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Hierarchical methods and sampling design for conservation monitoring of tropical marine hard bottom communities

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ABSTRACT

1. A 4-year study developed methods for annual monitoring of shallow-water tropical marine benthic communities to detect changes in spatial patterning and benthic diversity. Two low-relief sponge/octocoral communities were selected from natural colour photography to gain a broader perspective on spatial variability in the benthic community structure of similar community types.
2. Changes in benthic spatial patterning were studied using four methods: (i) substrata and lifeform coverage characterization, (ii) species inventories, (iii) belt quadrat measurements of taxa-level (algae, sponges, octocorals and stony corals) density, area coverage and size, and (iv) belt quadrat measurements of species-level density, area coverage and area per individual or colony.
3. A sampling hierarchy of multiple parameters was utilized to detect changes in benthic community diversity. Substrata and lifeform characterizations (at the taxa- versus species-level) were the least sensitive and serve as indicators of catastrophic change in community structure.
4. Changes in spatial patterning of the benthos that may be attributed to low-level, chronic anthropogenic disturbances can be best studied utilizing belt quadrat measurements. The use of multiple study sites and a sampling hierarchy was useful in minimizing Type II errors and to determine the level of monitoring necessary to segregate natural rates of change from anthropogenic impacts.

INTRODUCTION

Ecological monitoring of natural communities constitutes the collection of specific information concerning the state of a given system and its changes on a temporal and spatial scale (Dahl, 1981; Goldsmith, 1991; Spellerberg, 1991). Monitoring is often initiated both to understand the dynamics of change in a natural system (e.g. hurricane impacts on coral reefs; see Knowlton *et al.*, 1981, 1990; Porter *et al.*, 1981; Rogers *et al.*, 1982, 1983) and to evaluate management of coastal zones or to detect anthropogenic disturbances (Banner, 1974; Tomascik and Sander, 1987; Wittenberg and Hunte, 1992). The structure of any monitoring programme is a function of its objectives, which must be clearly established at the onset of the study. A real and acute need exists throughout the tropics to develop guidelines for conservation monitoring in marine parks and protection areas that will combine both sound ecological methods with the pragmatic considerations of resources and logistics.

A central challenge to marine ecological studies in the tropical western Atlantic is segregating natural changes in a system from changes that can be accelerated or influenced by low-level chronic anthropogenic

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stressors (e.g. nutrient loading, degradation in water quality or changes in run-off patterns, alteration of fresh-water flow into estuarine systems, non-point sources of pollutants or fisheries practices). Low-level chronic stresses may not produce immediate or acute impacts on the resource, but could cause subtle degradation over yearly or decadal time scales. Management plans for coastal zones may address apparent threats to coastal ecosystems and such plans require methods to measure the success of management policies and action. Natural disturbances can mask anthropogenic stressors in both frequency and severity of change in natural communities. It remains difficult to assess which impacts have what effects on benthic community structure (Brown and Howard, 1985; Brown, 1988).

Acute impacts on benthic communities such as anchor damage, vessel groundings and recreational impacts, may be easier to address in terms of both monitoring and management programmes (Tilmant and Schmahl, 1981; Rogers *et al.*, 1988). Chronic low-level stress, such as changes in water quality, may have subtle and more gradual impacts on coastal ecosystems. These gradual changes are the most challenging to address from a management perspective and may pose the greatest threat to ecosystem function and diversity. The goal of conservation monitoring is to provide the necessary long-term database needed to catalyse a change in management action to protect ecosystem function and maintain diversity with natural changes in spatial patterning. Conservation monitoring can differ from ecological monitoring in scale and detail. The objectives in many monitoring programmes would be to set limits on measurement parameters for both early identification of potentially damaging trends likely attributed to low-level chronic stressors and to focus research needs in conservation science.

The marine hard bottom complex found along the south Florida shelf represents a community mosaic that exhibits extreme variability in all parameters used to evaluate biological communities (Jaap, 1984). Many of the hard bottom communities can be physically characterized as shallow-water, wave-resistant, three-dimensional complex carbonate accretions constructed by limestone-secreting organisms on a pre-existing hard substrate (Hoffmeister and Multer, 1968). These communities represent an ecologically dynamic system that is potentially threatened by increases in local human population, changes in freshwater input to the adjacent Florida Bay, and changes in land-use throughout the Florida keys and the south Florida watershed. This system appeared ideal for the examination of sampling methods for sensitivity of survey methods and monitoring strategies for complex benthic communities.

The purpose of this investigation was to evaluate benthic survey methods that could be used for both the characterization and long-term monitoring of shallow-water hard bottom communities in tropical oceans. The protocol includes the identification and characterization of hard bottom communities, and the employment of a hierarchy of sampling methods aimed at describing the rate and nature of change in the spatial patterning of benthos. This paper aims to outline the design guidelines, methods and data analyses for long-term monitoring of community function and diversity.

METHODS

Survey site selection

Natural-colour 1:6000 aerial photography of the middle Florida Keys was examined to determine the occurrence of discrete nearshore hard bottom communities and to select specific survey sites. Low-relief hard bottom communities were shown in earlier marine benthic community maps to constitute the largest community class in the Florida Keys compared with other hard bottom types (channel patch reefs and offshore bank reef communities) (Marszalek, 1981). The two study sites were initially characterized in 1988 as 'mixed algae-sponge-coral, sparse, low-relief hard bottom communities' composed of a co-dominance of benthic algae, sponges, octocorals and stony corals. The two hard bottom sites were similar in size (2–8 ha) and were both within 100 m of a tidal channel. The Fiesta Key Reef site (FKR), at 24° 50.444′ N, 80° 47.785′ W, is located on the bay side of the keys and is about 150 m from a campground resort that utilizes a shallow-water injection well for disposal of raw sewage. The Craig Key Reef site (CKR), at 24° 49.703′ N, 80° 45.826′ W, is located on the ocean side of the keys and is about 200 m from shore along a fill-island created for the overseas highway.

The initial hypotheses and assumptions made for this study were: (1) both hard bottom communities should show similar dynamic changes in the spatial patterning of the benthos, (2) the nature and rate of these changes should be similar, (3) species occurring on each community may be different, but the benthic diversity at each site should be similar and constant over time, and (4) larger meso-scale water quality or oceanographic events (e.g. cold fronts) would be likely to influence both sites.

Benthic survey methods

Both communities were mapped from 1:6000 natural-colour aerial photographs and ground-truthed with a global positioning system receiver. The aerial photography was also used to select the direction and location in the placement of belt quadrats within each site. Visual assessment of the photographs was used to orient transects of belt quadrats across the reefs to capture the maximum spatial heterogeneity (e.g. 'splotchiness' in the photos) or the dominant physical gradient (e.g. inshore to offshore). New photography was used each year to aid in the placement of belt quadrats; these transects were not permanent.

Survey methods are diverse in their application as well as goals (see review in Loya, 1978; Weinberg, 1981; Dodge *et al.*, 1982). The methods chosen for this study were arranged in a hierarchy of time required, expertise needed and the power of the method to measure parameters sensitive to changes in community spatial patterning and diversity over space and time. Survey methods for marine benthic communities are numerous (e.g. quadrat, nearest neighbour, point-quarter, line intercept) and have been derived in part from ecological studies of terrestrial plant communities (Kershaw, 1957; Thompson, 1958; Greig-Smith, 1961). These methods have been used in marine ecosystems to examine: (1) variability in reef community types (barrier, fringing or patch) over time and space and (2) definition of zones within a particular type (e.g. reef flat, reef crest, fore-reef). The methods selected for this investigation were modified and carried out as follows.

Substrata and lifeform characterization

A series of parallel 25 m line transects, marked in 1 m increments, were placed across each site each year. Permanent sampling stations were not used, therefore transect lines were oriented in different locations on each site based on the heterogeneity observed on aerial photographs. The appropriate length of the transect lines (25 m) was determined using species-area curves for sponges and corals combined (Gleason, 1922; Loya, 1972). Transect lines were used as a guide for the placement of 1 m^2 quadrats, which were continuously placed along each transect.

For initial characterization, each quadrat was scored for coverage of both substrata and lifeform coverage features. Scoring was visually estimated in each quadrat based on the percent coverage by each category, and included: (0) for 0%, (1) for less than 10%, (2) for 10%–30%, (3) for 30%–70%, and (4) for greater than 70% coverage. These coverage classes were exponentially scaled for easier field discrimination of coverage. Substrata categories were delineated as follows: sand–mud–finer grain sediments (<0.12 mm); coarse biogenic or oolitic sand and gravel; rubble—moveable rocks for 2 cm in diameter to over 1 m in diameter; and hard reef or platform—any continuous and consolidated rocky platform with less than 2 cm of sediment covering it. Benthic lifeform categories included: algal turf or algal canopy, seagrass, sponges, octocorals (Alcyonacea) and stony corals (milleporid hydrocorals and scleractinians). For each quadrat assessed, each substrata and lifeform category was scored independently for a coverage class designation.

Species presence and absence checklists

The first year of this investigation was spent developing species checklists for the major taxa groups observed at the survey sites. Checklists included conspicuous benthic algae, sponges, octocorals and stony corals that could be identified in the field. For benthic algae, conspicuous species that could be identified to the genera level in the field were included (e.g. *Ceramium*, *Gracilaria*). For species identifications and taxonomic guides used for the Florida Keys, see Sullivan *et al.* (1992). The checklists consisted of 75 species of benthic algae, 65 species of sponges, 55 species of stony corals, and 40 species of octocorals, with a total of 235 species in all. This was not designed to be a complete inventory, but rather an indication of the dominant, subdominant, or conspicuous benthic species to be used in the characterization of the communities. Sponges and octocoral samples were most commonly brought back to the laboratory for spicule preparation and verification of field identifications.

The overlap of occurrence of species between hard bottom communities allows adjacent communities to be grouped into a broader system (e.g. the Florida Reef Tract). This overlap can be quantified by several indices of community similarity (e.g. coefficients of Dice or Jaccard). Thus, species checklists provide qualitative and quantitative data to: (1) characterize a community within a system and (2) detect seasonal changes in conspicuous benthos, such as benthic macroalgae, or document catastrophic change.

Belt quadrats: taxa-level sampling

Belt quadrat sampling of hard bottom communities as used by Dana (1976) and Doge *et al.* (1982) allows for the collection of detailed information on the spatial patterning of benthos. Benthos were identified to the taxa level, for example the stony corals (milleporid hydrocorals and scleractinians). In addition to parameters that can be assessed using line transect techniques, plot methods allow for the direct measurement of individual and colony sizes. From each quadrat, the numbers of individuals or colonies were counted and sizes (planar areas for sponges and stony corals or heights for octocorals) of individuals or colonies measured for taxa groups.

A sponge individual or coral colony was defined as any individual or colony growing independently of its neighbours. In cases where a colony was clearly separated into two or more portions by the death of intervening parts, each living part was considered to be a separate individual (Loya, 1972). When branching colonies occurred in thickets, branches that could be traced to a common origin were considered to be part of a single colony (Dustan and Halas, 1987). Dimensions of colonies and individuals were measured *in situ* with calipers to the nearest 0.5 cm. Relative dimensions (length, width, radii) were measured to estimate the planar area coverage (cm^2) of each colony or individual using appropriate areal formulas (e.g. circle or rectangle).

Belt quadrats: species-level sampling

This method followed the taxa-level sampling, but carried the identification down to the species level. This method required the most time and taxa expertise to identify species observed within each quadrat. Similar to taxa-level sampling, for each quadrat algae, sponges, stony corals and octocorals were identified to species. Individuals and colonies were counted and measured to quantify planar area coverage. Algae and seagrass species were identified in each quadrat and assessed for percent coverage according to the coverage classes outlined in the substrata and lifeform characterization methods. Sampling adequacy was tested by plotting species-area curves for all taxa groups combined.

Data analyses

Substrata and lifeform coverage data were converted to percent coverage values. Graphs of lifeform coverage were produced to analyse gross changes in the abundance of biotic components on each community over the study period.

Species inventory data were summarized from standard species checklists and similarity values between sites and between years were compiled using the coefficient of Jaccard (Sneath and Sokal, 1973). This binary index was chosen based on the criteria outlined in Hubalek (1982). Similarity values were utilized to construct species presence/absence matrices to compare overall species composition between sites and within sites over time. A dendrogram was constructed for cluster analysis of similarity values using a group-average sorting strategy (Pielou, 1977).

For belt-quadrat data, analyses were divided into taxa-level and species-level quantitative descriptors for sponges and corals. For taxa-level analyses, information for a taxa group (e.g. stony corals) was pooled for all species. All quantitative data were standardized to 1 m^2. Parameters were broadly grouped into 'density' (individual or colony numbers per sampling unit) and 'area coverage' measurements.

For taxa-level data, one-way analysis of variance (ANOVA) was used to test for differences between sites and within sites over time based on mean values of colony or individual densities, area coverage and area per colony or individual. Prior to ANOVA testing, homoscedasticity of variances was assessed using Bartlett's test for homogeneity of variances (Sokal and Rohlf, 1981). Variances between sites and within sites for colony or individual density, area coverage and area per individual or colony were determined to be heteroscedastic ($p > 0.05$). Because the variances were consistently higher than the mean values, transformation of the raw data $[\log_{10}(x+1)]$ was executed to stabilize the variance ($p < 0.005$) (Zar, 1984). For those cases where the null hypothesis was rejected, Tukey's least significant difference test (LSD) was used as a multiple comparison test procedure (Zar, 1984). Individual and colony sizes were pooled for all species in each taxa and grouped into logarithmic (base 10) size classes as follows: (1) 0.0–0.9 cm^2, (2) 1.0–9.9, (3) 10.0–99.9, (4) 100.0–999.9, and (5) greater than 1000 cm^2. These size classes were chosen to assess marked changes in the size-frequency distribution of individuals or colonies such as size-selective mortality or recruitment events.

Taxa-level density information was used to assess changes in the spatial patterning of individuals or colonies within sites over time. Because the sampling units (quadrats) chosen were arbitrary, quadrat-variance techniques were utilized to analyse patterns on both survey sites (Ludwig and Reynolds, 1988). Quadrat-variance methods are used to examine the changes in the mean and variance of the number of individuals per sampling unit over a range of different sampling unit sizes. Two methods were used: (1) a blocked-quadrat variance (TTLQV) method to identify pattern intensity and the grain of pattern via the blocking of quadrats (Hill, 1973) and (2) a paired quadrat variance (PQV) method to analyse changes in sample unit spacing as related to the patterning of individuals (Ludwig and Goodall, 1978). Plots of the variance versus quadrat size/spacing were constructed based on individual and colony abundances.

For species-level information, the percent relative density and percent relative area coverage were calculated based on each species contribution to the total individual or colony numbers and area coverage for a particular taxa group (e.g. stony corals). For relative density and area coverage values for each species, percentage similarity (Czekanowski's quantitative index) values were computed (Similarity $P =$ Sum (minimum value (p_{1i}, p_{2i})) where p_{1i} and p_{2i} are the percentage of colony or individual density or area coverage contributed by species in communities 1 and 2 respectively) (Bray and Curtis, 1957; Field *et al.*, 1982). Similarity values for individual or colony density and area coverage were used to construct percentage similarity matrices. Similarity matrices were then utilized to construct dendrograms based on group average sorting of values. Similarity values were also calculated between sites and within sites based on the logarithmic classification of individual or colony sizes. Similarity was determined based on the relative contribution of each size class to the total individual or colony abundance for each site.

Indices of diversity and species evenness were examined as to their utility in monitoring biodiversity in a benthic community. Diversity and evenness indices were calculated for comparing sites over time and space. Diversity ($H'n = -\text{Sum } p_i \log_e p_i$) and evenness components ($J' = H'_n / H'_{max}$) were calculated (Pielou, 1975) based on abundance values for sponge individuals and coral colonies. Evenness calculations were based on the theoretical maximum diversity (H'_{max}), which was computed based on the natural logarithm of the number of species sampled in the belt quadrat surveys.

RESULTS

The methods were arranged in a hierarchy of least sensitive to diversity/benthic patterning changes and least time invested to the most sensitive to diversity/patterning changes and most time invested. Specific results are presented to examine (1) the time required and expertise required for each survey method used, (2) parameters measured in each method, and (3) spatial and temporal comparisons of data, statistical analyses, and interpretations.

Substratum and lifeform characterization

This method required the least amount of time (about 2.0 h to complete 50 grids of 1 m^2 on a 5-hectare site) and the least amount of expertise (taxa-level identification). This survey method required two skills: (1) an ability to discriminate benthic algae, sponges, octocorals and stony corals and (2) an ability to estimate area coverage of the major substrata and lifeform categories. The characterization of substrata and lifeform features constitutes ground-truthing for natural-colour aerial photography to confirm an initial community classification.

Changes in lifeform coverage over time are presented in Figure 1 for each site. The coverage of algae, sponges, octocorals and stony corals can provide some indication of year-to-year changes within and between sites; however, there are no appropriate statistical tests to determine levels of significance. The graphs indicate an overall increase in the percent coverage of benthic algae at both sites, with an overall lower coverage of other taxa groups at FKR relative to CKR. Coverage of sponges, octocorals and stony corals has also fluctuated more at FKR relative to CKR. This information might become more important as collateral information in the interpretation of species checklists or belt quadrat data.

Species inventories

Using standardized checklists developed for this project, approximately 10 survey hours per site per year were spent completing the inventories for benthic algae, sponges, octocorals and stony corals. This method required the most pre-survey training and preparation in identification of a given taxa group. Table 1 illustrates the information collected from the stony coral checklist at both sites over time. Similarity indices were calculated and used to create a percent similarity dendrogram (Figure 2A). Figure 2A clearly shows the dissimilarity in stony coral species composition at the two sites. The largest changes in species composition were observed at both sites between 1989 and 1990 (correlating to a severe cold front event in December of 1989). The statistical power of species checklists used to detect benthic community change increases with the use of several taxa groups (more species). The results from a single group (e.g. stony corals) are preferable to identification errors attributed to lack of taxa expertise. Similarity indices can be applied to track changes in benthic species richness over time and between communities.

In 1989, FKR had fewer, but a subset of the coral species found on CKR. The coefficient of Jaccard was 50.0% between the two sites in 1989; this should be interpreted as a baseline similarity in coral species between the two sites at the onset of monitoring. Over 3 years, FKR lost three of seven stony coral species and no new species were reported. Over the same 3 years, CKR lost only one of 14 stony coral species (Table 1). The coefficient of Jaccard was 30.8% between the two sites in 1992. The change in similarity, as well as the disappearance of coral species at FKR, indicates a difference between the two sites in the nature and rate of change in benthic species richness. The use of similarity coefficients introduces a non-normally

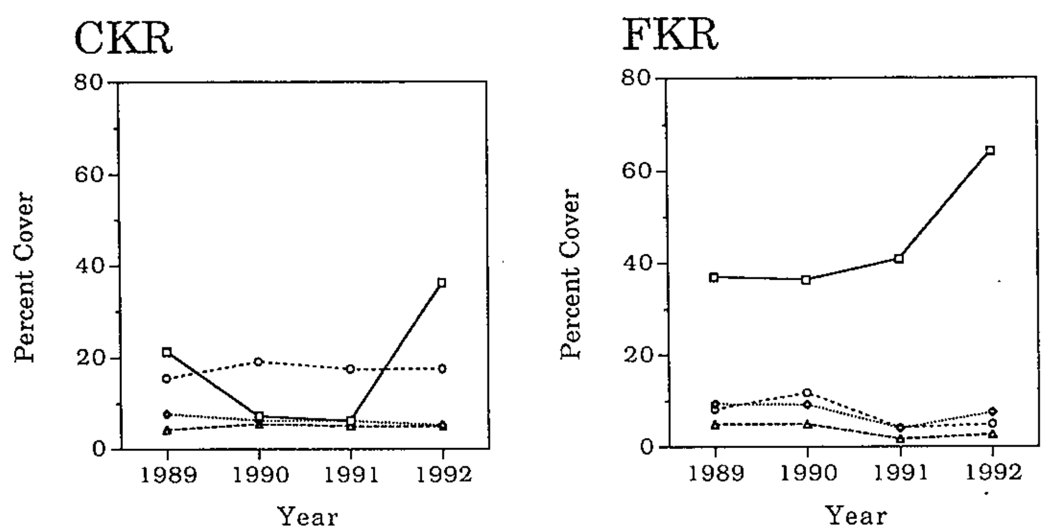

Figure 1. Lifeform coverage changes at sites over study period. □, Algae; ◇, sponges; ○, octocorals; △, stony corals. CKR, Craig Key site; FKR, Fiesta Key site.

Table 1. Stony coral (Milleporina and Scleractinia) species presence and absence list for Craig Key (CKR) and Fiesta Key (FKR) sites during 1989–92. An asterisk (*) indicates species that were recorded in the general survey area of each community

Species	Craig Key site 1989	1990	1991	1992	Fiesta Key site 1989	1990	1991	1992
Family Milleporidae								
Millepora alcicornis	*	*	*	*	*			
Family Agariciidae								
Agaricia agaricites	*							
Family Faviidae								
Cladocora arbuscula	*	*	*	*				
Diploria clivosa	*	*	*	*				
Favia fragum	*	*	*	*	*			
Manicina areolata	*	*	*	*	*	*	*	*
Montastraea cavernosa	*	*	*	*				
Solenastrea bournoni	*	*	*	*				
S. hyades	*	*	*	*	*	*	*	*
Family Poritidae								
Porites astreoides	*	*	*	*	*			
P. porites divaricata	*	*	*	*	*	*	*	*
Family Siderastreidae								
Siderastrea radians	*	*	*	*	*	*	*	*
Family Oculinidae								
Oculina diffusa	*	*	*	*				
Family Mussidae								
Isophyllia sinuosa	*	*	*	*				
Total number of species	14	13	13	13	7	4	4	4

distributed index that requires 'boot-strap' methods of testing for levels of significance. A less formal appraisal allows examination of dendrograms in concert with other parameters to infer limits on monitoring species' losses or gains.

Belt quadrat measurements: taxa-level density and area coverage

Belt quadrat measurements were both time-consuming and required a relatively high skill level for taxa identification. Typically, 10 1 m^2 quadrats can be completed by a SCUBA or snorkelling (2–3 m depth) team in 1 hour. The number of species recorded over a sampled area was used to determine appropriate levels of sampling; both FKR and CKR required 25 quadrats per site per year. Taxa-level data consisted of: (1) density and area measurements of sponge individuals and stony coral colonies, (2) density and height measurements of octocoral colonies, and (3) area coverage of benthic algae.

An example of taxa-level changes in stony corals from both study sites is summarized in Tables 2 and 3 for both density and area coverage parameters. The information collected allowed the analyses of diversity and spatial patterning over time. Similarity indices for species relative colony numbers and area coverage as well as colony size classification are presented in Figures 2B, C and D. The results indicate that FKR is: (1) changing in the patterning of coral colonies, (2) changing faster (greater dissimilarity) than the rate of change on CKR, and (3) becoming more dissimilar to CKR with time. The overall diversity of FKR is lower than CKR (Table 2), but diversity indices were not found to be informative in examining changes over time.

At CKR the density of coral colonies fluctuated from year to year. From 1989 to 1990 coral colony density increased significantly (Tukey's LSD; $p<0.05$), while from 1990 to 1991 there was a non-significant (Tukey's LSD; $p>0.05$) decrease in colony density. Overall coral colony density increased significantly (Tukey's LSD; $p<0.05$) at CKR from 1989 to 1992, but not at FKR. In 1989, FKR had a higher density of stony coral colonies than CKR; both sites showed an increase in coral density in 1990. The most dramatic change occurred in FKR in 1991 with a large loss of coral colonies (from 4.55 to 1.32 colonies m^{-2}). Figure 3 illustrates the change associated with the size-frequency distributions of coral colonies over time. The use of size-frequency distributions helps interpret the dendrogram in Figure 2D; both reefs have relatively few large stony coral colonies, and change from year to year occurred predominantly in one size class of colonies. Both sites exhibited a significant decrease (Tukey's LSK; $p<0.01$) in stony coral colony sizes over the study period.

Quadrat-variance methods were used as an additional tool in this study to assess changes in the patterning of coral colonies. Quadrat-variance methods were used to observe the effect of blocking and spacing of sampling units (quadrats) on the variance of colonies. Higher variances associated with quadrat blocking or spacing indicate the degree and magnitude of patchiness of certain attributes, in this case coral colony density. Figure 4 describes the quadrat size and spacing of coral colonies in the two communities. At CKR, both the size and spacing of colony patches remained unchanged over the study period. At FKR, two trends were inherent in the patterning of coral colonies during the study: (1) patch sizes decreased and (2) patches became more widely separated (8–10 m).

Area coverage parameters for both taxa- and species-level were more variable than colony density estimates. Coral coverage in these communities was low, ranging from 0.1% to 3.9% live coral cover. The most powerful use of area measurements was in the comparison of mean coverage per m^2 over time and in examining the size-frequency distributions of individuals and colonies over time (Figure 3). These data provided information on potential size-selective mortality or recruitment events.

In summary, CKR exhibited increases in coral colony density over the study period, but lost a significant portion of larger colonies. This resulted in a decrease in coral area coverage and mean colony size at CKR (Figure 3). At FKR coral colony density decreased from 1989–92, with the greatest decline in small colonies. CKR and FKR have become less similar in terms of coral colony density, but the mean size of colonies

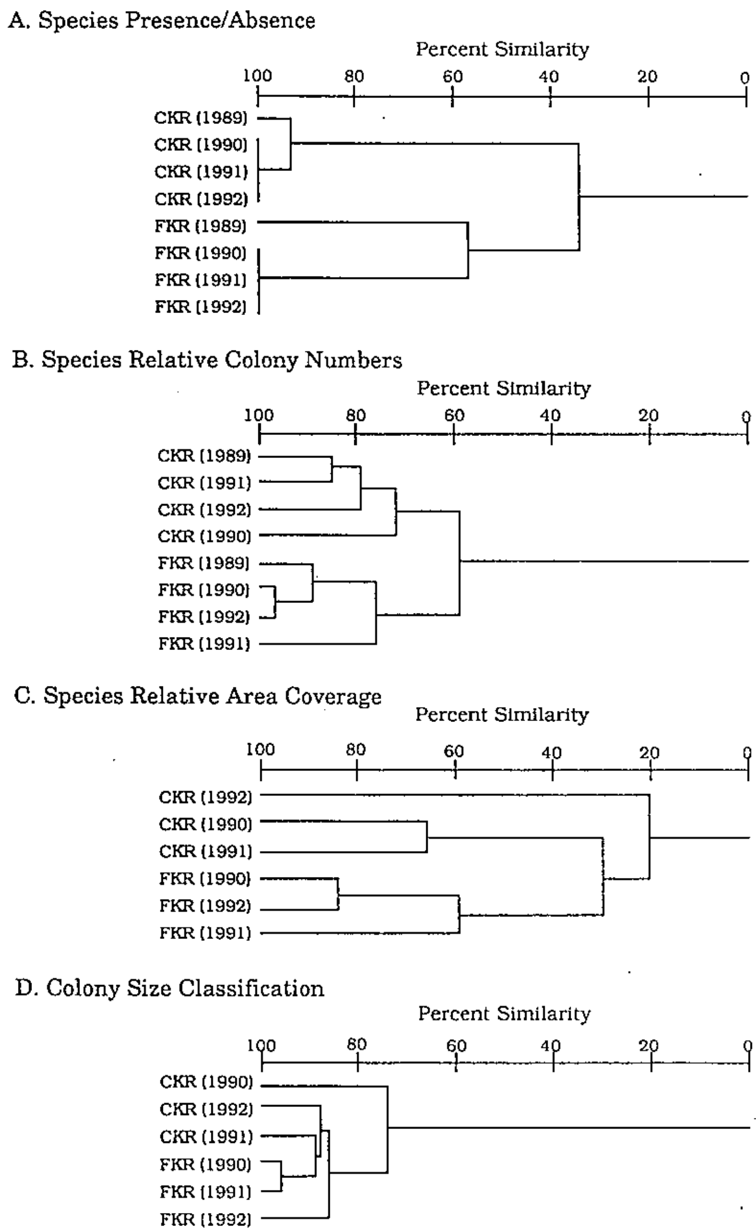

Figure 2. Similarity dendrograms for qualitative and quantitative data collected from study sites. A, similarity based on species presence/absence using the coefficient of Jaccard; B, similarity based on species relative colony numbers using the Bray–Curtis Index; C, similarity based on species relative area coverage; D, similarity based on colony size classification. CKR, Craig Key site; FKR, Fiesta Key site

Table 2. Belt quadrat data summary for stony coral species and colony density for Craig Key (CKR) and Fiesta Key (FKR) sites during 1989–92. Values are expressed as the mean (± 1 SD) number of species and colonies per m^2. The maximum and minimum number of colonies recorded in a given quadrat is shown. Diversity ($H'n$) and evenness ($J'n$) are based on coral colony numbers. Diversity was calculated using $\log_e$.

Site	Year	Quadrats sampled	Number of species m^{-2}	Number of colonies m^{-2}	Max	Min	$H'n$	$J'n$
CKR	1992	44	2.3 (0.9)	4.09 (1.74)	9	1	1.531	0.736
	1991	24	2.2 (1.0)	5.21 (3.06)	13	2	1.247	0.641
	1990	50	2.6 (1.1)	6.96 (5.15)	26	1	1.391	0.633
	1989	50	1.3 (1.0)	2.06 (1.99)	9	1	1.251	0.643
FKR	1992	46	0.7 (0.6)	2.30 (2.73)	10	1	0.373	0.538
	1991	44	0.6 (0.6)	1.32 (1.94)	6	1	0.699	0.636
	1990	20	1.3 (0.6)	4.55 (4.74)	19	1	0.323	0.466
	1989	26	0.9 (0.8)	2.50 (3.39)	13	1	0.564	0.407

Table 3. Belt quadrat data summary for stony coral area coverage and colony sizes for Craig Key (CKR) and Fiesta Key (FKR) sites during 1989–92. Values are expressed as the mean (± 1 SD) coverage per m^2 and colony size. The maximum and minimum coverage in a quadrat and colony size are given.

Site	Year	Coverage $cm^2\ m^{-2}$	Max	Min	Area colony^{-1}	Max	Min
CKR	1992	87.9 (188.6)	1140.5	0.2	26.8 (103.5)	1075.2	0.2
	1991	48.8 (82.7)	383.3	2.3	10.0 (30.0)	254.5	<0.1
	1990	388.6 (553.5)	2287.2	1.8	55.8 (192.3)	1963.5	0.2
FKR	1992	10.5 (13.3)	49.5	<0.1	4.6 (5.17)	23.8	<0.1
	1991	13.0 (27.5)	144.0	0.8	9.9 (20.9)	144.0	0.2
	1990	34.7 (38.0)	154.0	3.1	7.6 (10.9)	95.0	0.8

at each site have become more similar, particularly because a few large corals (> 100 cm^2) suffered mortality at CKR while smaller colonies (< 100 cm^2) suffered a massive mortality at FKR.

Belt quadrat measurements: species-level colony density and area coverage

The analysis of species-level parameters, including colony density and area coverage, provided the most detailed information concerning specific shifts in community structure at the study sites. This method required extensive training prior to surveys as well as the collection of voucher specimens to confirm species identifications (done in conjunction with species check lists). No unique trends in species-level parameters emerged that were not already evident in the taxa-level information (Tables 4 and 5). Analysis of species-level parameters was similarly partitioned into density and area coverage measurements.

For colony density measurements, the dominant species at CKR from 1989 to 1992 were *Siderastrea radians*, *Millepora alcicornis* and *Porites porites* forma *divaricata*. These three species contributed greater than 85% of the total stony coral colony numbers at CKR (Table 4). The most significant change occurred in the density of *P. porites* forma *divaricata* colonies, which suffered a large decrease from 1990 to 1992 at CKR. At FKR, similar results were found for colony density between 1990 and 1992. In both years *S. radians* and *P. porites* contributed greater than 90% of the total coral colony numbers. Changes in colony abundance at FKR were not significant for *S. radians* over the study period.

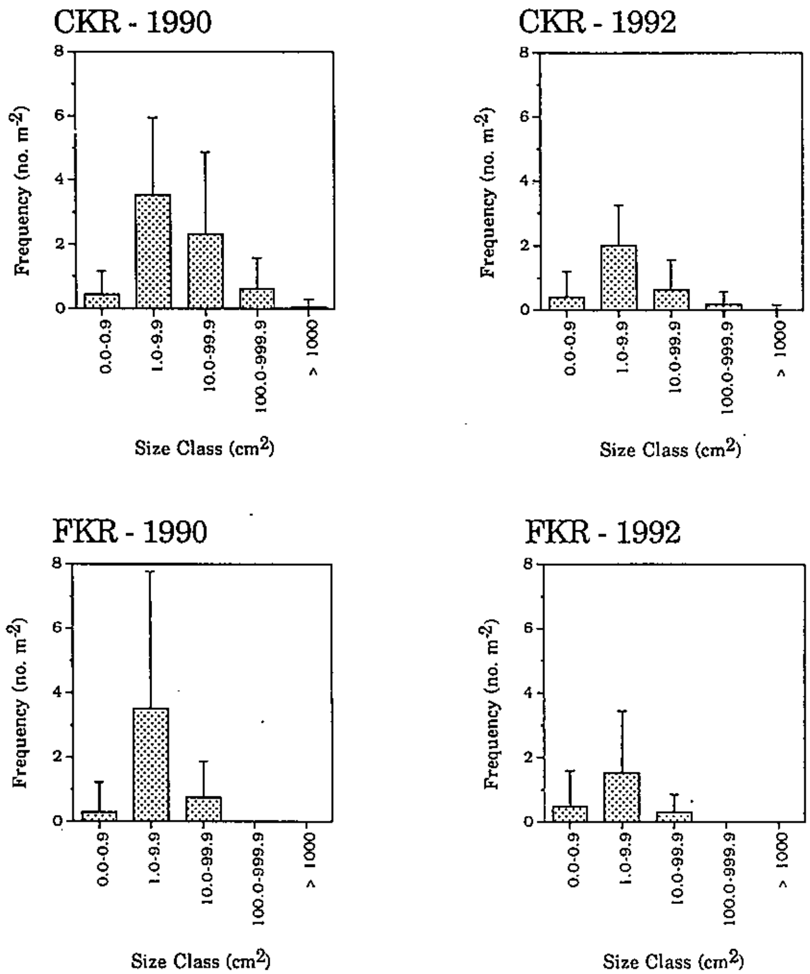

Figure 3. Size-frequency histograms of coral colony sizes at sites from 1990–92. Values are expressed as the mean number of colonies within each size class per m^2. Error bars represent 1 SD. CKR, Craig Key site; FKR, Fiesta Key site.

Shifts in the relative contribution of area coverage by species resulted in decreased similarity within CKR from 1990 to 1992 (Table 5). In 1990, area coverage at FKR was dominated by *Siderastrea radians*, but by 1991, the large loss in area coverage of this species resulted in the increased relative area coverage of *P. porites* forma *divaricata*. Similarity between CKR and FKR was remarkably lower for area coverage estimates compared to colony density measurements. In contrast to the low similarity between the two sites based on species area coverage, higher similarity was observed when coral colonies were grouped into logarithmic size classes (Figure 2D). This is a taxa-level analysis which illustrates that colony sizes at each site were very similar in terms of the size distribution of colonies. Species-level information was critical to the calculation of diversity indices (Table 2).

Diversity indices

Diversity measures were used for each taxa group based on numbers of individuals or colonies for sponges, stony corals and octocorals. Diversity measures proved to be the least useful parameter computed

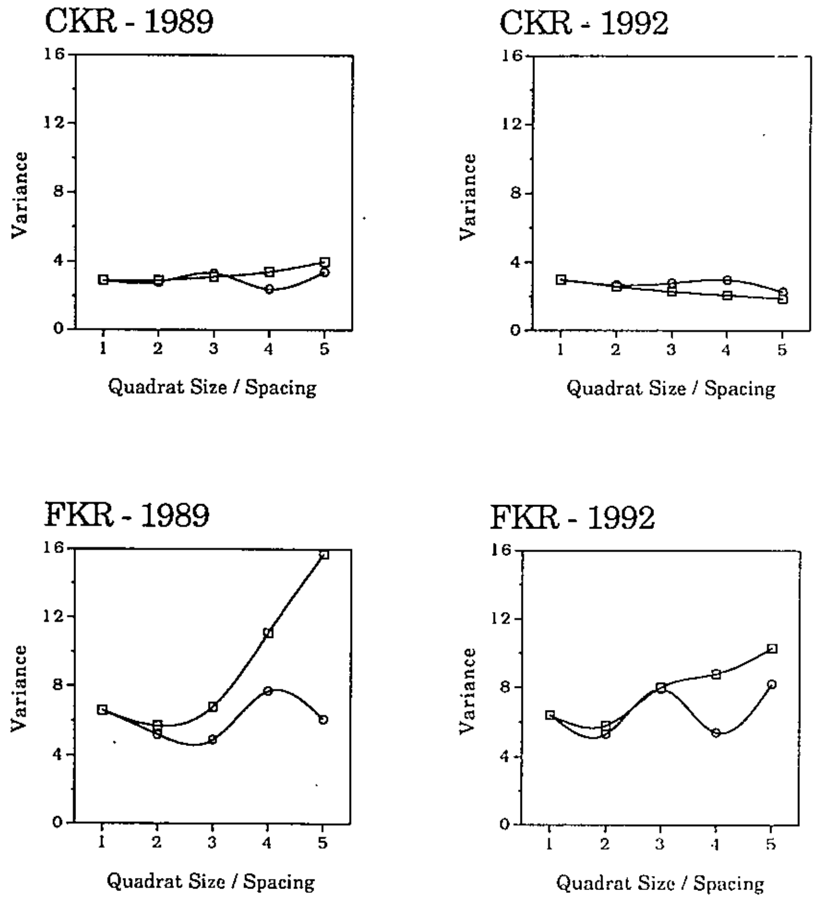

Figure 4. Spatial patterning analysis of stony coral colony density. □, two-term local quadrat variance method (TTLQV); ○, paired quadrat variance method (PQV). CKR, Craig Key site; FKR, Fiesta Key site.

Table 4. Species-level belt quadrat data of colony density for stony corals at Craig Key (CKR) and Fiesta Key (FKR) sites from 1989–91. Values represent coral colony density (number m^{-2}). Values in parentheses represent 1 SD.

Species	Craig Key site				Fiesta Key site			
	1989	1990	1991	1992	1989	1990	1991	1992
D. clivosa				0.02 (0.15)				
F. fragum	0.22 (0.46)	0.44 (0.76)	0.42 (0.78)	0.43 (0.85)	0.23 (0.65)			
I. sinuosa	0.02 (0.14)	0.02 (0.14)						
M. areolata	0.06 (0.24)	0.04 (0.28)						
M. alcicornis	0.48 (0.68)	0.82 (1.04)	0.83 (1.05)	1.11 (1.17)				
O. diffusa			0.04 (0.20)	0.11 (0.39)				
P. astreoides	0.04 (0.20)	0.06 (0.31)	0.04 (0.20)		0.04 (0.20)			
P. divaricata	0.08 (0.27)	2.24 (3.90)	0.63 (0.92)	0.50 (1.11)	0.12 (0.33)	0.45 (0.60)	0.41 (1.30)	0.28 (0.83)
S. radians	1.16 (1.68)	3.04 (2.38)	3.08 (3.12)	1.68 (1.16)	2.12 (2.96)	4.10 (4.55)	0.89 (1.45)	2.02 (2.55)
S. bournoni		0.04 (0.20)		0.18 (0.39)				
S. hyades		0.26 (0.49)	0.17 (0.38)	0.05 (0.21)			0.03 (0.15)	

Table 5. Species-level belt quadrat data of area coverage for stony corals at Craig Key (CKR) and Fiesta Key (FKR) sites from 1989–91. Values represent coral area coverage ($cm^2 m^{-2}$). Values in parentheses represent 1 SD.

	Craig Key site			Fiesta Key site		
Species	1990	1991	1992	1990	1991	1992
D. clivosa			0.1 (0.5)			
F. fragum	2.4 (5.0)	1.4 (2.7)	2.0 (4.2)			
I. sinuosa	0.6 (4.0)					
M. areolata	0.4 (2.8)					
M. alcicornis	250.9 (472.8)	31.4 (93.9)	7.6 (16.3)			
O. diffusa		0.1 (0.6)	6.8 (23.4)			
P. astreoides	5.4 (37.0)	5.5 (27.1)				
P. divaricata	60.8 (149.3)	4.1 (8.6)	1.3 (2.7)	10.3 (22.4)	4.9 (15.8)	1.4 (5.8)
S. radians	27.2 (30.3)	12.5 (14.4)	14.2 (22.6)	24.4 (22.0)	4.9 (8.8)	9.1 (11.6)
S. bournoni	29.1 (151.5)		58.0 (182.6)			
S. hyades	11.9 (42.7)	2.2 (6.1)	0.6 (1.2)		3.3 (21.7)	

for either study site. At CKR the Shannon–Weiner diversity index (H'_n) and evenness (J'_n) did not significantly increase from 1989 to 1992 based on stony coral colony numbers. At FKR, diversity and evenness were variable from 1989 to 1992. Increases in the Shannon–Weiner index were caused in part due to the decreased dominance of *Siderastrea radians* and the increase in relative importance of *Porites porites* forma *divaricata*. Stony coral diversity (H'_n) measures were higher at CKR than at FKR for the duration of the study.

DISCUSSION

Design of monitoring programmes for tropical hard bottom communities

There are three facets of monitoring design that became evident in the course of this investigation: (1) the problems of historical perspective for survey sites, (2) the utility of multiple sites to avoid Type II errors, and (3) establishing meaningful limits for monitored community attributes. Even in low coral-coverage communities such as FKR and CKR, the use of only one taxa group (stony corals) can provide details on the nature and rate of change of benthos if levels of data (species lists, colony abundance, area coverage) are incorporated in the survey design. The use of additional taxa groups increases the sensitivity and statistical power of surveys that include species checklists and belt quadrat surveys.

Sampling design in benthic community monitoring calls for a balance of sensitivity and sufficient ecological information to set limits on the expected rate and nature of changes in marine benthic communities. Monitoring programmes should be statistically conservative, that is, the design should be more likely to allow Type II rather than Type I errors to occur. Type II errors, or not detecting a change in sites when in fact significant changes have occurred, may prevent proper management and conservation action. Type II errors may therefore not allow for the detection of subtle irreversible damage of benthic communities from anthropogenic impacts. A conservation monitoring programme may provide the initial trend analysis or background information for more in-depth ecological investigations. A hierarchical survey and sampling design would allow for the most efficient use of resources for both the characterization and assessment of tropical hard bottom marine communities.

History of survey area

The power of monitoring programmes will be in their history and scale; it becomes easier to interpret dynamics when changes can be observed over several sites (larger spatial scale) and over a number of years (larger temporal scale). Hierarchical surveys that can relate very coarse levels of change can incorporate anecdotal information or historical photography to infer trends or changes on larger spatial scales. Relatively few marine ecosystems in the tropical western Atlantic will have pristine baseline information on benthic diversity and dynamics that can be used to develop a survey and monitoring programme. Anecdotal information will suggest previous impacts or events that have influenced present-day community structure (for the Florida Keys, see Dustan, 1985; White and Porter, 1985; Jaap *et al.*, 1988; Porter and Meier, 1992).

For example, the south Florida continental shelf can experience cold fronts every several years that can have a large impact on the structure of nearshore hard bottom communities (Roberts *et al.*, 1982). A cold-front event in December of 1989 preceded a recorded die-off of milleporid hydrocorals (*Millepora alcicornis* and *M. complanata*) and the increase in coral rubble as a substrata on outer bank reefs in the Florida Keys. *Millepora alcicornis* was not extirpated from CKR, but was not recorded at FKR after 1989 (Table 1). For both reefs, this single event is likely to have had the largest impact on community similarity based on species presence/absence (Figure 2). This event impacted both reefs, but the nature and rate of change was different at the two sites. The question of interest in conservation monitoring is, 'was this species loss significant and indicative of a trend towards loss of diversity and eutrophication at FKR; was the difference in community response to a cold-front event caused by anthropogenic impacts on the site?' The importance of historical information for survey sites is vital in formulating the best possible response for resource management.

FKR was initially less speciose than CKR. Anecdotal information suggested widespread decline in nearshore marine communities of the Florida Keys over tens of years due to dredge-and-fill development and changes in land use. The difficulty in managing tropical marine resources lies in the multiple causes of change in nearshore water quality, sedimentation and circulation. CKR and FKR were different at the onset of the study, but significant differences were found in the nature and rate of change documented during the monitoring. Despite the loss of some larger colonies at CKR, coral colony density has increased since the start of the monitoring programme (Figure 3). FKR lost more species and exhibited a decrease in stony coral colony density with a concurrent increase in algal coverage. These changes suggest that low-level chronic stressors have caused further degradation at FKR in terms of loss of species and potentially reduced recruitment.

Multiple survey sites

In the monitoring of marine resources, there are two types of errors that can arise from survey design and sample number: (1) Type I errors which result in the inappropriate detection of 'natural' changes in diversity or spatial patterning that are attributed to anthropogenic causes or (2) Type II errors in which changes in diversity or spatial patterning by anthropogenic sources on communities go undetected. Monitoring is often intended to evaluate the success or failure of coastal management programmes or to identify management needs; thus the interpretation of results needs to have a known statistical reliability. Conservation monitoring, at the very least, can provide some direction and scope to identify research needs (e.g. coral or sponge recruitment patterns in the middle Florida Keys). Using multiple sites in a conservative sampling design tended to minimize 'Type II' errors (i.e. attributing anthropogenically induced change to natural community dynamics). The combination of using hierarchical sampling at multiple sites strengthens the ability to detect specific changes likely to be exacerbated by anthropogenic stressors.

The argument for anthropogenic stress at FKR is strengthened by comparisons to CKR. FKR suffered significant decreases in coral colony density, while CKR experienced recruitment of colonies (Figure 3). The selection and sampling of paired sites increased the appreciation for biological variability from two initially similar ecological communities and allowed for some way to interpret the rate and magnitude of changes in species patterning.

Parameter limits

Substratum and lifeform characterization

In the monitoring of marine communities, both the overall area occupied by a community as well as changes within the benthic structure are of concern. The substratum and lifeform characterization provided a coarse filter on characterizing the overall community and assessing whether the basic structure of the community was the same or different from previous visits. CKR and FKR were similar in community structure with two notable differences: (1) algal coverage was consistently higher at FKR and (2) octocoral coverage was consistently higher at CKR. Both sites exhibited an increase in benthic algal coverage in 1992 compared to previous years.

The substrata and lifeform coverage method may be used effectively for ground-truthing benthic community base maps made from natural colour aerial photography. Substratum and lifeform characterizations are of limited use in a comprehensive conservation monitoring programme. There are no statistical tests that can be easily applied to the data to determine levels of significance in viewing spatial and temporal change. This method is best used for qualitative review of community structure and the detection of larger-scale changes in area coverage of benthos (e.g. benthic algal blooms, mass mortality events). Substratum and lifeform coverage information may be useful in monitoring community structure after a storm or hurricane; though results from this study do not reflect changes following the cold-front event in late 1989. This level of monitoring must be employed at a large number of sites dispersed throughout an ecosystem of interest.

Species inventories

Species inventories can be used in two ways: (1) the total number of species present on a community as an indication of species richness and (2) the comparison of species present from year to year. On hard bottom communities, such as CKR or FKR, that are part of an extensive nearshore ecosystem, one would not expect conspicuous benthic species to disappear over a time frame of a few years. Colony abundance and area coverage would vary with space and time on the community, particularly for fast-growing corals such as the milleporid hydrocoral *Millepora alcicornis*. Changes of 10% or more for species checklists between years are drastic and indicate significant changes in the benthos. Even in catastrophic events such as hurricanes, coral species are rarely lost from larger reef sites. Davis (1982) documented 100-year changes on reefs and noted that species and community types shifted spatially over this time period. Species loss from year to year must be evaluated with both the size of the reef and with the appearance of new species. FKR lost three species during the monitoring period. This is interpreted as an anthropogenically induced change, and not a natural rate of species extirpation from the area.

Belt quadrats

Density and area measurements are essential in identifying trends in benthic patterning. Reefs and other tropical hard bottom communities are characterized by clonal organisms which exhibit complex life histories. Monitoring of hard bottom communities for low-level chronic stresses must take into account the complexity associated with modular processes of clonal organisms (e.g. partial mortality, fission and fusion; see Hughes and Jackson, 1985). The number and size of individuals or colonies can be used in concert as an indication of reproductive potential and mortality events.

The measurement of colony sizes in this study answered two questions: (1) were the two communities characterized by a dominance of larger or smaller individuals or colonies and (2) were there size-selective mortalities of individuals or colonies during the study period? Colonies were grouped into broader size classes, which minimized the importance of the inherent error in area coverage estimates. Monitoring studies can determine the error in field measurements of area coverage to avoid Type II errors in hypothesis testing. Sites were chosen for this study based on low coral cover, low topographic complexity, and the dominance of smaller colonies. It is expected that the error in both density and area coverage estimated will be significantly higher for complex, three-dimensional reefs that exhibit higher coral colony density and coverage.

Symptoms of low-level chronic stress

The symptoms of community or ecosystem stress have been recently reviewed (Rappaport *et al.*, 1985). A central challenge to monitoring studies is the segregation of change caused by low-level chronic stresses on an ecosystem from the natural dynamics of communities. The symptoms of community degradation on tropical hard bottom communities over a short-term (years) period include: (1) the rapid disappearance of species from the area, (2) loss of specific size-classes of individuals or colonies, and (3) decreasing similarity between two initially similar sites over time based on density and area coverage measurements.

FKR exhibited much different changes than CKR, which indicate that some anthropogenic factor is impacting FKR. At the onset of this study, FKR was dominated by small coral colonies and lacked larger colonies. The symptoms of community degradation at FKR are evident; the loss of species and the dramatic decrease in colony density indicate a suspected unnatural rate of change. Disturbances to natural communities are both diverse in intensity and frequency, but the decrease in species richness with the lack of benthic recruitment to a community indicates potential degradation. This conclusion is strengthened by the review of several scales of detail and data measurements. CKR, a similar community with respect to both location and topographic complexity, changed in a much different manner.

Tomascik and Sander (1987) recorded similar benthic degradation phenomena on fringing reefs along the west coast of Barbados. This study documented the effects of a 'eutrophication gradient' on nearshore reef community structure, and found that sites impacted from nutrient loading were characterized by lower species richness, decreased coral abundance, and reduced colony sizes compared to less eutrophicated communities. Wittenburg and Hunte (1992), in their study of juvenile coral abundance and mortality along the west coast of Barbados, observed that eutrophicated reefs exhibited lower juvenile abundance which was attributed to higher mortality and lower recruitment. While the comparison of results from different coastal marine ecosystems must be interpreted with caution, the results from the monitoring of CKR and FKR are similar to other studies (Banner, 1974; reviewed in Pastorak and Bilyard, 1985).

The assumption made in many conservation monitoring programmes is that the benthos will respond to long-term changes in water quality. A challenge in assessing the effects of nutrient loading on tropical marine benthic communities is to provide a link between water quality parameters and specific changes in benthic community patterning. The logistical problems associated with water quality monitoring are similar to biological monitoring. To monitor water quality for evidence of nutrient loading, one must establish the following: (1) parameters to measure, (2) sampling periodicity, and (3) limits or ranges for water quality values. Nutrient surveys typically focus on concentrations of readily measurable dissolved inorganic macronutrients (NH_4^+, PO_4^{3-}, NO_3^-). This emphasis obscures the fact that carbon, nitrogen and phosphorus in both marine and freshwater aquatic systems are usually sequestered in organic forms, particularly in the benthos (Furnas, 1992). The relative importance of direct and indirect effects of nutrient enrichment of hard bottom communities varies with the community type and trophic status (Hawker and Connell, 1992).

The hierarchical approach of survey methods may prove important in the selection and design of water quality monitoring. Hydrography and descriptions of physical gradients on reef communities are poorly understood, but essential in understanding spatial patterns (Roberts *et al.*, 1975; see review by Wolanski, 1992). Changes in benthic patterning are more easily interpreted when viewed with water quality and oceanographic parameters. A hierarchical survey design may help to initiate water quality monitoring when patterns of benthic communities and spatial change have been described. The pattern of communities from inshore to offshore in the tropical western Atlantic typically includes nearshore hard bottom or rocky platform areas (Glynn, 1973). It stands to reason that if the nearshore communities can be monitored for and protected from low-level chronic stressors, then such information will aid in protecting offshore reefs and other ecosystem components. Nearshore communities will demonstrate symptoms of stress before offshore or more distant communities (Tomascik and Sander, 1987). Monitoring nearshore coastal communities may lead to less ambiguous conclusions and facilitate conservation and management action.

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