7-1-1982

Quantitative Reef Assessment Studies in Bermuda: A Comparison of Methods and Preliminary Results

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Recommended Citation

Dodge, Richard E., Alan Logan, and Arnfried Antonius. 1982. "Quantitative Reef Assessment Studies in Bermuda: A Comparison of Methods and Preliminary Results." Bulletin of Marine Science no. 32 (3):745-760.

BULLETIN OF MARINE SCIENCE, 32(3): 745-760, 1982

QUANTITATIVE REEF ASSESSMENT STUDIES IN BERMUDA: A COMPARISON OF METHODS AND PRELIMINARY RESULTS

Richard E. Dodge, Alan Logan, and Arnfried Antonius

ABSTRACT

To compare in quantitative terms both ecological characteristics of the stony coral fauna at various reef sites in Bermuda and available assessment methodologies, we present a study of four separate methods at each of three reef sites. Three plotless (Intersected-length, Quarter point, Point) and one quadrat (Belt-quadrat) methods were employed. Each technique gave similar results but had inherent advantages and disadvantages which involve trade-offs in quantity and type of information generated and time required for use.

Pooling of method results revealed that total coral coverage was highest at North Rock (26%), intermediate at Three Hill Shoals (17%), and lowest at South shore (13%). Diversity statistics were highest at Three Hill Shoals, intermediate at North Rock, and lowest at South shore. At all three sites the most dominant species in terms of coverage was *Diploria strigosa*; six coral species accounted for 90% of the total coral coverage.

This study represents a quantitative comparison of the results and performance of common reef assessment methodologies and the first truly quantitative data on coral coverage, diversity, and distribution for selected reef sites in Bermuda.

The importance of detailed knowledge about the ecological characteristics of coral and other benthic communities of coral reefs is now recognized and has been recently stressed by Loya (1978). Quantitative, as opposed to qualitative, methodologies allow more standardized and accurate descriptions of the desired reef community to be made. In this way meaningful intercomparisons of different reef areas as well as of various zones on a single reef or reef complex become feasible. Ecological parameters such as species richness, abundance, diversity, coverage, density, and zonation are common statistics of comparison and become available through quantitative methods.

Classical studies on coral reefs prior to the 1970's (see reviews by Stoddart, 1969; 1972) have been primarily qualitative. Although many have utilized quadrats in various ways as data sampling units, it has been difficult to compare between methods and results. Generalizations based on such data are therefore tenuous.

More recently, as interest in quantification of aspects of reef ecology has grown, two general classes of methodologies have emerged: (1) plot techniques, utilizing quadrats as sampling units either randomly or arranged belt fashion along a transect line for guidance; and (2) plotless techniques, essentially an outgrowth of the methodology of terrestrial plant ecologists, utilizing a distance (and/or other measurements) from or on a sampling structure, which is usually a transect line of specified length but with no breadth. Loya (1978) provides a comprehensive review of existing plotless methodologies and suggests new procedures for coral reefs which have had success in terrestrial plant ecology.

The only previous comparison of reef survey methodologies known to us is by Goodwin et al. (1976) who compared grid, transect and random quadrat methods to total samples in a 400-m^2 grid on Grenadine reefs. They concluded that a series of parallel line transects was adequate to delimit dominant species but 4-m^2 quadrats were preferable for recognition of less abundant species.

We present here results using four different assessment methods to characterize

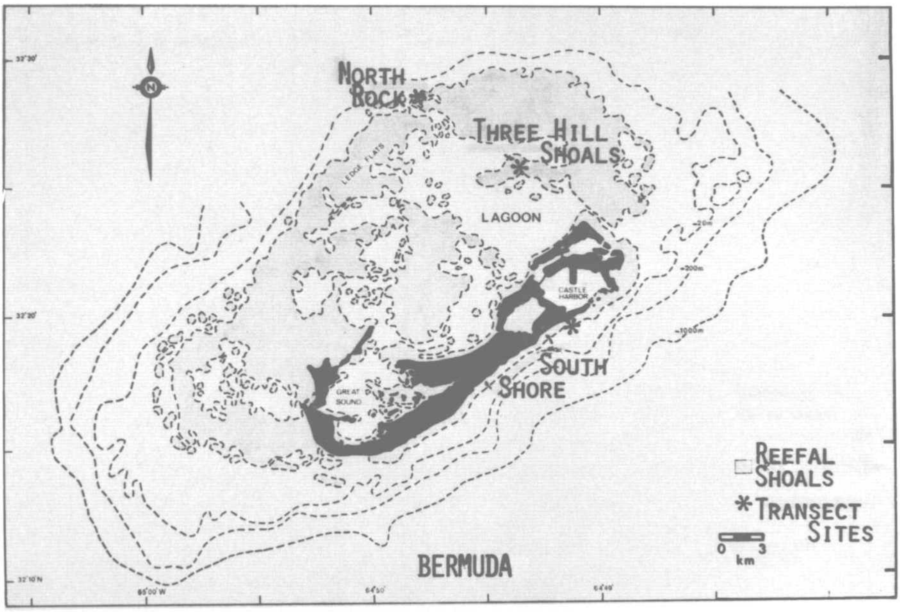

Figure 1. Map of Bermuda Platform, showing location of 3 transect sites.

three reef sites off Bermuda. We have conducted these assessments both in order to intercompare the individual methods for time, accuracy, and the amount of information generated and to provide some basic quantitative information about the reefs of Bermuda.

For our study we chose three representative reef locations on the Bermuda Platform (Fig. 1): South shore reefs near Natural Arches, shoreward of the algal cup-reef tract, on the "nearshore platform" of Meischner and Meischner (1977); the North reefs, immediately adjacent to North Rock (ledge-flat reefs); and North Lagoon patch reefs at Three Hill Shoals. Because of time limitations and our additional purposes of comparing methodologies, we restricted reef characterization to the nearly horizontal reef tops at relatively shallow depths of 3–5 m. Reef sides and slopes at greater depths were avoided because of possible depth zonation effects.

We have utilized three plotless techniques: The Intersected-length (=line transect method of Loya, 1978) method because of its proven success in past work and as a standard with which to compare other methodologies; the Point Centered Quadrant or Quarter Point method, and the Point method. For our quadrat technique we have chosen a belt-quadrat transect where equal area quadrats as sampling units are continuously arrayed and photographed along a transect line. Each assessment method was applied to each reef site. We first briefly explain the methods. Next we describe our field applications. Finally, we present our results and a discussion of individual method performance and the data.

Description of the Methods

Intersected-length Method

This method was first adopted for and used on coral reefs by Loya and Slobodkin (1971) and Loya (1972) and has since been used considerably (Ott, 1975; Loya, 1975; 1976). It was re-described as the

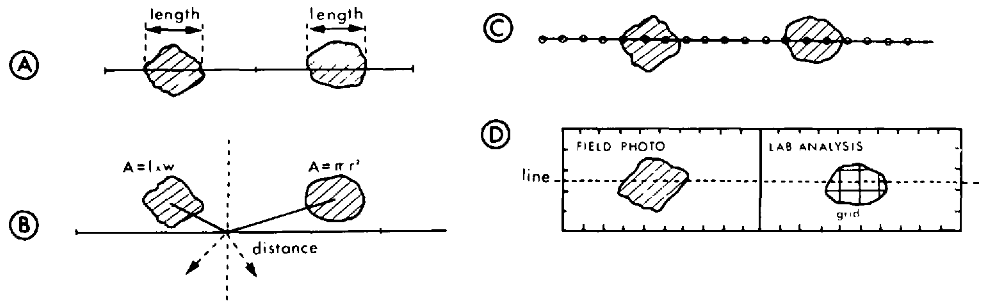

Figure 2. Methodology for A, Intersected length; B, Quarter Point; C, Point, and D, Belt Quadrat transect methods (see text for explanations).

"line transect method" by Loya (1978). A variation of the basic method has been reported by Porter (1972).

The sample consists of a line transect of 10-m length (length determined by a species-distance curve) overlaying the desired reef area. The intersected length (in plan view) of any coral species underlaying the line is recorded to the nearest centimeter (Fig. 2a). The method is therefore based on the premise that: total length of coral tissue intersected on the transect/total transect length = coral coverage (or frequency) = total tissue area of the coral population/total substrate area over which the coral population is living. We calculate relative coverage (or relative frequency of occurrence) by: total length of a particular species/total length of all species on the given transect.

Diversity statistics are calculated using either the number of individuals of the different species or the data on relative coverage of the different species. We use Shannon and Weaver's (1948) formula: $H'_N = \sum_i p_i \ln p_i$ information units; where for number of individuals: $p_i = N_i/N$ is the proportion of the total number of individual coral colonies (N) belonging to the ith species (N_i). We also use the relative coverage information in a similar way as Loya (1972) and calculate: $H'_C = \sum_i p_i \ln p_i = C_i/C$ where $p_i = C_i/C$ is the proportion of the total coverage of corals (C) belonging to the ith species. The evenness index (Pielou, 1966) was also calculated; the measure is: $J' = H'$ (observed)/H max, where H max = ln S. S is the total number of species encountered. Evenness for both H'_N and H'_C was calculated.

For this study an individual coral is defined as a colony growing independently of its neighbors. Only the intersected length of living tissue on a particular colony is recorded. For cases where a coral colony is clearly and recently separated into two or more portions by selective colony mortality, the separate parts are considered as the same individual, yet only the living tissue is recorded for coverage analysis. Loya (1972; 1978) makes the distinction of two or more corals growing one above the other and underlying the transect. In these cases the largest coral length is used for living coverage calculations but the length (and species) of any other overlapping specimens underlaying the line at that point is used for species diversity calculations. In practice, this situation was rare on the Bermuda reefs.

Point Centered Quadrant (or Quarter Point) Method

This method was discussed by Cottam et al. (1953) and its application to coral reefs reviewed by Loya (1978). It has been employed with considerable success in terrestrial studies.

We used a transect line with 10 equally spaced sample points 1 m apart. Each point is considered the center of four quarters (Fig. 2b). The distance from the sampling point to the center of the nearest individual coral colony is measured in each of the four quarters at each point. The coral species and the approximate area of the coral tissue (using the measured diameter of hemispherical specimens or the length and width of nearly rectangular specimens) is recorded. The mean of the 40 distances from the 10 sampling points is equal to the square root of the mean coral population area (Cottam et al., 1953). Mean population area describes the average empty area surrounding a coral as a point source. Because an estimate of coral tissue area is provided by the diameter or length and width measurements, it is possible to calculate coral coverage information by: average coral tissue area/mean population area. Density of individuals is obtained by dividing the mean population area into the appropriate unit area in which density is desired to be expressed (e.g., say the mean population area is 1,000 cm^2 and density is desired in individuals/m^2, then: (10,000 cm^2/m^2)/1,000 cm^2 = 10 individuals/

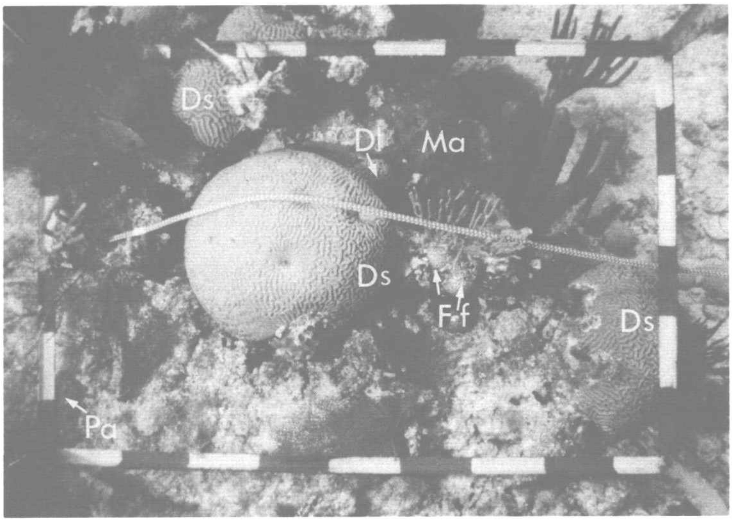

Figure 3. Typical Belt quadrat photograph, Three Hill Shoals. Area 0.5 m^2. Ds = *Diploria strigosa*, Dl = *Diploria labyrinthiformis*, Ma = *Montastrea annularis*, Ff = *Favia fragum*, Pa = *Porites astreoides*.

m^2. Relative frequency or coverage data is calculated by: the sum of the tissue area of the coral species of interest/total coral tissue area of all species measured. Diversity, as with the Intersected-length method, may be calculated on either number of individuals of each species (H'_N) or the relative coverage (H'_C) information on each species.

Point Method

The technique of point counting has been developed and used extensively in the geological sciences for determining the quantitative mineralogy of thin or polished rock sections. Mineral grains are identified and counted under the microscope at each point in a grid of equally spaced points. Subsequent calculations can provide the ratio of area of a given mineral to the area of all the minerals (which is a consistent estimator of the volume percent of the mineral in the rock) (Galehouse, 1971).

There seems to be no extensive use of a point counting method in the terrestrial ecology literature; however, Pielou (1967) has described and used a similar technique. Variations of the method using "sampling blocks" at each sampling site have been widely used (Loya, 1978). For quantitative assessment of coral distributions in Venezuela and Puerto Rico, Antonius (1980), and Antonius and Weiner (In Press) have used a variation of the basic Point method we describe below.

Our method consists of discrete sampling points arranged along a transect line. We used a 100-m line with 200 points equally spaced at 0.5-m intervals (Fig. 2c). The transect line is deployed over the area of interest and the quality of substrate falling directly beneath each point is characterized. For our work, if coral tissue was encountered under the point, the species was recorded. Thus the method is based on the expectation that: total number of coral points/total number of transect points = coral coverage = total living coral tissue area/total substrate area of the living coral population. Relative frequency or coverage of species is easily determined by total number of points covering the species of interest/total number of all coral points. Diversity (H'_C) may be calculated from the relative coverage information. It should be noted that individual colonies are never counted or measured. The characterization of a point is whether or not it covers coral tissue and the species of the coral tissue.

Belt Quadrat Method

Variations of this basic method have been described by Goldberg (1973), Laxton and Stablum (1974), Maragos (1974) and Ott and Auclair (1977). We employed a 30-m line to act as a guide along which a continuous strip of adjoining quadrats, each 0.5 m^2 in area (Fig. 2d) were photographed. A typical photograph is shown in Figure 3. In the laboratory the photographs were analyzed using a binocular microscope and a grid overlay of 50 squares, each square representing 100 cm^2 of actual bottom area. Fractions of a square were estimated using a smaller grid divided into 16 squares and objectivity was maintained by using the same person for all counts.

For each quadrat we obtained the number of coral species present, the number of colonies of each species and the percent coverage of each species. Percent coral coverage for the transect was obtained by dividing the sum of coverage values for all quadrats by the total number of quadrats sampled. Relative coverage was percent cover of individual species/total percent cover of all species. Frequency may be calculated from the number of quadrats in which a species occurred/total number of quadrats sampled; relative frequency may be expressed as the frequency of a species/total frequency of all species. Finally, density was calculated as the total number of colonies of a species in a transect/total area of the transect in m^2.

Diversity indices were calculated in a way similar to the Intersected-length method by using number of colonies to obtain H'_N and relative coverage to obtain H'_C.

Field Applications

At each of the three field sites all four methods were employed. In general, all methods were applied to a relatively small reef area of approximately 300–400 m^2. Ten-m Intersected-length and Quarter Point transects were randomly oriented and maintained as straight as possible, given the varying reef topography. A fiberglass measuring tape graduated in meters and feet was used as a transect line. Lead diving weights were used to keep the line fixed to the bottom. Aluminum meter sticks were used for additional measurements. In many cases the Intersected-length and Quarter Point methods were applied on the same transect line. Rarely, however, were the same corals measured in each. For the Point method a 100-m line with prominent numbered markers as points every 0.5 m was deployed in a random looping pattern in order to more closely stay in the general area of the transects of the other methods. A grid of points as specified for classical point-counting of mineral grains was not used. The line was secured to the bottom by tying or wrapping to bottom protuberances.

For the Belt-quadrat method a 30-m weighted line (Sinko type) was deployed randomly in as straight a line as possible, given the heterogenous bottom characteristics. This line served merely as a guide for the quadrats. Each quadrat was defined by a rectangular metal frame 0.5 m^2 in area, which was braced at each corner by metal bars joined at the top to form a camera mount (Fig. 4). A Nikon F2AS

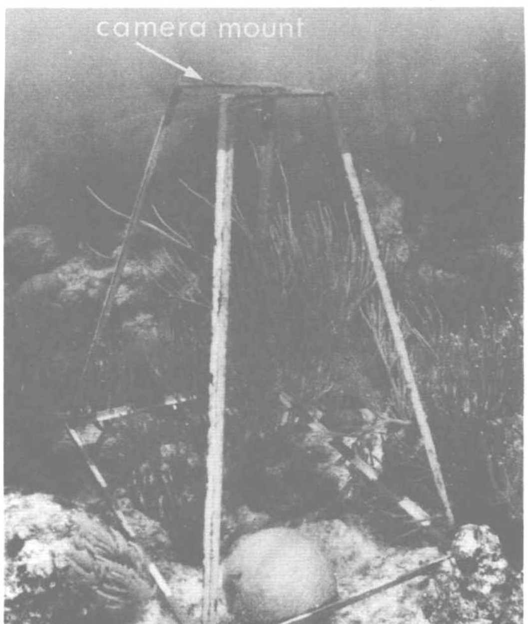

Figure 4. Quadrat frame and camera mount used in Belt quadrat transects in place on sea floor, North Rock.

Table 1. Average data for each method at North Rock

Method	Quarter Point		Intersected Length		Point		Belt Quadrat	
# transects (n)	n = 6		n = 10		n = 5		n = 4	
Relative Coral Coverage by Species (%)	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Diploria strigosa	40.6	18.2	41.2	10.4	34.0	4.6	43.6	9.4
Diploria labyrinthiformis	25.8	17.4	25.8	9.1	31.7	5.9	28.6	11.5
Montastrea annularis	16.6	12.7	11.5	6.0	6.9	4.0	6.0	1.4
Montastrea cavernosa	2.6	4.2	1.0	1.5	3.6	1.5	2.6	1.7
Porites astreoides	9.5	3.6	13.4	7.3	15.4	4.3	15.8	4.0
Isophyllia sinuosa	1.0	1.3	1.0	1.2	1.0	.9	.2	.4
Favia fragum	.5	.4	1.4	1.2	.4	.8	.8	.5
Millepora alcicornis	2.9	5.0	4.6	4.4	6.4	2.9	2.3	.8
Stephanocoenia michelinii	.2	.4	.1	.3	.7	.9		
Siderastrea spp.*	.3	.3					.1	.1
Porites porites								
Madracis decactis								
Oculina ssp.*								
Agaricia fragilis								
Dichnocoenia stokesi								
Madracis mirablis								
Total Coral Coverage (%)	30.7	10.3	22.2	5.5	28.4	2.9	22.2	1.5
Density (# corals/m²)	29.4	5.9					18.0	3.7
# corals meas./transect	40.0	—	29.0	7.3	56.8	5.8	264.0	25.0
# species	8.2	1.2	6.4	1.0	7.2	1.1	8.5	.6
DIVERSITY								
H'_N	1.718	.156	1.607	.132			1.524	.087
H'_C	1.341	.292	1.418	.130	1.552	.068	1.382	.122
H'_N/Hmax	.841	.049	.872	.043			.713	.043
H'_C/Hmax	.640	.123	.767	.060	.792	.051	.647	.037

* Individual species within the genera were not able to be separated in the Belt Quadrat method and are therefore only identified to genera for all methods.

35-mm camera with 24-mm, wide-angle lens, housed in an Ikelite waterproof housing, with side-mounted flash, was pre-focused and mounted atop the frame; a photograph was taken of the area enclosed by the frame, as it was laid successively along the transect line. Ektachrome 200 film was used throughout and had the advantage that it could be processed immediately by the user. It is of interest to note that at a subject-lens distance of 1.2 m, the Nikon 24-mm, wide-angle lens gives a virtually distortion-free high quality image which is eminently suitable for quantitative analysis (Fig. 3).

Results

Tables 1, 2, and 3 present summarized results for each method by site. Included are averages of all transects of a given method for the relative coverage of each coral species (percent), the total coral coverage (percent), density (for Quarter Point and Belt-quadrat methods only), the actual number of coral specimens encountered, the number of species, and the diversity statistics (H'_N, H'_C, H'_N/H'max, H'_C/H'max).

We verified that our sample size (transect length for plotless, belt area for quadrat) was sufficient for each method by plotting the average cumulative number of species encountered versus transect length for each method at each site (Fig. 5). In the majority of cases the plotted lines begin to level off near the end of the specified transect length. The shapes of the lines are comparable to those of Loya (1972). We have not plotted average cumulative diversity indices (H'_C

Table 2. Average data for each method at Three Hill Shoals

Method	Quarter Point		Intersected Length		Point		Belt Quadrat	
# transects (n)	n = 8		n = 8		n = 5		n = 4	
Relative Coral Coverage by Species (%)	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Diploria strigosa	34.3	15.3	16.7	7.3	27.9	7.0	32.2	6.5
Diploria labyrinthiformis	2.8	3.5	5.0	3.5	6.3	2.7	3.1	2.6
Montastrea annularis	26.7	14.4	22.7	10.6	28.6	19.2	29.8	11.7
Montastrea cavernosa	6.2	4.1	5.8	7.2	4.9	2.4	2.7	1.1
Porites astreoides	24.3	15.1	27.8	9.8	14.8	3.1	15.2	2.1
Isophyllia sinuosa	.3	.5						
Favia fragum	.7	.3	6.2	5.2	1.2	1.2	1.4	.1
Millepora alcicornis	1.7	1.8	9.1	9.1	12.6	8.4	14.6	5.8
Stephanocoenia michelinii	1.4	1.5	1.2	2.4			.1	.1
Siderastrea spp.*	.9	1.4	2.1	4.4	.9	1.2	.3	.2
Porites porites	.1	.2	.3	.9			.5	.5
Madracis decactis	.2	.4	1.6	2.3	1.0	1.4	.1	.1
Oculina ssp.*	.5	.9	2.4	2.8	.9	1.3	.5	.1
Agaricia fragilis			.2	.5				
Dichnocoenia stokesi							.02	.03
Madracis mirablis					.9	1.2		
Total Coral Coverage (%)	13.7	3.3	16.1	2.8	23.1	4.5	18.9	3.6
Density (# corals/m²)	18.6	5.5					14.6	1.7
# corals/transect	40.0	—	22.9	4.3	46.6	9.4	225.0	24.9
# species	9.5	.8	7.8	.9	8.2	1.3	10.0	.8
DIVERSITY								
H'_N	1.870	.113	1.840	.165			1.819	.054
H'_C	1.425	.160	1.671	.115	1.707	.106	1.575	.101
H'_N/Hmax	.833	.055	.902	.028			.792	.049
H'_C/Hmax	.634	.064	.820	.057	.817	.050	.686	.056

* See footnote Table 1.

or H'_N) versus transect length; however, it is clear that these would level off even more abruptly because of the logarithm scaling.

For all methods the Belt-quadrat technique indicates the fastest and most abrupt leveling. This is because in area sampling a much larger number of corals is encountered. The three plotless methods appear similar at each site. The Intersected-length method is generally the lowest curve because over the 10-m transect length it tended to sample the least number of corals. The curves for North Rock and South shore are similar. For Three Hill Shoals increased species diversity at approximately equal densities makes for the least amount of curve leveling.

The data in Tables 1, 2, and 3 indicate that at a given site each method provides similar results. It is necessary, however, to statistically test this hypothesis. As representative parameters we chose values for Total Coral Coverage and H'_C and conducted one-way ANOVA tests (Zar, 1974) of methods for these at each site. Results are presented in Table 4 for Total Coral Coverage and in Table 5 for H'_C. For both the South shore and North Rock sites no differences between methods were revealed. For Three Hill Shoals differences were indicated for coral coverage ($.0005 < P < .001$) and for H'_C ($.0025 < P < .005$). To determine specific method differences we performed SNK tests (Zar, 1974) shown in the lower parts

Table 3. Average data for each method at South shore

Method	Quarter Point		Intersected Length		Point		Belt Quadrat	
# transects (n)	n = 6		n = 6		n = 5		n = 4	
Relative Coral Coverage by Species (%)	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Diploria strigosa	49.3	12.0	36.4	12.3	63.5	9.2	53.8	9.8
Diploria labyrinthiformis	14.3	6.6	6.8	7.7	6.5	4.9	2.7	1.3
Montastrea annularis	.8	1.3	.5	1.2	1.8	3.9	.3	1.6
Montastrea cavernosa	1.3	2.6	2.7	4.7	2.4	2.2	2.3	3.0
Porites astreoides	25.7	11.9	38.5	8.4	19.0	6.2	27.0	8.7
Isophyllia sinuosa	1.8	2.6	2.8	2.2			1.7	.6
Favia fragum	1.1	.7	9.0	5.6	5.2	4.4	10.3	3.6
Millepora alcicornis								
Stephanocoenia michelinii	4.2	7.3	2.7	6.5			.2	.3
Siderastrea spp.*	1.6	1.8	.6	1.0	1.7	3.7	1.9	.3
Porites porites								
Madracis decactis								
Oculina ssp.*								
Agaricia fragilis								
Dichnocoenia stokesi								
Madracis mirablis								
Total Coral Coverage (%)	14.8	7.8	13.9	3.0	14.8	7.0	8.0	.7
Density (# corals/m^2)	25.8	7.1					16.4	4.2
# corals/transect	40.0	—	22.2	1.9	25.6	5.8	243.0	55.2
# species	6.8	1.0	5.5	.5	4.6	1.1	7.5	1.0
DIVERSITY								
H'_N	1.548	.089	1.377	.036			1.401	.049
H'_C	1.279	.244	1.299	.137	1.044	.242	1.225	.115
H'_N/Hmax	.812	.043	.807	.056			.700	.049
H'_C/Hmax	.671	.128	.765	.073	.693	.070	.614	.093

* See footnote Table 1.

of Tables 4 and 5). At the $P < .01$ level it is clear that while certain methods differ slightly in their results, overlap is high and no consistent method differences are apparent. We attribute the differences between methods at Three Hill Shoals to the greater spatial heterogeneity we observed and the higher species diversity. It seems probable that with an increased sample size and/or more transects per method, such differences would decrease or vanish.

At each site we also compared the Density values given by the Quarter Point and Belt-quadrat methods using a t-test (Zar, 1974). No differences between methods were apparent at South shore and Three Hill Shoals at $P < .01$. At North Rock no difference was present at $P < .005$.

Because at a given site each method (for coverage, diversity, and density) produces similar results, an estimate of the characteristics of a site is provided by pooling all transect data, regardless of method, into a site average. This is provided in Table 6. To determine if site differences existed, we performed a one-way ANOVA between sites for Total Coral Coverage, H'_C, and Density. These are provided in Table 7. Significant differences between sites were indicated for coverage and H'_C. SNK tests were performed to isolate specific differences with the result that each site is statistically distinct ($P < .01$) for H'_C and coral coverage. Density values are similar at each site.

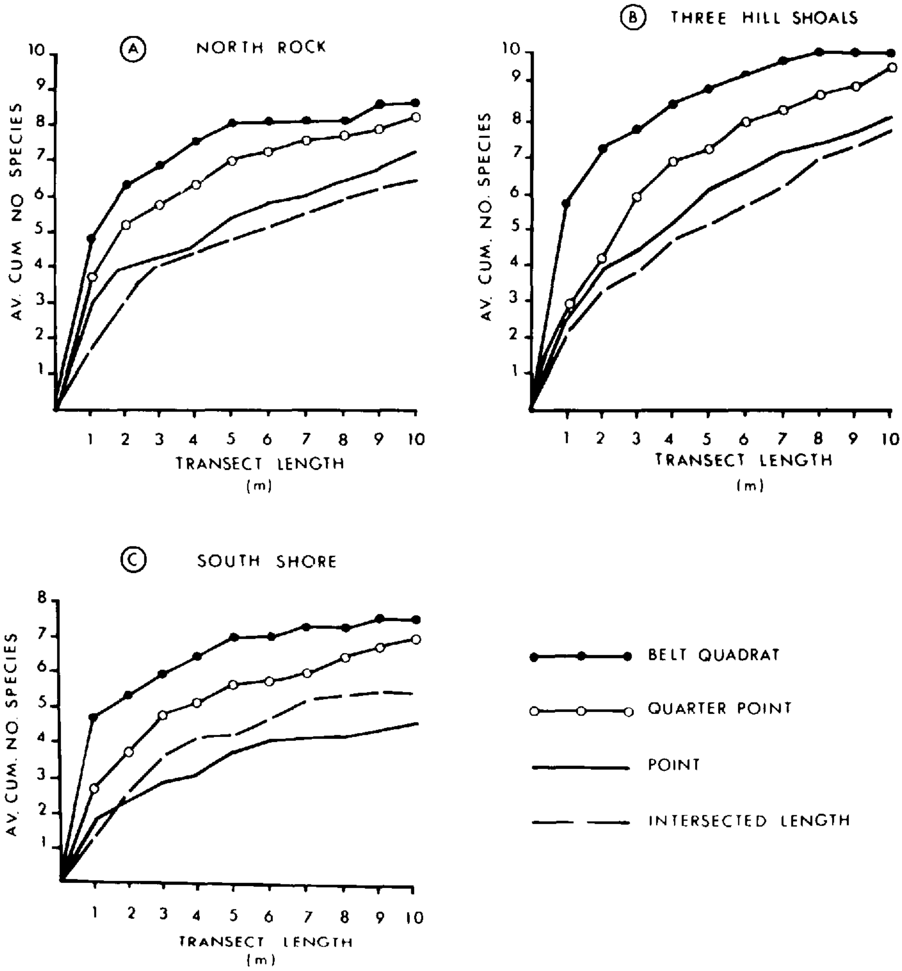

Figure 5. Average cumulative number of species as a function of transect length for all three localities, using all transect methods. Transect interval every meter for Intersected length and Quarter point methods, every 3 m for Belt quadrat method and every 10 m for Point method.

Table 4. ANOVA for methods total coral coverage

	North Rock			South Shore			Three Hill Shoals		
Source of Variation	SS	DF	MS	SS	DF	MS	SS	DF	MS
Total	95,032.28	24		685.88	20		544.27	24	
Groups (methods)	356.73	3	118.9	139.21	3	46.40	293.28	3	97.76
Error	94,675.55	21	4,508.4	546.67	17	32.16	250.99	21	11.95*

SNK test for specific method differences ($P < 0.01$)

Quarter Point	Intersected Length	Belt-Quadrat	Point
$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$

* Significant ($.0005 < P < .001$).

Table 5. ANOVA for methods relative frequency of occurrence H'_C

	North Rock			South Shore			Three Hills Shoals		
Source of variation	SS	DF	MS	SS	DF	MS	SS	DF	MS
Total	.7716	24		.8790	20		.6858	24	
Groups (methods)	.0130	3	.0434	.1833	3	.0611	.3387	3	.1129
Error	.5969	21	.0305	.6957	18	.0387	.3471	21	.0165*

SNK test for specific method differences ($P < 0.01$)

Quarter Point	Belt-Quadrat	Intersected Length	Point
$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$

* Significant ($.0025 < P < .005$).

Method Performance: Comparison and Discussion

It should be clear that the objectives of a particular assessment study will govern, to a large extent, the methodology chosen for conducting that study. We have compared the results of four methods for characterization of coral coverage

Table 6. Average data of all transects of each method for each site

	North Rock		South Shore		Three Hill Shoals	
# transects	n = 25		n = 21		n = 25	
Relative Coral Coverage by Species (%)	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Diploria strigosa	40.0	11.6	49.8	14.5	27.0	12.5
Diploria labyrinthiformis	27.4	11.0	8.1	7.0	4.3	3.4
Montastrea annularis	10.9	8.1	.8	2.0	26.3	11.7
Montastrea cavernosa	2.3	2.9	2.2	3.2	5.3	4.8
Porites astreoides	13.3	5.8	28.0	11.3	22.2	11.2
Isophyllia sinuosa	.9	1.1	1.6	2.0	.1	.3
Favia fragum	.9	1.0	6.1	5.3	2.7	3.8
Millepora alcicornis	3.7	3.6	—	—	8.3	8.1
Stephanocoenia michelinii	.2	.5	2.0	5.2	.8	1.7
Siderastrea spp.*	.08	.2	1.4	2.0	1.2	2.6
Porites porites	—	—	—	—	.2	.6
Madracis decactis	—	—	—	—	.8	1.5
Oculina ssp.*	—	—	—	—	.8	1.5
Agaricia fragilis	—	—	—	—	.5	2.6
Dichnocoenia stokesi	—	—	—	—	.004	.02
Madracis mirabilis	—	—	—	—	.2	.6
Total Coral Coverage (%)	25.5	5.9	13.3	5.2	17.2	3.2
Density (#/m²)	(n = 10)		(n = 10)		(n = 12)	
	24.9	7.7	22.0	7.6	17.3	4.9
DIVERSITY						
	(n = 20)		(n = 16)		(n = 20)	
H'_N	1.624	.145	1.447	.101	1.848	.125
H'_C	1.420	.176	1.219	.212	1.584	.168
	(n = 20)		(n = 16)		(n = 20)	
H'_N/Hmax	.831	.075	.782	.057	.852	.061
H'_C/Hmax	.722	.100	.692	.103	.738	.103

* See footnote Table 1.

Table 7. ANOVA for sites, total coral coverage (all method data pooled), frequency of occurrence (all method data poooled), and density (data of both methods pooled)

	Total Coral Coverage			Frequency of Occurrence (H'_C)			Density		
Source of Variation	SS	DF	MS	SS	DF	MS	SS	DF	MS
Total	4,257.2	70		3.8419	70		1,635.3	31	
Groups (sites)	2,616.4	2	1,308.2	1.5255	2	.7628	326.8	2	163.4
Error	1,640.8	68	24.1*	2.3164	68	.0341*	1,308.5	29	45.1**

* Significant ($P < .0005$).
** Significant ($.025 < P < .05$).

and diversity at three sites on Bermuda reefs. To a first approximation, our results indicate that each method produces similar results. Each method has, however, its own special advantages and disadvantages in terms of quantity and quality of information obtainable, ease of application, and amenability to assessment of reef flora and fauna other than strictly the hermatypic corals. Below we discuss these advantages and disadvantages in more detail.

Intersected-length

The basic Loya (1972) method that we have employed has been proven in nearly a decade of reef assessment work. It is reliable and straightforward to apply underwater, requiring only one working diver. We estimate an average method deployment and recording time of approximately 30 min per 10-m transect on Bermuda reefs. Once ashore, data reduction time is also relatively short.

The method does not provide density values, nor direct estimates of coral sizes. With certain modifications requiring extra measurements (and an increase of underwater work time) such values can be obtained (Cox, 1972 as cited in Loya, 1978). The method is amenable to the inclusion of other reef flora and fauna where the investigator need only record the intersected length of individuals of the desired extra categories.

Quarter Point

For reef assessment work we have found this method to be reliable and straightforward to apply, requiring, as with the Intersected-length method, only one working diver for deployment and measurement. We estimate an average time underwater for the method use to be approximately 35 min per transect making field time nearly equivalent to the Intersected-length technique. Data reduction is somewhat more involved but is generally fast.

Density values are obtained as well as estimates of coral size (approximations of coral tissue area in plan view). It should be noted that because densities are approximations from distance measurements and coral tissue areas, the standard deviations of density values obtained in this way were always greater than by the more precise Belt-quadrat method (Tables 1, 2, and 3). The method is not amenable to the inclusion of other reef plants and animals on a given pass along the transect. However, the same transect line and location can be used a second time for the newly desired category of organisms.

Point

We have found this method reliable and easy to apply underwater. Two working divers made deployment and recording most convenient. An average time underwater for both divers is approximately 40 min. Data reduction time is somewhat faster than the other plotless methods.

An advantage of this method is the greater length of the transect line which surveys a much wider reef area on a given transect. Problems associated with site heterogeneity are, therefore, minimized with an equivalent number of samples (transects) as the other plotless techniques. Transect length, point spacing, and the number of points can all be varied in response to the goals of the study. Galehouse (1971) provides guidelines for these considerations in mineralogical point counting. The method does not provide density values or an indication of coral size. In addition H'_N diversity values are not obtainable because only coverage information is generated.

The method is amenable to the inclusion of other organisms where the quality of any substrate, plant, or animal falling under the given point may be recorded. Perhaps the greatest value of this method lies in its simplicity since it requires only characterization of the substrate at a point with no distance or length measurements.

Belt-quadrat

Our application of the Belt-quadrat method provided the greatest quantity of information with a quality equivalent to that of the plotless techniques over the same reef area. This is because a relatively large reef area is sampled and all corals within that area are measured. Density is obtained and the technique is amenable to the inclusion of other organisms in the analysis. Further advantages lie in the photographic nature of the method which allows a leisurely analysis together with a permanent record of the study area.

Disadvantages are those inherent in any photographic-quadrat technique. Two divers are needed for ease of operation and the quadrat frame with photography gear can be cumbersome, especially in heavy swell. Of necessity photography requires clear, well-lighted water. Even under best conditions we could not distinguish some coral specimens beyond generic level (e.g., *Siderastrea* and *Oculina*). We estimate an underwater time of approximately 40–50 min to complete one transect of 30 m. Data reduction requires development of film and subsequent extraction of pertinent information thus making this technique the lengthiest of all tested. This is a potential problem in that the great amount of information generated requires long analysis time to produce results which are essentially the same as the faster plotless methods. Modifications including less frequent quadrat placement (and photography) per transect (Laxton and Stablum, 1974) could significantly cut analysis (and deployment) time without affecting the amount and quality of information.

Summary of Method Performance

No one method is perfect for complete characterization of a reef community. Choices must be balanced by the quantity and quality of information desired and the time and personnel available for the underwater study. We have found all four of the methods we employed to provide essentially equivalent results for the parameters of Total Coral Coverage, the H'_C diversity statistic, and Density (Quarter Point and Belt-quadrat only). We have not tested relative coral coverage by species between methods because inspection of Tables 1, 2, and 3 indicates similar results for the most abundant corals. For the rarer and/or smaller specimens of other species, more samples are required for adequate confidence in the characterization. This is true for all plotless methods. The Belt-quadrat technique may have performed the best in this regard in the specific bottom area that it covered.

Certain methods contain biases and idiosyncracies which can be avoided or accounted for once they are recognized and understood. For example, use of an unweighted line requires fixing to the bottom by weights or wrapping to bottom protuberances. In both cases "slack" transect lines or lines slightly raised off the bottom can cause difficulty in selecting the specific corals for measurement or characterization and in the actual measurement itself (as with the Intersected-length method). With unweighted line the most common bottom protuberances on some reefs are *Millepora alcicornis* which tends to account for a higher relative percent composition for this species in the Point method. Such biasing can be rectified by using a weighted line; however, this creates a greater manipulation problem underwater and a concomitant increase of field deployment time.

Branching corals or highly overlapping coral growth are not common on Bermuda reefs and therefore we were not faced with this analytical complication. In the more diverse and spatially heterogeneous reefs of other areas special consideration may have to be given to these conditions. In neither the photographic-quadrat nor the plotless methods are techniques for handling the overlap and branching of corals completely satisfactory. The approach of Loya (1972; 1976) is, perhaps, the best so far devised.

If extra field time is available, the value of any of the plotless methods can be enhanced by photographing the transect line after the data have been recorded, thus providing a permanent record of the transect for future reference and study.

The goals and time requirements of any reef assessment study will dictate the best methodology for characterization. Each of the methods presented and discussed here contains inherent advantages and disadvantages which are essentially trade-offs between time available and information desired. For example, both the Belt-quadrat and Quarter-point techniques supply density and coral size data which can be particularly valuable ecological parameters. A particular study, however, may wish to sacrifice this information in favor of a more rapid gathering of data such as coral coverage alone over a broad area (e.g., the Point method).

Loya (1978) recommends that for any reef assessment the investigator initiate a preliminary study of promising techniques. Our results here help define methodological choices available within the goals and time constraints of the investigation.

Although not addressed in this study, it should be noted that all of the above methods need not be used solely for coral reef areas but could also apply to any bottom areas where visible benthic and sessile epibenthic flora or fauna are desired to be assessed. With certain modifications other bottom types (e.g., rocks, sediments, etc.) could also be described quantitatively.

Quantitative Data for Bermuda Reefs: Comparison and Discussion

Comparion of Results Between Sites

It should be remembered that reef characterization at the three designated localities was restricted to the nearly horizontal reef tops at depths of 3–5 m. Species belonging to the genera *Madracis* and *Oculina,* which typically colonize steep and vertical faces at the edge of sand channels and pockets are therefore under-represented in the transect data. The same applies to cavity-dwelling forms, such as *Agaricia fragilis* and sand-channel dwelling species such as *Stephanocoenia michelinii* and *Siderastrea* spp. Bearing in mind these biases, several conclusions can be drawn.

Coral coverage is highest at North Rock, near the margin of the Bermuda Platform, and gradually reduces along our general NW–SE traverse through Three Hill Shoals to the South shore. Highest coral coverage of all, however, may occur on the reef-front terrace seaward of North Rock where, according to Garrett and Scoffin (1977), Bermuda's most flourishing reefs exist. We were not able to sample this biotope.

The dominant species at all three localities, in terms of coverage, is *Diploria strigosa*. *Porites astreoides* is the second most important species in terms of coverage at Three Hill Shoals and South shore. At North Rock it is third ranked in coverage while *Diploria labyrinthiformis* is second. *P. astreoides* shows consistently high quadrat frequency of occurrence values and high density of individual coral colonies and was the most frequently occurring coral at North Rock and Three Hill Shoals.

Two species of *Diploria*, two of *Montastrea*, *Porites astreoides* and the hydrozoan *Millepora alcicornis* account for about 90% of the total stony coral coverage at all three localities.

Anomalies between South shore data and those from North Rock and Three Hill Shoals include the following. *Millepora alcicornis* was not recorded in any growth form in 21 transects on the South shore near-shore platform, yet was relatively common at the other two locations. *M. alcicornis* has been reported in the encrusting form on nearby South shore algal cup reefs, however (Ginsburg and Schroeder, 1973). This particular biotope was not sampled.

Montastrea annularis is uncommon on the South shore, yet common at the other two localities.

Favia fragum is much more common on the South shore than elsewhere. It was found to have the highest density of any coral species on the South shore, yet ranks fourth in coral coverage because of the small size of its colonies. This large number of small *Favia fragum* colonies accounts for the higher overall coral density on the South shore, compared to Three Hill Shoals.

Diversity values (H'_C and H'_N) based on species/coverage and species/colonies respectively, can be correlated with species counts at each locality. Highest diversities occur at Three Hill Shoals, lowest on the South shore. Diversity values (H'_N) are higher at Three Hill Shoals than Castle Harbour (Dryer and Logan, 1978) in spite of the greater number of species (18) recorded from Castle Harbour reefs. This can be accounted for by low coral coverage values and fewer numbers of colonies on the Castle Harbour reefs.

Discussion

A comparison of these conclusions with previously published data from the Bermuda Platform is difficult as there is a general dearth of such quantitative studies.

Ginsburg and Stanley (1970) report higher diversity values of corals (based solely on species counts) at Three Hill Shoals than at North Rock and highest of all in Castle Harbour. They did not sample the South shore nor did they describe their methodology. Their general trend agrees with the results presented here and with those of Dryer and Logan (1978) for Castle Harbour.

Garrett et al. (1971) and Scoffin and Garrett (1974) include semiquantitative data on coral contribution to North Lagoon patch reefs. These reefs are comparable to the Three Hill Shoals patch reef we studied. Garrett et al. (1971) estimate overall coral coverage as 10–45%. Scoffin and Garrett's (1974) estimates of abundance of primary frame-builders is based on mapping and measuring in

Table 8. Comparison of relative percent coral species coverage for lagoonal patch reefs

	Scoffin and Garrett (1974)	This Study*
D. strigosa / *D. labyrinthiformis*	30%	32.1%
M. annularis	20	27.0
M. cavernosa	6	4.9
P. astreoides	10	20.5
M. alcicornis	8	9.5
Others	26	6.0

* Averages of individual method (n = 4) means, Table 2.

the field and from underwater photographs. A comparison of their relative data, based on reef tops, cavities, sand and channel flanks, with ours is shown in Table 8. The results are similar, bearing in mind the wider range of reef environments sampled by Scoffin and Garrett (1974).

The results of this study provide the first truly quantitative data comparing coral abundance and distribution between selected sites on the Bermuda Platform. Clearly more work needs to be done, specifically aimed at characterizing other biotopes and for revealing zonation patterns with depth and/or other factors. Nevertheless, a beginning has been made to which additional data sets may eventually be added.

Acknowledgments

This research was supported by NSF Grant PCM-78-11081 to Dodge and NSF Grant DEB-79-12371 to Antonius, grants from the Max and Victoria Dryfuss Foundation, and the Bermuda Biological Station for Research. Additional support was received from NSERC Operating Grant A 4331 to Logan. We wish to thank the staff of the Bermuda Biological Station for discussions and assistance. This paper is Bermuda Biological Station Contribution #843.

Literature Cited

Antonius, A. 1980. Occurrence and distribution of stony corals in the Gulf of Cariaco, Venezuela. Int. Revue Ges. Hydrobiol. 65: 321–338.

———, and A. Weiner. In Press. Coral reefs under fire. Paper presented at 4th Int. Coral Reef Symp., Manila, The Philippines, May, 1980. Marine Ecology Progress Series.

Cottam, G., J. T. Curtis, and B. W. Hale. 1953. Some sampling characteristics of a population of randomly dispersed individuals. Ecology 34: 741–757.

Cox, G. W. 1972. Laboratory manual of general ecology. W. C. Brown, Dubuque, Iowa. 195 pp.

Dryer, S., and A. Logan. 1978. Holocene reefs and sediments of Castle Harbour, Bermuda. J. Mar. Res. 36: 399–425.

Galehouse, J. S. 1971. Point counting. Pages 385–409 *in* R. E. Carver, ed. Procedures in sedimentary petrology. Wiley Interscience, N.Y.

Garrett, P., and T. Scoffin. 1977. Sedimentation on Bermuda's Atoll rim. Proc. 3rd Int. Coral Reef Symp. 2: 87–95.

———, D. L. Smith, A. O. Wilson, and D. Patriquin. 1971. Physiography, ecology and sediments of two Bermuda patch reefs. J. Geol. 79: 647–668.

Ginsburg, R. N., and J. H. Schroeder. 1973. Growth and submarine fossilization of algal cup reefs, Bermuda. Sedimentology 20: 575–614.

———, and S. M. Stanley. 1970. Reports of research 1969 seminar on organism-sediment interrelationships. Spec. Publ. Bermuda Biol. Sta. 6: 108 pp.

Goldberg, W. M. 1973. The ecology of the coral-octocoral communities off the southeast Florida coast: Geomorphology, species composition and zonation. Bull. Mar. Sci. 23: 465–488.

Goodwin, M. H., M. J. C. Cole, W. E. Stewart, and B. L. Zimmerman. 1976. Species density and associations in Caribbean reef corals. J. Exp. Mar. Biol. Ecol. 24: 19–31.

Laxton, J. H., and W. J. Stablum. 1974. Sample design for quantitative estimation of sedentary organisms of coral reefs. Biol. J. Linn. Soc. 6: 1–18.

Loya, Y. 1972. Community structure and species diversity of hermatypic corals at Eilat, Red Sea. Mar. Biol. 13: 100–123.

———. 1975. Possible effects of water pollution on the community structure of Red Sea corals. Mar. Biol. 29: 177–185.

———. 1976. Effects of water turbidity and sedimentation on the community structure of Puerto Rican corals. Bull. Mar. Sci. 26: 456–466.

———. 1978. Plotless and transect methods. Pages 197–217 *in* D. R. Stoddart and R. E. Johannes, eds. Coral reefs: research methods. UNESCO.

———, and L. B. Slobodkin. 1971. The coral reefs of Eilat (Gulf of Eilat, Red Sea). Symp. Zool. Soc. Lond. 28: Pages 117–139 *in* D. R. Stoddart and C. M. Yonge, eds. Regional variation in Indian Ocean coral reefs. Academic Press, London and New York.

Maragos, J. E. 1974. Coral communities on a seaward reef slope, Fanning Island. Pac. Sci. 28: 257–258.

Meischner, D., and U. Meischner. 1977. Bermuda south shore morphology: a preliminary report. Proc. 3rd Int. Coral Reef Symp. 2: 243–250.

Ott, B. 1975. Quantitative analysis of community pattern and structure on a coral reef bank in Barbados, West Indies. Ph.D. dissertation, McGill Univ. 156 pp.

———, and A. N. Auclair. 1977. Cluster-analytic definition of species ecological groups for a submerged barrier reef in Barbados, West Indies. Int. Revue Ges. Hydrobiol. 62: 41–51.

Pielou, E. C. 1966. Species diversity and pattern-diversity in the study of ecological succession. J. Theor. Biol. 10: 370–383.

———. 1967. A test for random mingling of the phases of a mosaic. Biometrics 23: 657–670.

Porter, J. W. 1972. Ecology and species diversity of coral reefs on opposite sides of the Isthmus of Panama. Pages 89–116 *in* M. L. Jones, ed. The Panama biota—a symposium prior to the sea level canal. Bull. Biol. Soc. Wash. No. 2.

Scoffin, T. P., and R. Garrett. 1974. Processes in the formation and preservation of internal structure in Bermuda patch reefs. Proc. 2nd Int. Coral Reef Symp. 2, Brisbane: 429–448.

Shannon, C. E., and W. Weaver. 1948. The mathematical theory of communication. Univ. of Ill. Press, Urbana. 117 pp.

Stoddart, D. R. 1969. Ecology and morphology of recent coral reefs. Biol. Rev. Camb. Philos. Soc. 44: 433–498.

———. 1972. Field methods in the study of coral reefs. Pages 71–80 *in* Proc. Symp. Corals and Coral Reefs. Mar. Biol. Assoc. India.

Zar, J. H. 1974. Biostatistical analysis. Prentice-Hall, Inc., Englewood Cliffs, N.J. 620 pp.

DATE ACCEPTED: June 9, 1981.

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