ability to survive human influences. In a previous study, *P. astreoides* and *S. siderea* were identified as tolerant species (Tomasick and Sander, 1987).

Because coral growth and recruitment should be adversely affected by human activities, we expected the number and size of coral colonies to increase with distance from disturbance. The number of colonies (density) at SG was not correlated with distance, but several measures of colony size were, including average colony surface area, total coral cover, and live coral cover. Heterogeneity of colony size (CSA-CV) increased at stations further from disturbance, implying the presence of species with different size ranges, recruitment of new colonies through time, or both.

A greater proportion of live tissue on coral colonies, an indication of colony health, was expected further from the center of disturbance. This was previously described at the Great Barrier Reef (Fabricius and De'ath, 2004). Yet at SG, percent live surface area was higher at stations closer to the center of disturbance. Contributing to this result was the combination of small colonies with high %LT near the center of disturbance and larger colonies with low %LT away from the center of disturbance. A possible explanation for this unexpected finding is that the small colonies (with

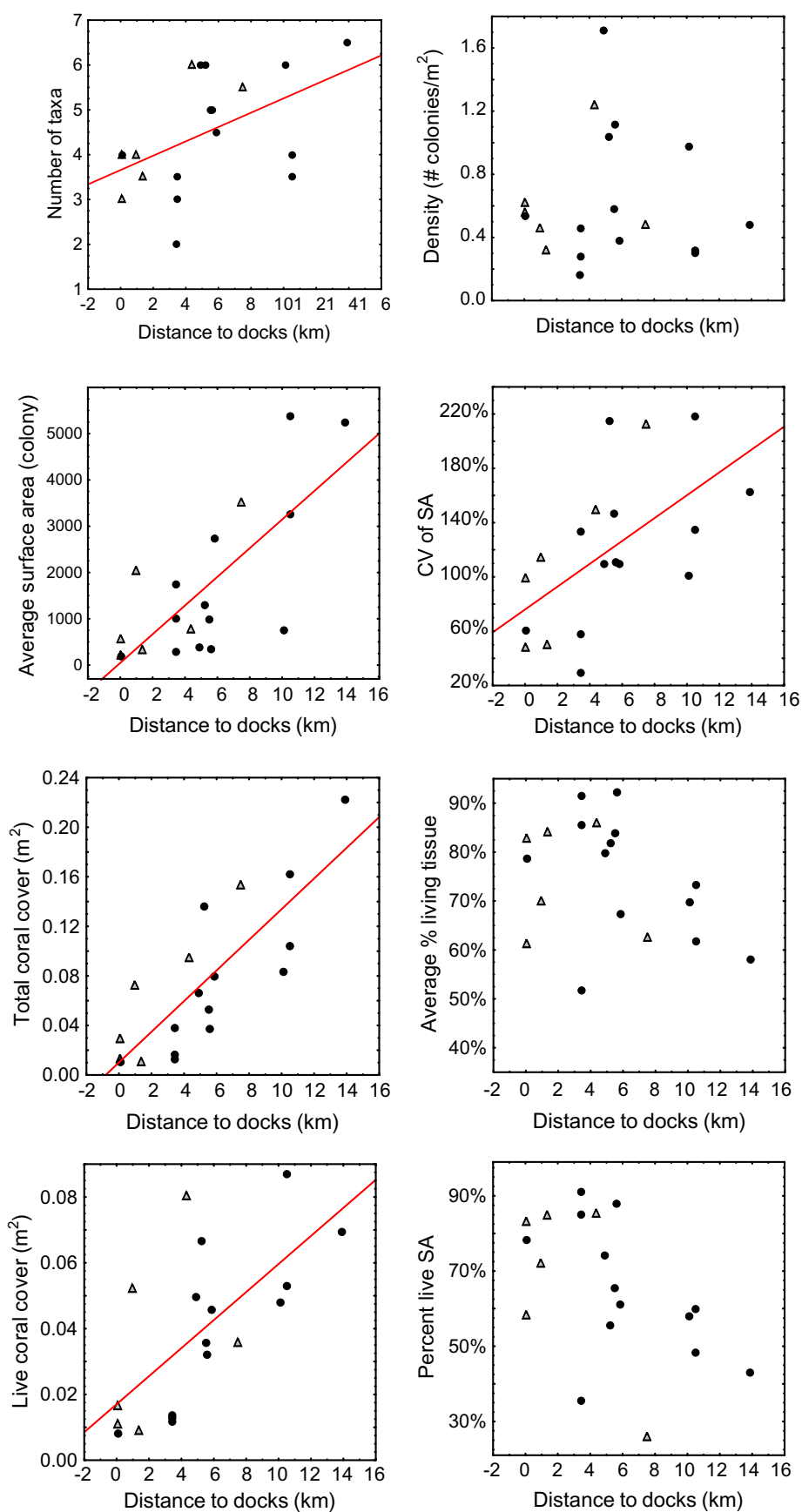


Fig. 2. Relationship of coral indicators and distance from the commercial docks on the south side of St. Croix (SG). Triangles represent stations west of the dock, circles are stations east of the dock ($n = 19$ stations). Regression lines are only shown for indicators with significant correlations (note %LSA was significantly correlated with distance to docks but in the opposite direction predicted).

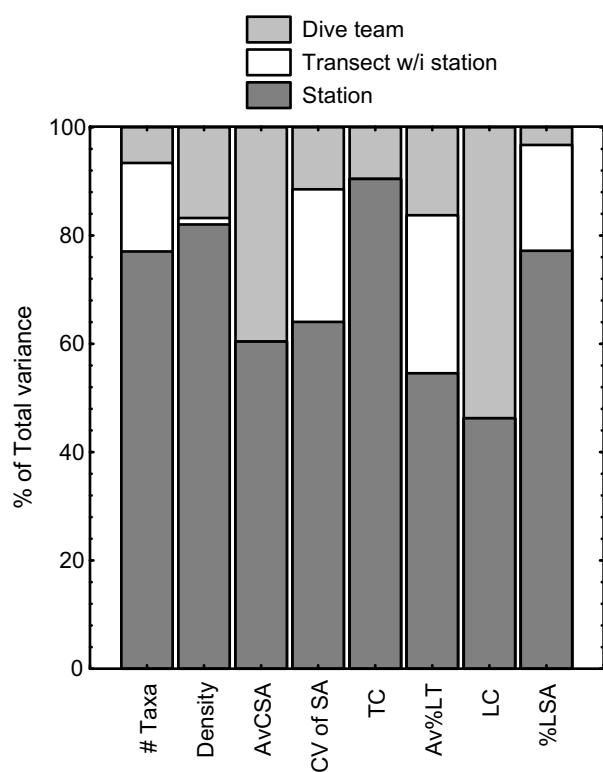


Fig. 3. Components of variance for seven coral indicators. Shown are percentages of total variance associated with different survey dive teams on the same transect, different transects within stations, and stations differences ($n = 10$ stations at Buck Island National Monument).

Table 5

Indicator, mean and variance for 28 stations (NG = 16, WG = 12) and percent change that would be significantly different for $N = 10, 20$ or 30 stations sampled each year

Indicator	% Change needed				
	Mean	Variance	$N = 10$	$N = 20$	$N = 30$
Number of taxa	10.6	6.2	28	19	16
Density (col/m ²)	2.5	0.9	45	31	25
AvCSA (cm ² /col)	1431	408, 543	53	37	30
CSA-CV (%)	1.66	0.39	45	31	25
TC (m ² /m ²)	0.35	0.050	75	52	42
Av%LT	68.2	65.6	14	10	8
LC (m ² /m ²)	0.17	0.007	59	41	33
%LSA	53.1	195.4	31	22	18

Percentage calculated as minimum detectable difference/mean $\times 100\%$.

high %LT) were newly recruited and as yet unaffected by the adverse conditions at the industrial docks.

The primary indicators tested in this study are relevant to coral reef managers (Fisher, 2007) because they quantify abundance and composition (taxa richness, density), physical status (AvCSA, CSA-CV, TC) and biological condition (Av%LT, LC and %LSA) of stony corals. This is important because stony corals form the infrastructure of the reef and provide physical habitat for the abundant and diverse community that makes a coral reef unique. For example, the number of colonies and proportion of live tissue of a coral community describes its potential to grow and reproduce. The size of colonies not only provides hindsight to past conditions (good conditions if colonies have survived long enough to become large), but also to value ecosystem services such as shoreline protection and habitat for harvested fish and invertebrates. The size heterogeneity indicator, CSA-CV, can capture the important relationship between coral reef complexity and fish abundance and diversity (Risk, 1972;

Luckhurst and Luckhurst, 1978; Roberts and Ormond, 1987). These biological indicators of reef condition provide managers with information that can be relayed to stakeholders on the economic value and ecological health of coral reefs.

Based on these findings, the primary indicators appear to be reasonable candidate metrics for application in regulatory monitoring. For such a purpose, indicators must show a consistent response to independent measures of human disturbance and have sufficient statistical precision to detect a change in resource condition should a change occur. Our initial goal was to demonstrate a correlation with human influence in each of the three zones surrounding St. Croix. Instead, we found correlation of the candidate metrics with disturbance on the industrial south side only; therefore, additional verification at an independent location is needed before these indicators can be fully vetted as metrics and used in a regulatory context.

The more exploratory indicators of rarity, reproductive strategy, and taxonomic affiliation appear less promising as indicators of reef condition. These indicators potentially merit additional testing in new locations, but should be cautiously interpreted. For example, rare does not necessarily imply sensitive, and those taxa identified as locally rare in St. Croix may be abundant in nearby environments and simply at the edge of their distribution. Also, indicators related to reproductive type and strategy failed to respond to disturbance as predicted. For example, we expected that brooders and spawners would respond in opposite directions in relation to disturbance, but instead all taxonomic groups simply paralleled the general decline of indicators observed across all species. For indicators derived from individual species, *M. faveolata* and *M. annularis* declined with disturbance whether measured as relative abundance, relative surface area, or total cover. Edmunds and Elahi (2007) also documented a decline in *M. annularis* associated with human disturbance in USVI. The data did support the finding that *P. astreoides* is a tolerant species (Tomasick and Sander, 1987), and possibly identified *D. strigosa* as well. Nonetheless, additional confirmation in different locations is needed before indicators related to these taxa should be considered as metrics for bioassessment.

In order to be protective, a long-term monitoring program should rely on indicators that are sufficiently precise to detect a change in coral condition (Dayton, 1998; Houk and Van Woesik, 2006; Lam et al., 2006). Comparison of results from duplicate surveys at the same stations showed that variance of all eight primary indicators associated with different dive teams (measurement error) was small relative to differences associated with station location. The highest measurement error was for LC, suggesting that the coarse quartile method used to estimate %LT for this study may require improvement. While all surveyors had expertise in coral identification, some had only one day of training in the bioassessment protocol, so this low measurement error demonstrated the efficacy of technical transfer. This aspect of the data collection protocol is key to the success of any long-term monitoring program because personnel change through time while data collection methods must remain consistent.

Statistical power analysis demonstrated that significant differences for the indicators could be detected from a reasonable number of stations. A decline of 8–42% (depending on indicator) would represent a significant change in coral condition if 30 stations were compared either in different years or different locations. We emphasize that this precision was attained at a regional-scale, i.e., incorporating stations that varied in depth, hydrology, substrate and community composition, and that the indicators were sufficiently robust to overcome habitat variability at this spatial scale. The two-sample *t* test reported here assumes that different stations would be sampled on each occasion. For a trend monitoring design, the same stations would likely be revisited through

time and would likely provide a much higher statistical power (Larsen, 1997; Urquhart et al., 1998; Fore et al., 2006). We could not evaluate the power of a trend monitoring design because repeat data from these reef locations were not available.

Although the survey design for this study was not probabilistic, future sampling in USVI will have a random component to allow unbiased local and regional comparisons with other reefs (Olsen et al., 1999). However, the stations we surveyed were well distributed around St. Croix and can support some preliminary observations. It appears that *Montastraea* spp. contributed the overwhelming majority of coral surface area for St. Croix reefs. These were primarily *M. annularis* at WG and both *M. faveolata* and *M. cavernosa* at NG. The difference may be related to hydrology because WG is usually in the lee of the strongest prevailing currents. Depth may also influence coral community composition at St. Croix; depth is a natural driver of coral assemblage structure and could potentially confound analytical associations with human influence. In general, *Diploria* spp., *M. cavernosa* and *S. siderea* occurred at shallow depths relative to *M. annularis*, *M. faveolata* and *P. porites*.

The survey was performed only a few months after a massive high-temperature bleaching event in USVI, including St. Croix. There was little evidence of the event—only patchy bleaching and rare instances of recent tissue loss—and a strong recovery seemed possible. Since then, corals throughout USVI have suffered severe latent effects, including high mortality and substantial losses of tissue. Under these dramatically altered conditions, responses to a human disturbance gradient would likely have been more difficult to detect.

Several aspects of this study hold promise for implementation of water quality standards based on stony coral assessment and monitoring. Five candidate metrics were highly correlated with distance from a zone of human disturbance. Indicators demonstrated adequate precision without the need for classification of habitat types within the region. Statistical power was sufficient to keep sample number reasonably low for a monitoring program. Finally, the method was easily and effectively transferred—surveyors new to the method obtained results very similar to experienced divers for the same survey area. Although additional testing at St. Croix and in other geographic areas is needed, these results provide a promising foundation for the development of biocriteria for protection of USVI coral resources.

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