

**Habitat Characteristics as determinants of shelf edge fish communities, with emphasis on Scarid populations, off La Parguera, PR**

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## **Abstract**

Shelf edge reefs provide valuable habitat to a wide variety of marine organisms. Yet, because of their depth and highly sloping bottom these areas are not understood with respect to fish habitat relationships and even the way these environments can be characterized and mapped. In order to investigate the relationship between habitat complexity and fish utilization, this study has concentrated on the factors affecting Scaridae abundance at the shelf edge off of La Parguera, Puerto Rico. For remotely sensed data sets as well as *in situ* measurements, rugosity was classified using new techniques, developed for this study, that minimize bias associated with the slope of the substratum. An empirical orthogonal function analysis showed that parrotfish abundance on the shelf was associated primarily with structural variables. The results obtained from this study provide a novel approach to data interpretation that can be used in determining critical habitat to sensitive fish species.

## **Resumen**

Los arrecifes del veril proporcionan un hábitat valioso a una gran variedad de peces y otros organismos. Por la profundidad e inclinación del arrecife, estos arrecifes son entendidos mal con respecto a pez utilización y son difíciles para cuantificar. Para investigar la relación entre la complejidad del hábitat y la utilización del hábitat de peces, este estudio se ha concentrado en el efecto que la rugosidad tiene en la abundancia de los Scaridae en La Parguera, Puerto Rico. La rugosidad y la complejidad del hábitat se han clasificado usando nuevas técnicas que reducen el sesgo en los datos geográficos asociados a la pendiente del substrato al mínimo. Un análisis de función ortogonal empírico demostró que la abundancia de peces loros en el estante estaba asociado sobre todo a variables estructurales en el ambiente del arrecife. Los resultados obtenidos de este estudio proporcionan un acercamiento nuevo a la interpretación de datos que pueden ser utilizados en la determinación de hábitats críticos de especies sensibles de peces.

## **Dedication**

This work is dedicated to my wife Katharine for all her patience and support during this tumultuous process. In addition I would like to thank my grandfather, Dr. Alan Rowe, for always encouraging my scientific curiosity and insisting that I “just write it down”.

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## Preface

The following manuscript has been written in two chapters. Each of the two chapters will be submitted for publication in a scientific journal and has been formatted accordingly.

The study undertaken over the last two and a half years has concentrated on the scarid community at the shelf edge reef ecosystem off of La Paguera, Puerto Rico. While these structurally complex reef systems provide rich habitat for fish communities, the physical factors operating at the shelf edge are thought to facilitate larval survival and/or retention (Johannes 1978; Barlow 1981; Doherty et al. 1985) such that spawning aggregations of many large reef fish species are found at or near shelf edge locations (Heyman and Kjerfve 2008). The preservation of shelf-edge environments via Marine Protected Areas (MPAs) is a proven conservation strategy to increase fish abundances by safeguarding spawning sites (Samoilys 1997; Mumby et al. 2007). Evidence suggests that such strategies have proven efficient in efforts to revitalize endangered fish populations (Beets and Friedlander 1998). Effective delineation of MPAs can be orchestrated via an accurate habitat characterization to predict sites that are ecologically important to targeted fish species (Monaco et al. 2007).

Rugosity can be used as a powerful indicator of fish communities when accurately portrayed in the field (Charton and Ruzafa 1998). This novel approach has been extrapolated with new technologies and used in remote sensing algorithms. While these algorithms can be used in a variety of capacities, the essence of the initial measurement of spatial relief along a depth gradient has been lost. The study undertaken here has invented new methods for accurately measuring rugosity both *in situ* and via remote sensing that minimize bias in high sloping shelf edge environments. The effective scale of each measurement powerfully describes rugosity at two distinct spatial scales.

# **Chapter 1: Innovative Rugosity Measurement Techniques Pertinent to High Sloping Environments**

## **Introduction**

Successful ecosystem-based management strategies can be implemented, in part, by spatial zoning based on quantitative field data. The strong correlation that exists between fish community composition and habitat classification can be used to designate management zones (Tolimieri 1998; Chapman and Krammer 1999; Sluka and Miller 2001; Garpe and Ohman 2003). Substratum preferences and resource utilization by targeted species will dictate habitat types for such a designation (McAfee and Morgan 1996; Van Rooij et al. 1996). A primary challenge for quantifying substratum preferences, particularly through benthic composition and habitat complexity, involves using data that correspond to the appropriate spatial scale relevant to targeted organisms and marine communities of interest (Gust et al. 2001; Arias-Gonzalez 2006; Sabater and Tofaeono 2007). As a first approximation, abundance data of targeted fish species can be used to generalize habitat preferences for those individuals (Mumby and Wabnitz 2002; Espinoza and Salas 2005; Foley and Appeldoorn 2005; Shumway et al. 2007). In this way, predictive maps can be generated to project zones of higher reef fish biodiversity and probable habitat preferences of targeted species (Pittman et al. 2007; Purkis et al. 2008).

As remote sensing techniques continue to improve, the data generated are becoming increasingly more useful. Innovative methods simultaneously characterize the physical structure of a particular locale while allowing for habitat identification, determined by benthic community composition (Riegl and Purkis 2005; Collier and Humber 2007; Purkis et al. 2008; Shcherbina et al. 2008; Wedding and Friedlander 2008). Increasingly, the information gathered from such imaging techniques is being used to produce geographical maps of fish abundances, including probable species composition (Monaco et al. 2005; Mellin et al. 2009). While these new techniques are useful for predictive mapping, slope related limitations may compromise their

capabilities, and spatial scale issues may violate assumptions underlying fish-rugosity relationships (Mellin et al. 2009). *In situ* techniques are invariably more accurate than remote sensing techniques, such as for habitat identification of small areas (Garpe and Ohman 2003), but these methods cannot provide synoptic coverage. Similarly, classical rugosity measurements have proved effective when the characterizations of small reef areas are of interest (Luckhurst and Luckhurst 1978; Rooker et al. 1997; Charton and Ruzafa 1998). Predictive habitat mapping appears to be most effective when based on remote sensing algorithms that are firmly grounded and tested against *in situ* measurements to create a system of checks and balances (Pittman et al. 2007).

Remotely sensed and *in situ* rugosity values have recently been used to predict fish assemblages over broad shelf areas of coral ecosystems (Brock et al. 2004; Kuffner et al. 2007; Wedding et al. 2008). Based on the success of these initial efforts, the use of measurements based on remote sensing data are being extended into different environments (Brock et al. 2006; Shumway et al. 2007). However, the existing algorithms for measuring rugosity are limited in scope and biased due to slope or spatial scale issues. For example, one common algorithm of rugosity, Benthic Terrain Modeler (BTM), uses the ratio of surface area derived from depth values over the area of its projected plane (i.e. equal depth). In this formulation, rugosity is detached from the concept of *in situ* rugosity, where measures are assumed to be taken horizontal to the reef contour. Thus, using BTM, any high sloping environment will yield extremely rugose values. Analyses done over broad areas that encompass many habitat types will find high ‘rugosity’ values to occur where high sloping environments exist (e.g., Kuffner et al. 2007; Wedding et al. 2008). The designations of these ‘highly rugose’ areas are, in fact, typically rugose coral reefs among relatively flat benthos (Dunn and Halpin 2009). As a consequence, the correlation of fish communities with high rugosity areas are in fact being driven by the high correlation, over broad areas, between reefs and slope. Rugosity calculators such as BTM make minimal distinction between highly rugose fore reefs and flat benthos with similar slopes, such as steep back reefs, sloping hard bottom or even large sand waves. A central issue to all existing rugosity algorithms applied to remotely sensed bathymetry remains how to separate slope measurements from true rugosity values.

Shelf edge environments are ecologically important and support a high diversity of marine life (Carpentieri et al. 2006). In coral reef ecosystems, the shelf edge provides essential habitat and spawning grounds for both commercially and ecologically important species (Colin 1992; Beets and Friedlander 1998; Koenig et al. 2000; Brule et al. 2003; Heyman et al. 2005). Unique physical, geological and biological factors create structurally complex habitats in shelf edge environments, which in turn lead to high fish abundance and biodiversity values (Friedlander and Parrish 1998; Garcia-Charton and Perez-Ruzafa 2001; Gratwicke and Speight 2005; Gratwicke and Speight 2005B; Lingo and Szedlmayer 2006; Wilson et al. 2007). The dense fish communities and extreme sloping environment at the shelf edge provide ideal conditions to test the effect of slope on remotely sensed and *in situ* rugosity values and their usefulness in describing shelf edge fish communities.

In this study, the performance of traditional rugosity measures (chain and BTM) are compared at insular slope locations off the southwest coast of Puerto Rico to three new measures (one *in situ*, two from remote sensing bathymetry) designed to remove the slope affect from existing measures. These measures are then used, along with other traditional indicators of benthic composition, to assess their relative roles in quantifying aspects of fish community structure within high slope environments.

## Methods

### *Study Sites*

This study took place along the shelf edge reef in southwestern Puerto Rico. The shelf runs nearly parallel to the coastline between Guanica and La Parguera, although the distance between the coastline and the shelf edge reef varies between two and six miles. Eleven sites were chosen for analysis that maximized rugosity variability along the shelf (Figure 1.1). Within each site, comparisons were made between the reef top location that leads up to the drop off, and the reef slope location itself. Within site, these comparisons did not vary in depth by more than 5m. Among sites, data were collected from 17m to 29m, depending on the topography of the site. All transects conducted ran horizontal, either on the reef top or along the slope.

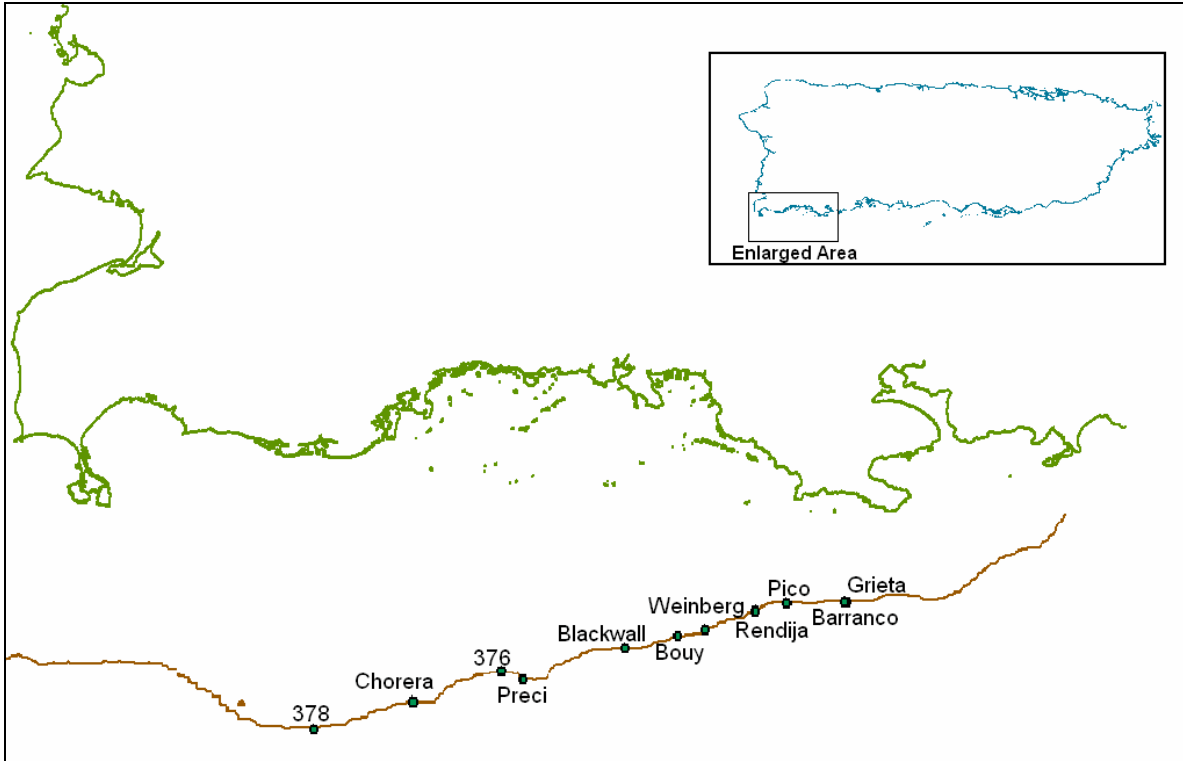


Fig. 1.1. Study sites along the shelf edge of southwest Puerto Rico.

### *Visual Census Transects*

Eight 25 x 4m belt transects (4 reef top, 4 slope) were performed at each site to determine fish community composition. A species richness saturation curve was used to determine the appropriate number of visual census transects. Fish were identified to the species level and total length was estimated into 5-cm size classes. Plankton feeding fishes substantially up in the water column above the transects (e.g., Creole wrasse) were not counted. The data generated from these transects were later used to derive biodiversity values at each site. Diversity was calculated using the Shannon-Wiener index,  $H'$  (Krebs 1999).

### *Benthic Transects*

Point intercept techniques were employed to determine the benthic composition along each transect. Four transects at each site were used as representations of the local benthos. Two transects were run horizontally along the reef top, while the other two ran along a horizontal depth gradient on the reef slope. Points were recorded every 25cm along a 10-m transect line. Hard corals were classified to the species level, algae were



classified to the genus level whenever possible, while all other benthos were classified at the order level. Once data were compiled, statistical analysis concentrated on differences among orders.

### *In situ Rugosity Measurements*

Classical chain rugosity was measured at each site for comparison purposes. A 6-m chain with 1.3-cm links was laid down over the reef, along each benthic transect. The chain was laid out in an attempt to follow the reef face along the transect as much as possible. The actual length of the chain was then divided by the distance between the two endpoints of the chain to determine a 'Chain Rugosity Value'. These values were difficult to obtain in high slope environments due to the effects of gravity. Chain rugosity measurements utilize gravity effectively on flat reef tops to pick up on small crevices. This same property proves detrimental when running a chain along a near vertical wall.

By modifying an existing rugosity calculation technique (McCormick 1994), this study aimed to produce *in situ* rugosity values that were not biased in high sloping environments. The new technique, here termed 'Integral Rugosity', is based on the variance of the perpendicular distances from the benthos to a constant level parallel to the substrate measured along the transect. For sites along the reef top, depths were taken every half meter along a 10-m transect line and the variance was calculated to derive an Integral Rugosity value. To obtain values at sites along the reef slope, two stakes were first nailed into the substrate, at right angles to the slope of the shelf. These stakes were 1m in length and were placed 10m apart along a depth contour. A measuring tape was then tied to the end of each stake, connecting the two points. This tape then served as the constant level parallel to the reef slope by which to measure distances to the benthos. Again, Integral Rugosity was calculated as the variance of the distances, measured every half meter, from the tape to the benthos (Figure 1.2).

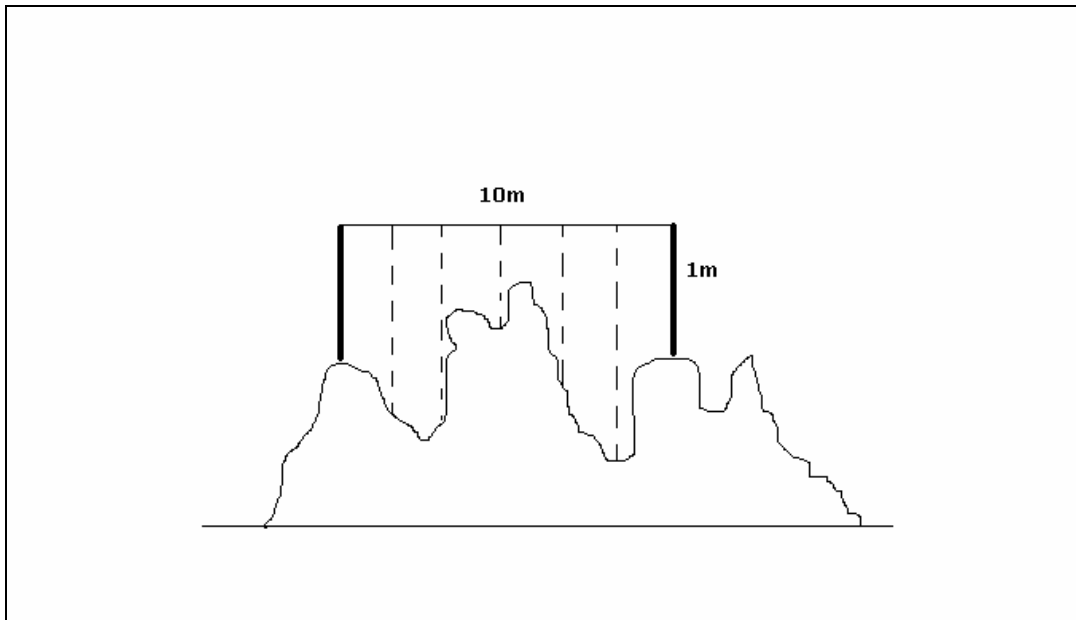


Fig. 1.2. Representation of *in situ* Integral Rugosity measurements. Integral Rugosity is the variance of the distances of all dotted lines (0.5-m intervals) along the transect.

#### *Remote Sensing Rugosity Measurements*

High resolution LiDAR (4-m) and multibeam (3-m) bathymetries were obtained via the National Oceanic and Atmospheric Administration's Seafloor Characterization Program ([http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi\\_nps.html](http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi_nps.html)). Multibeam values typically were not available for areas shallower than 18 meters, while LiDAR values did not exceed 20 meters at most sites. In this study, most remote sensing calculations were made using multibeam data. In a few instances, LiDAR data were used where multibeam data did not exist. Bathymetric data were manipulated using the Spatial Analyst extension of ArcMap 9.2 to calculate slope and aspect values, while derived rugosity values were calculated using neighborhood statistics on a 3x3 grid centered on each benthic transect position as determined by GPS waypoints.

A comparison of the BTM rugosity algorithm to the new remote sensing derived methods was made from data from each site. Once a layer was created in ArcMap 9.2, BTM values were generated at each site based on LiDAR and Multibeam bathymetric data, depending on the depth and location of the transect. Three points were averaged to obtain a reliable estimate of the value at each site centered at the same central position as determined by GPS waypoints.

In an effort to minimize the bias due to slope in calculating derived rugosity, two new algorithms were created. The first was based on depth measurements made perpendicular to the slope, using the aspect angle (compass orientation of the slope) of a central point. This method attempted to retain the original assumption of in-situ rugosity measures, where variability is measured along a depth contour. Measurements were made on three rows of three cells each, starting with the center cell of a 3x3 grid. Neighboring cells to be used depended on corresponding aspect angles. Angles of 0° - 30° used horizontally adjacent cells (either side of the mid-point), angles of 31° - 60° used adjacent diagonal cells and those of 61° - 90° used vertically adjacent cells. A similar process was followed for a row “above” and a row “below” the original center cell. For each row, the average depth of the three cells was calculated, and this was subtracted from the depth of each cell to obtain three values of residual depth. The variance of these nine residuals was used as a measurement of rugosity. This new method was termed ‘Benthic Linear Terrain’ (BLT) rugosity.

The second algorithm, termed ‘Slope Neutral (SN) Rugosity’, was calculated as a ratio of the actual surface area derived from bathymetric data over the plane representing the average slope calculated for the nine points (Figure 1.3). This new value differs from that of BTM rugosity as the denominator is the calculated slope and not the horizontal projection of the slope. Thus, slope neutral rugosity represents variations from the slope and not variations in absolute depth. The average of three points per site was used to represent the site-specific rugosity value.

In a similar manner, rugosity values derived from Benthic Terrain Modeler (BTM) were also calculated for each site. These were used to compare performance to the two new measures derived from remotely-sensed data

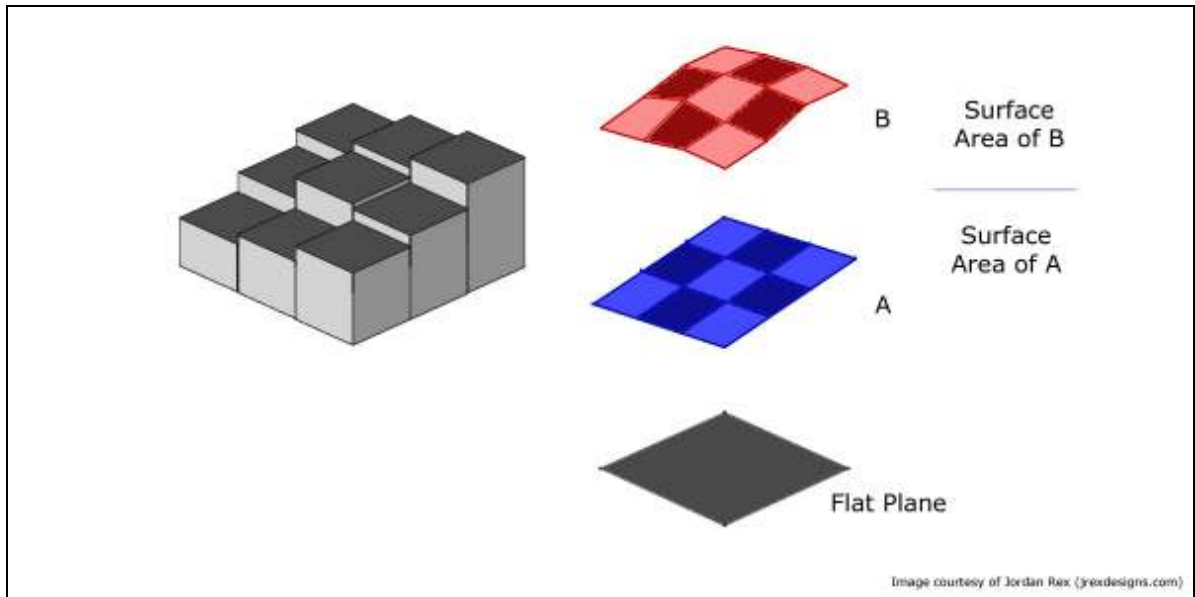


Fig. 1.3. Representation of the calculation of Slope Neutral Rugosity.

### *Statistical Analysis*

Fish community composition was analyzed using a reciprocal averaging ordination (Hill 1973) based on species abundances per reef location to determine representational groupings. Benthic site characteristics (*in situ* and remotely-derived rugosities and percent benthic cover) were used as input variables for an Empirical Orthogonal Function (EOF) analysis, which attempted to rationalize the variability inherent to the input data (Weare and Nasstrom 1982). The EOF was programmed and run using MATLAB version 7.5. Subsequent comparisons and analyses were based on the results of the EOF.

Correlations were generated among all the rugosity calculations and slope measurements at each site. In addition, measurements of reef fish biodiversity were derived using the Shannon-Wiener index ( $H'$ ), and then correlated with rugosity values.

## **Results**

A total of 88 visual census fish transects were conducted between February 24 and December 9, 2008. In addition, 44 benthic transect surveys were performed between February 28 and April 28, 2009. Sampling depth averaged 20m for reef top locations and 24.5m for slope locations. Overall, benthic composition consisted of approximately 67%

algae, 16% hard coral, 9% sponge, 6% soft coral and <1% of both sand and rubble. Site specific data on benthic composition, rugosity values and reef fish biodiversity are given in Table 1.1.

Table 1.1. Depth, slope, benthic composition, rugosity and reef fish biodiversity at each study site along the shelf edge off southwest Puerto Rico. CC = Coral Cover; AC = Algae Cover; Sp = Sponge Cover; SC = Soft Coral Cover; Sand = Sand Cover; Rub = Rubble Cover; H' = Shannon-Wiener index.

Site	Location	Depth (m)	Slope (°)	Benthic Cover										RUGOSITY					Biodiversity	
				CC(%)	AC(%)	Sp(%)	SC(%)	Sand(%)	Rub(%)	Chain	Integral	BTM	BLT	Slope Neutral	H'					
Barranco	Reef Top	17.2	4.12	12.50	72.50	5.00	6.25	1.25	2.50	1.2500	0.0767	1.0100	0.0099	1.0004	2.3621					
Barranco	Slope	21.2	47.31	18.75	52.50	16.25	12.50	0.00	0.00	5.0980	0.0800	1.7367	1.2967	1.0297	2.5931					
Blackwall	Reef Top	19.3	7.22	16.25	61.25	3.75	2.50	13.75	1.25	1.1879	0.0760	1.0167	0.0325	1.0019	2.3969					
Blackwall	Slope	23.9	62.30	21.25	67.50	10.00	1.25	0.00	0.00	2.7329	0.0413	2.3433	0.4999	1.0346	2.3697					
Chorera	Reef Top	20.6	N/A	7.50	77.50	6.25	7.50	1.25	0.00	1.1882	0.0827	N/A	0.0263	1.0013	2.1327					
Chorera	Slope	26.8	41.73	15.00	63.75	15.00	5.00	1.25	0.00	3.0147	0.0399	1.4651	0.1910	N/A	2.4745					
Grieta	Reef Top	18.9	9.90	18.75	68.75	6.25	6.25	0.00	0.00	1.3086	0.0384	1.0333	0.0181	1.0007	2.3725					
Grieta	Slope	23.4	63.33	27.50	57.50	10.00	5.00	0.00	0.00	2.8043	0.0398	2.2667	0.0874	1.0166	2.3061					
La Boya	Reef Top	18.7	6.71	15.00	75.00	5.00	2.50	2.50	0.00	1.5192	0.0654	1.0300	0.0945	1.0007	2.4184					
La Boya	Slope	22.4	41.18	21.25	53.75	11.25	13.75	0.00	0.00	1.9677	0.0622	1.3633	0.0562	1.0036	2.6355					
Pico	Reef Top	18.5	11.34	7.50	76.25	10.00	5.00	1.25	0.00	1.2250	0.0543	1.0267	0.0276	1.0013	2.3891					
Pico	Slope	21.8	31.71	20.00	41.25	13.75	25.00	0.00	0.00	4.2647	0.0602	1.2233	0.0395	1.0011	2.4660					
Point 376	Reef Top	20.0	N/A	2.50	92.50	3.75	1.25	0.00	0.00	1.1207	0.0146	N/A	0.0021	1.0001	2.4542					
Point 376	Slope	25.9	45.16	3.75	88.75	3.75	3.75	0.00	0.00	1.8011	0.0253	1.4651	0.2673	N/A	2.5283					
Point 378	Reef Top	23.1	N/A	7.50	82.50	3.75	6.25	0.00	0.00	1.0436	0.0252	N/A	0.0128	1.0009	2.0799					
Point 378	Slope	28.1	18.47	12.50	63.75	10.00	13.75	0.00	0.00	1.5144	0.0355	1.0500	0.0071	1.0006	1.8031					
Precipicio	Reef Top	21.4	5.51	7.50	78.75	12.50	0.00	1.25	0.00	1.1010	0.0556	1.0100	0.0058	1.0001	2.2416					
Precipicio	Slope	26.3	38.59	12.50	72.50	12.50	2.50	0.00	0.00	2.0486	0.0699	1.3233	0.0594	1.0044	2.6731					
Rendija	Reef Top	21.0	15.24	25.00	60.00	13.75	1.25	0.00	0.00	1.3340	0.1666	1.1033	0.3124	1.0022	2.5541					
Rendija	Slope	23.5	32.23	28.75	50.00	13.75	7.50	0.00	0.00	1.3188	0.0566	1.5367	0.7173	1.0019	2.7669					
Weinberg	Reef Top	21.6	8.56	27.50	65.00	7.50	0.00	0.00	0.00	1.3795	0.0399	1.0367	0.0041	1.0008	2.3653					
Weinberg	Slope	25.9	21.82	20.00	62.50	13.75	3.75	0.00	0.00	1.3883	0.0371	1.0933	0.0216	1.0006	2.6011					

Coral cover among sites varied from 26.875% at Rendija to 3.125% at Point 376. Eastern sites were characterized by higher coral cover than western sites (Figure 1.4).

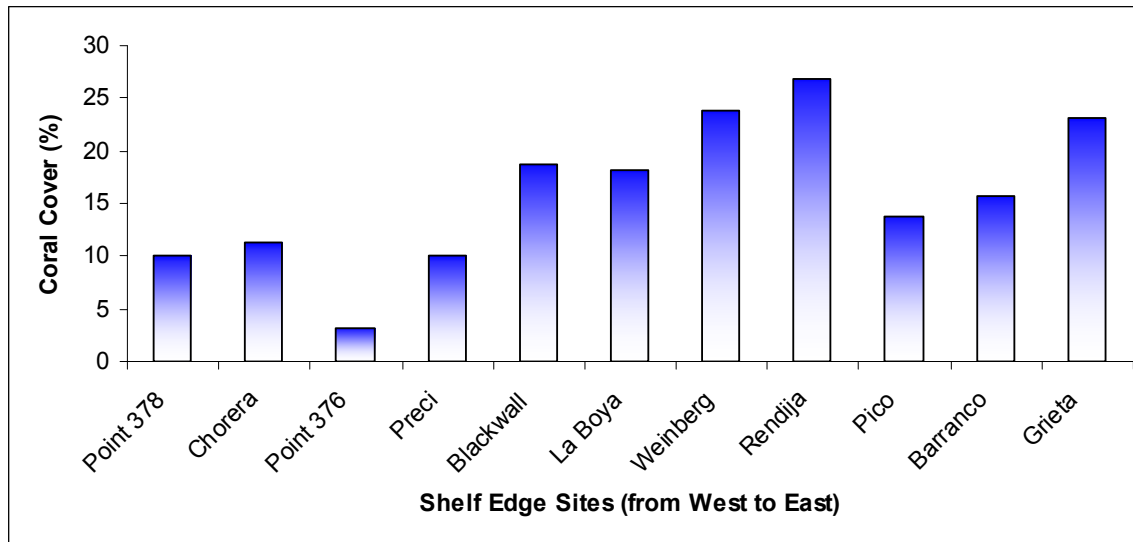


Fig. 1.4. Percent Coral Cover at each study site along the shelf edge.

### *Fish Assemblages*

Fish community structure differed within sites, with a basic division by reef location (slope vs. reef top). A reciprocal averaging ordination clearly distinguished communities along the slope from those along the reef top (Figure 1.5). The division within sites was clearest along 'axis 1' in the ordination.

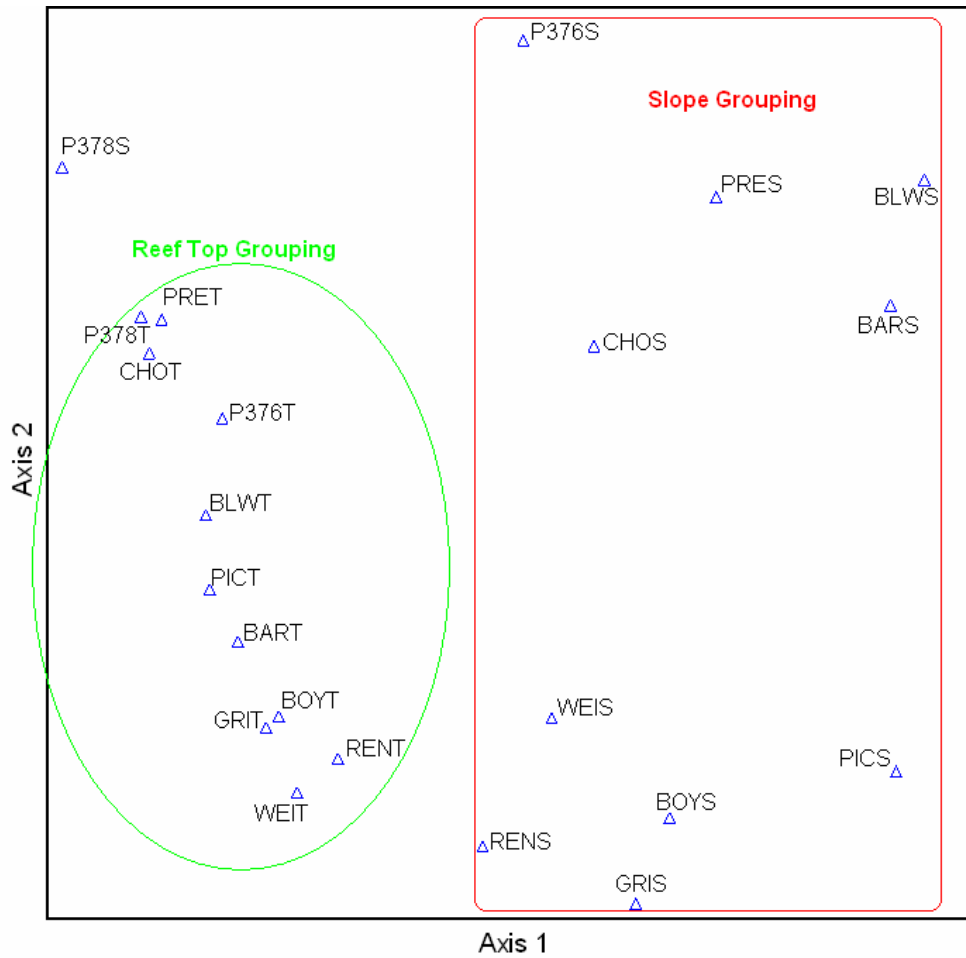


Fig. 1.5. Reciprocal averaging ordination of fish communities at reef top and slope locations along 11 shelf edge sites off southwest Puerto Rico. BAR = Barranco; BLA = Blackwall; CHO = Chorera; GRI = Grieta; BOY = La Boya; PIC = Pico; P376 = Point 376; P378 = Point 378; PRE = Precipicio; REN = Rendija; WEI = Weinberg. Reef top locations are marked with a 'T' at the end of the site name, while slope locations are marked with an 'S'.

### *Study Site Quantification*

The Empirical Orthogonal Function (EOF) analysis produced eight relevant modes, of which the first three account for 79% of the variability (Figure 1.6).



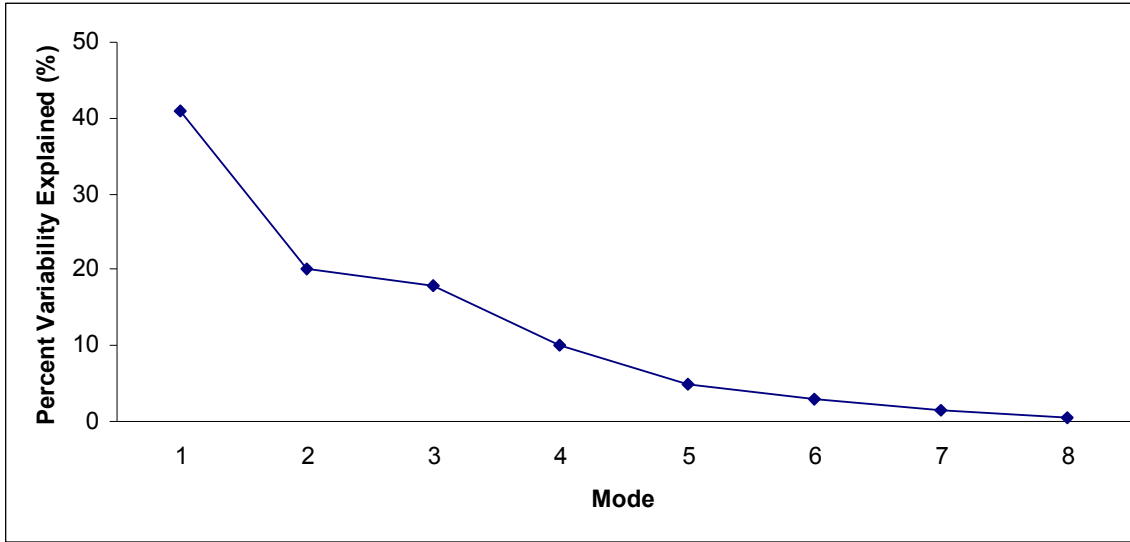


Fig. 1.6. Percent variability explained by each mode of the EOF analysis. Values of higher modes drop below 1%.

The first mode of the EOF analysis explained 41% of the variability in the data and highlighted positive relationships with the structural components of each site (Figure 1.7). All of the different measurements of rugosity values are positively and strongly correlated to the mode. Additionally, percent coral cover has the highest positive correlation, while percent algal cover is equally negatively correlated.

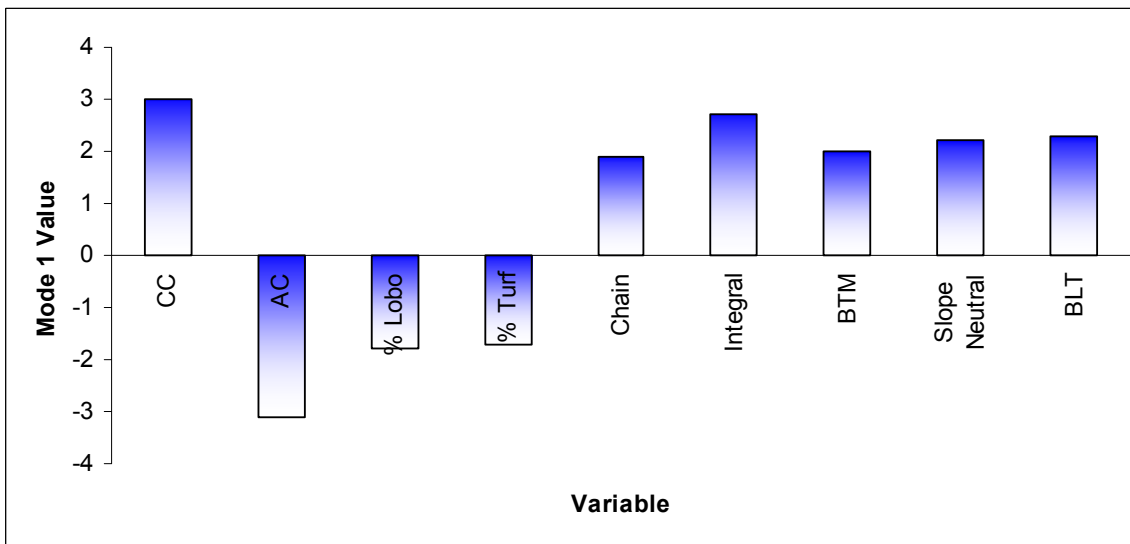


Fig. 1.7. Values for the first mode of the EOF analysis. Variables with positive values are positively correlated to the mode. CC = coral cover; AC = algae cover; % Lobo = percent *Lobophora* algae cover; % turf = percent turf algae cover; Chain = chain rugosity; Integral = integral rugosity; BTM = Benthic Terrain Modeler rugosity; Slope Neutral = slope neutral rugosity; BLT = Benthic Linear Terrain Rugosity.

The second and third modes described 20% and 18% of the variability in the benthic data, respectively. The second mode emphasized the differences between algal communities as well as an inverse relationship in small scale rugosity measurements (Figure 1.8). *Lobophora* was the most common macro algae in the shelf edge environment of La Parguera, and the second mode showed a clear inverse relationship between the two algal types. Similarly, this mode showed a disparity between the two types of small scale rugosity. The second mode has picked up on the differences inherent between the two measurement techniques. The third mode was driven by slope related rugosity measurements and algal cover (Figure 1.8). This mode also demonstrated a negative association to coral cover and integral rugosity measurements.

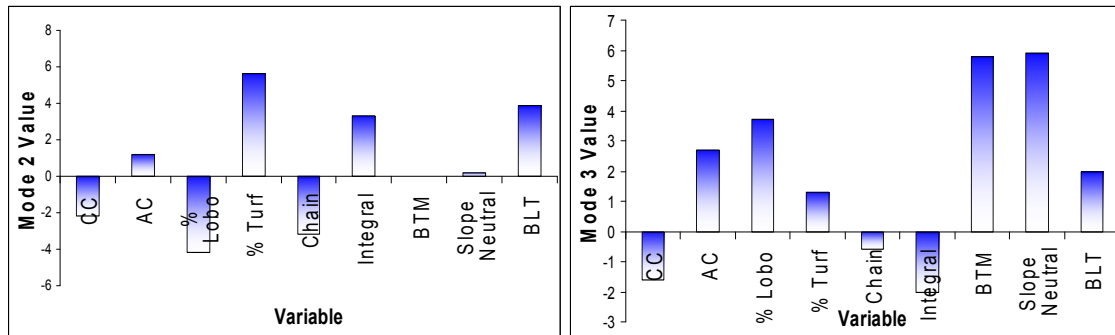


Fig. 1.8. Values for the second (left) and third (right) modes of the EOF analysis.

### *Small Scale Rugosity*

Given the inverse response of the two small scale rugosity measures in the second EOF mode, (and given unequal variances and non-normality of the Chain rugosity data) a pair-wise Mann-Whitney rank sum test (Sokal and Rohlf 1995) was used to test for differences between classical Chain and Integral rugosity by location within site. Integral rugosity values within sites had no significant differences between medians ( $P = 0.555$ ) of the reef top and slope, while those for chain rugosity differed substantially ( $P < 0.001$ ).

### *Large Scale Rugosity*

Rugosity values from Benthic Terrain Modeler were found to correlate almost directly, although nonlinearly, with slope values at each site (Figure 1.9). The best fit ( $r^2 = .90$ ) was obtained by an exponential function of the rugosity value. The positive correlation exhibited between BTM and slope was evident even in low slope environments (i.e. Reef tops) where the slopes did not exceed  $15^\circ$ .

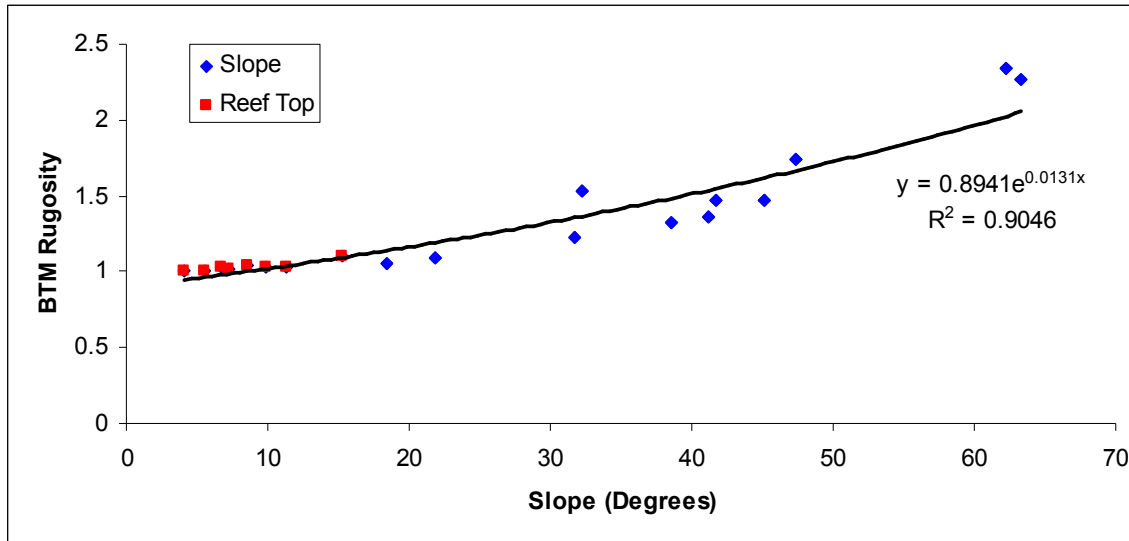


Fig. 1.9. Benthic Terrain Modeler rugosity values plotted against the slope at each study site location. Points at reef top locations are differentiated from those at slope locations.

The Benthic Linear Terrain rugosity measurements did not correlate to slope ( $r^2 = 0.21$ ) however its variance increased dramatically with slope (Figure 1.10).

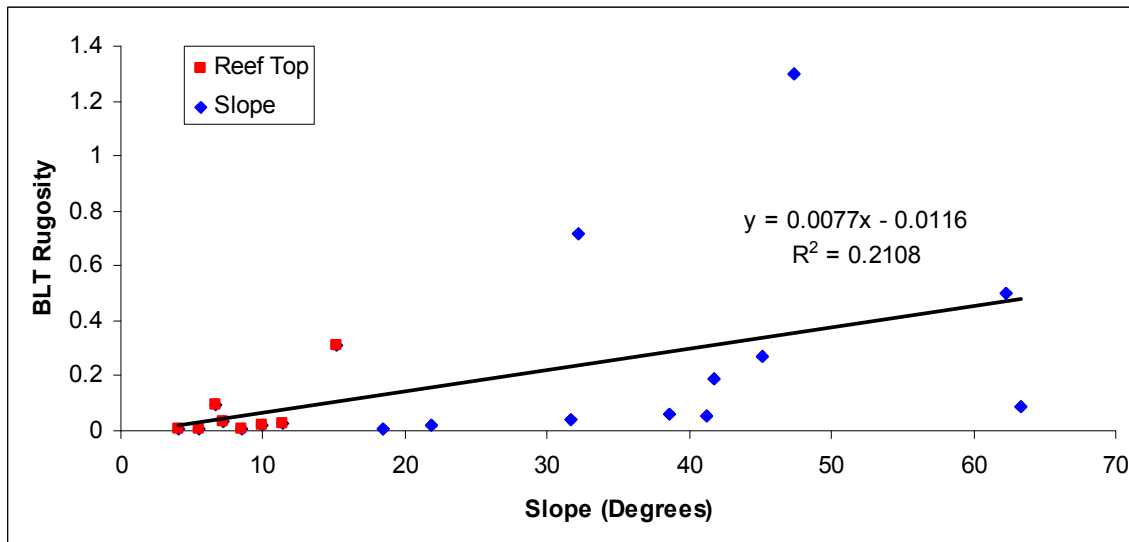


Fig. 1.10. BLT rugosity values at each study site plotted against slope and separated by reef location.

Slope neutral rugosity had a distinct nonlinear relation to slope (Figure 1.11). Values remained fairly flat over a broad range of slopes, indicating an apparent independence between SN rugosity and bathymetric slope. However, SN rugosity begins to become severely effected by slope in locations with inclinations greater than  $45^\circ$  and becomes

severely exaggerated at greater slope values. At sites with inclinations less than 35°, there is no significant correlation between SN rugosity and slope (Figure 1.12).

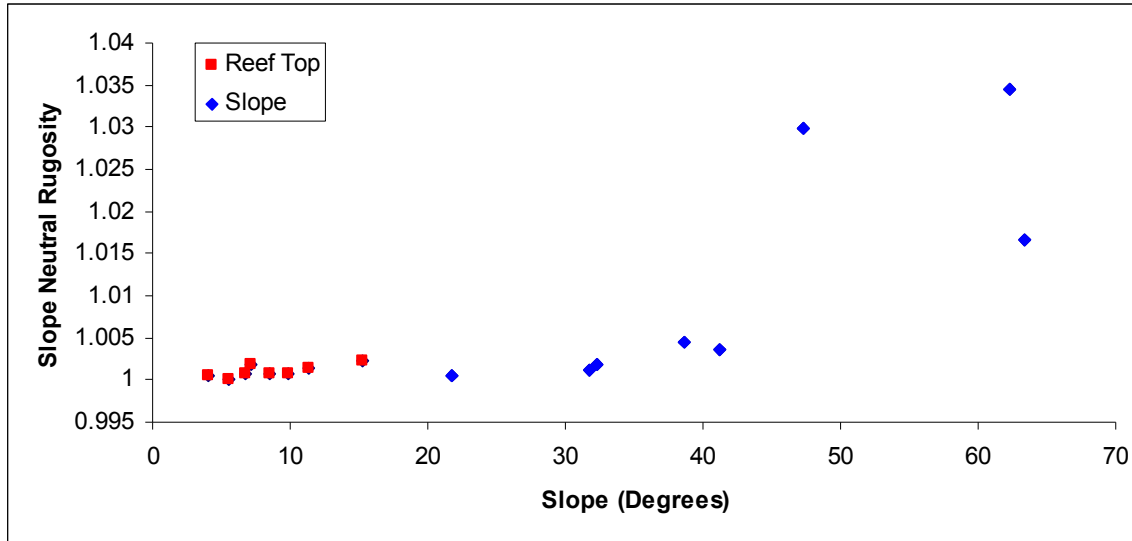


Fig. 1.11. Slope neutral rugosity values plotted against the slope at each study site location.

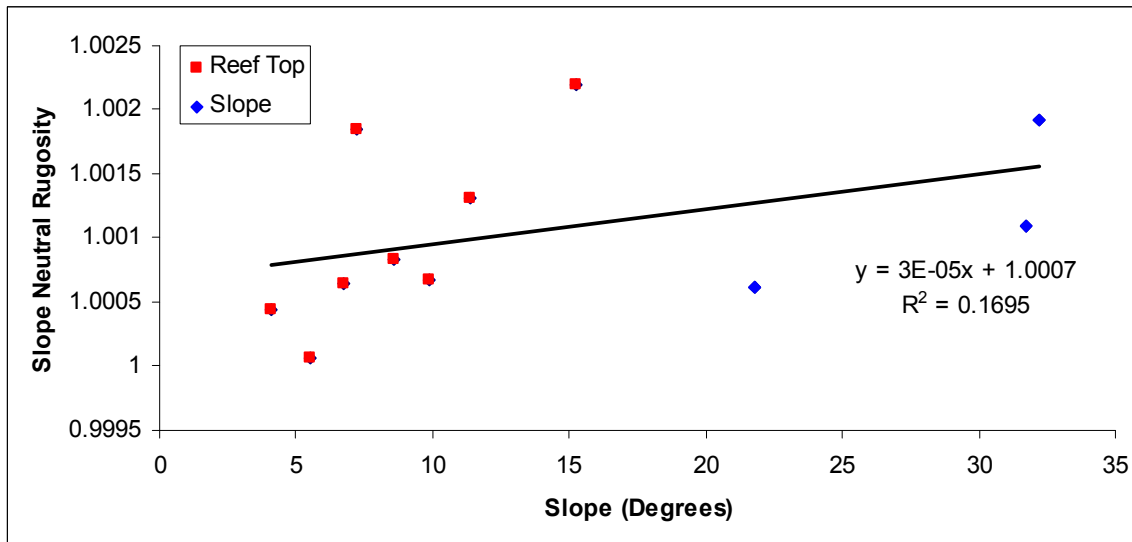


Fig. 1.12. Slope neutral rugosity values at sites with a slope of less than 35°. Reef locations within sites are differentiated.

### Rugosity Measurements

Table 2 presents the matrix of correlations between each rugosity method, as well as their respective correlations with slope. The coefficients of correlation show one consistent trend. The BTM rugosity shows a very high correlation to slope, where other

methods do not. Integral rugosity, SN rugosity (up to 35°) had no correlation to slope, making them the best *in situ* and remote sensing derived measures, respectively.

Table 1.2. Matrix of coefficient of correlation (r) values for each rugosity method and for slope. Correlations with  $p \leq 0.05$  are denoted with one asterisk (\*), while those with  $p \leq 0.01$  are denoted with two asterisks (\*\*).

	Slope (°)	Chain	Integral	BTM	BLT	SN
Slope (°)	1	-	-	-	-	-
Chain	0.64**	1	-	-	-	-
Integral	0.24	0.04	1	-	-	-
BTM	0.92**	0.55**	0.2	1	-	-
BLT	0.45*	0.6**	0.23	0.5*	1	-
SN <35°	0.41	0.02	0.61*	0.49	0.64*	1

### Reef Fish Biodiversity and Rugosity

The Shannon-Wiener ( $H'$ ) index, used to quantify reef fish biodiversity, was compared to values of integral rugosity. Results suggest a positive correlation between reef fish biodiversity and small scale rugosity,  $P = 0.09$ . Integral rugosity was used as a more reliable method for the slope environment, based on results obtained from the rank sum test and those presented in Table 1.2 (Figure 1.13).

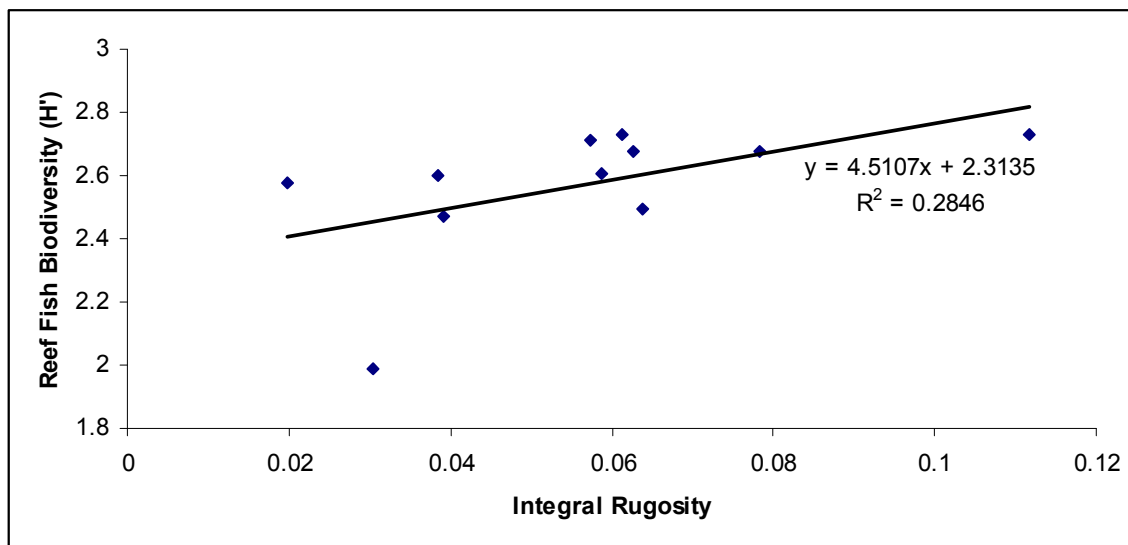


Fig. 1.13. Reef fish biodiversity as a function of Integral rugosity at shelf edge sites off southwest Puerto Rico.

Correlations between all other rugosity measurements (SN, BLT, BTM and Chain) and reef fish biodiversity were not significant.

## Discussion

Unique fish assemblages were observed over the course of this study between distinct reef locations within shelf edge sites. Fish communities at similar depths, geographical sites, and exposure to physical factors varied depending solely on their location within the shelf break environment, suggesting that these differences are largely due to individual species preferences for habitat on the reef top or on the slope. The slope location of point 378 was the one notable exception in the correspondence analysis. This location was on a gentle slope and was situated at the maximum allowable depth of recreational diving. The fish community observed at this site aligns with those communities of other reef top locations because this slope site was in fact an extension of the reef top.

The dominant mode of the EOF analysis suggested structure as a primary indicator for the characteristics at each study site. Later modes highlighted differences resulting from small scale rugosity sampling techniques and the dominance of turf versus *Lobophora* algae. The implications of the latter are of interest when describing herbivore fish communities that may be influencing the development of algal communities. The third mode highlighted the associations with coral cover and integral rugosity values. Identification and measurement of the pertinent features (structure, habitat type, and their spatial scales) that may underlie fish preferences and resulting distributions are thus of considerable importance to modeling fish community structure in shelf-edge environments.

The small scale, *in situ*, rugosity techniques utilized in this study conveyed significantly different results in high sloping environments. The classical chain method proved highly variable and unreliable in areas such as decidedly steep sloping fore reefs as evidenced by the Mann-Whitney rank sum test. Due to the nature of the measurement technique, this result was expected in high sloping environments. The effects of gravity that work to validate the chain technique on flat surfaces, work against this same technique in areas of extreme inclinations. The chain will simply fall off the substrate in these habitats. The new *in situ* method, Integral Rugosity, avoids this source of variability and can be used as an accurate indicator of topographical variability in high

sloping environments as well as flat reef tops, as supported by its correlation to slope being the lowest observed.

The positive correlation between integral rugosity measurements and  $H'$  suggests that integral rugosity may be used to predict reef fish biodiversity within a 90% confidence interval. A P-value  $< 0.10$  was accepted for this study because of the difficulty associated with extrapolating nuanced effects of rugosity in a highly rugose, low variability environment. A correlation coefficient of  $r = 0.53$  suggests that integral rugosity values explain over 28% of the variability in the fish community data. The seemingly low  $r^2$  is indicative of the predictive capabilities of rugosity measurements within a single habitat type. A previous study of reef fish communities within a single habitat type (coral reefs located at 10-m depth) along the Southwest Puerto Rican shelf (Bejarano 2006) reported a similar  $r^2$  value (0.239) between chain rugosity and fish biodiversity ( $H'$ ). As observed with chain rugosity, use of Integral rugosity across a broad range of habitat types and geomorphologies would be expected to lead to much higher correlation coefficients.

The remote sensing algorithms used to measure rugosity in this study are limited by current technologies and by geometrical properties of sloping planes. The Benthic Terrain Modeler rugosity, as currently used, is almost entirely dependent on slope with a correlation coefficient between the two of  $r = 0.92$ . This occurs because any change in depth has equal weight in the algorithm, and unless slope is minimal the variability in depth due to slope will outweigh the effect of rugosity (in the classic *in-situ* sense). Two theoretical corrections exist for the BTM algorithm. In the first, residual values can be estimated from a regression between slope and BTM. These residual values would be able to approximate rugosity from an average plane of slope, and would thus work in an area of uni-directional inclines. The second is to use the Slope Neutral method developed here.

The Slope Neutral rugosity method proves relatively useful for values of slopes less than  $35^\circ$ , as there was no significant correlation with slope (indeed, the correlation coefficient between the two was the lowest among methods based on remote sensing data). However, the usefulness of SN rugosity breaks down in areas of extreme slope. The cut-off seems to occur when the vertical variability of the sloping surface becomes

greater than the variability of the same surface in the horizontal direction. Tangent values on an angle, or slope, will approach infinity at 90° (Figure 1.14). As slope increases to high values, the horizontal variability on such surfaces eventually will become negligible.

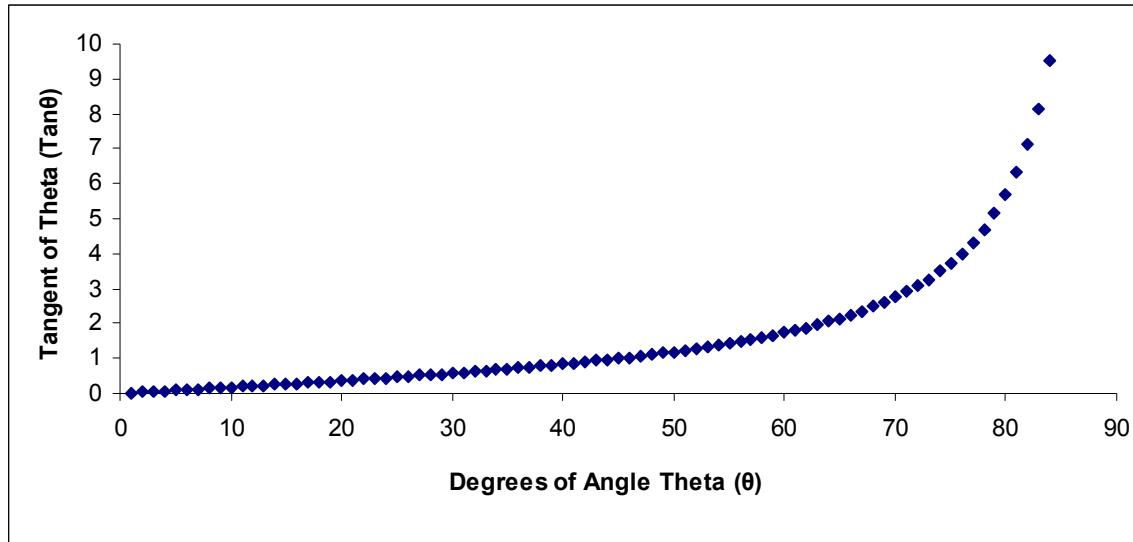


Fig. 1.14. Tangent values from 0° to 90° for slope angle.

Benthic Linear Terrain rugosity measurements had a much weaker correlation with slope than BTM rugosity, but it picked up large scale variations in areas of increasing slope. The BLT measurements accurately depicted the natural variability in the environment, but it is unclear if this variability is on a scale that is important for fish communities.

The objectives of this study aimed to describe structural variability on a scale that is relevant to shelf edge fish communities. The results suggest that reef fish biodiversity can be predicted via small scale rugosity values, as evidenced by the correlation between reef fish biodiversity and integral rugosity measurements. Higher integral rugosity values will lead to higher reef fish biodiversity within the shelf edge environment. The biodiversity values represented here are not indicative of all species. Individual investigations need to be conducted in order to decipher patterns for distinctive families or species.



## **Conclusions**

Differences in the fish communities observed between slope and reef top locations are representative of a disparity between the two positions. Considering several reef top locations at certain sites were deeper than slope locations at other sites, depth does not seem to be the driving physical factor within the range of depths studied. Visual surveys never differed by more than 5m within sites.

The shelf edge environment provided challenges for accurate rugosity value derivation on a 3x3 pixel grid. Due to the extremely steep nature of the sites in question, the slope or vertical variability dominated the algorithm being used. The BLT rugosity and the slope neutral rugosity methods presented here remain viable options for future projects. Higher resolution bathymetric images in less variable environments can effectively predict field rugosity conditions via the BLT and SN rugosity methods. As the technology for remote sensing continues to improve, the BLT and slope neutral method will become more useful for future investigation.

# **Chapter 2: Reef Structure as a Determinant of Scarid Species Composition on Shelf Edge Reefs in La Parguera, Puerto Rico**

## **Introduction**

The family Scaridae is comprised of many ecologically important species that help to graze Caribbean reefs and contribute to coral health by limiting algal growth (Mumby 2006). Herbivores such as scarids have come to numerically dominate historic fishing areas as fishes from higher trophic levels have been removed (Sabater and Tofaeono 2007). The presence of such herbivores is crucial to coral reef survival as calculations suggest that the removal of scarids on healthy coral reefs would lead to complete algal dominance in less than forty years (Mumby 2006). Of the fourteen scarid species present in the Caribbean, several are sympatric species, and abundances are often driven by the presence or absence of congeners (Bruggeman et al. 1996; McAfee and Morgan 1996; Mumby and Wabnitz 2002). Sympatric parrotfishes with different foraging habits work to limit algal growth in all reef zones and reef types by feeding in different manners to utilize all available algal food sources (Bruggeman et al. 1994; Van Rooij et al 1996). Thus, healthy scarid populations are beneficial to coral communities by facilitating coral colonization (Fox and Bellwood 2007; Mumby et al. 2007).

Parrotfish abundance is habitat dependent, and species composition directly correlates with habitat types or locations (Tolimieri 1998; Sluka and Miller 2001; Mellin et al. 2007). The three most common scarid species on the shelf reef system of La Parguera, Puerto Rico are *Scarus iseri*, *Sparisoma viride* and *Sparisoma aurofrenatum*, with *S. iseri* being numerically dominant. Within this ecosystem, the abundances of these three species all correlate positively with rugosity and negatively with water depth along the fore reef environments across the insular platform (Nemeth and Appeldoorn 2010).

Shelf edge reefs, as a subset of larger coral reef ecosystems, represent a physically dynamic and unique habitat (Shcherbina et al. 2008). The productivity associated with shelf edge reefs leads to high biodiversity, abundance and biomass of fish communities (Carpentieri et al. 2006).

Larger fish assemblages are typically associated with shelf edge reefs due to increased structural and topographical complexity (Friedlander and Parrish 1998). Several approaches have been taken to show that benthic complexity may play a more important role than habitat type or benthic composition. Friedlander and Parrish (1998) suggested that fish abundance and distribution are ultimately determined by hole sizes found in the substratum. More typically, benthic complexity is measured by rugosity, the ratio of actual distance over topographical distance, and this has been found to positively correlate with fish abundance and biodiversity (Garcia-Charton and Perez-Ruzafa 1998; Garcia-Charton and Perez-Ruzafa 2001; Collier and Humber 2007; Shumway et al. 2007). The use of rugosity as an indicator of fish community structure has been tested and found to hold merit on both natural and artificial reefs, except at extreme rugosity values (Rooker et al. 1997; Lan et al. 2004; Lingo and Szedlmayer 2006). The power of rugosity to predict fish biodiversity is strengthened when used in combination with habitat type (Chapman and Krammer 1999; Espinoza and Salas 2005; Gratwicke and Speight 2005; Arias-Gonzalez 2006).

Additionally, intra-familial species distributions, abundances and body sizes are also affected by reef location and can be clearly observed within parrotfishes (Gust et al. 2001; Foley and Appeldoorn 2005). Site-specific differences in size distributions frequently result from ontogenetic migrations, where shelf edge environments often represent ultimate destinations for many species, including some scarids (Cervený 2006). Fish assemblages are ultimately determined by a combination of factors, of which shelf location is invariably important, either directly or in correlation with other factors (McGehee 1994; Kendall et al. 2004). Thus, the task of modeling aspects of reef fish community structure will depend on our ability to measure the various aspects of benthic composition, habitat type, location, etc. on scales relative to the fish themselves. For synoptic coverage, as required for MPA design or larger marine spatial planning, the use of measures derived from remote sensing data will become critical. Within single reef zones, evidence suggests that habitat type dictates fish assemblages. In this way, distributions and abundances of individual species can be predicted via habitat mapping (Ohman et al. 1997; Garpe and Ohman 2003).

As remote sensing techniques continue to improve, useful physical descriptors have been derived, including bathymetry derived slope and rugosity values (Mellin et al. 2008,

Wedding et al. 2008). These derived rugosity values have proven to be efficient indicators of fish assemblages in shallow, flat reef systems (Kuffner et al. 2007; Wedding and Friedlander 2008). Due to the bias inherent to these algorithms in high sloping environments (Chapter 1), only slope values and newly developed rugosity measurements were used for analysis in this study.

The present study aimed to utilize habitat and structural reef characteristic data to determine scarid relationships to their environment. Characterizations were broken down to the species level. Primary factors including coral cover, algae cover and rugosity were considered.

## **Methods**

### *Study Sites*

This study took place along the shelf edge reef in Southwestern Puerto Rico. The shelf runs nearly parallel to the coastline between Guanica and La Parguera, although the distance between the coastline and the shelf edge reef varies between two and six miles. Eleven sites were chosen for analysis that maximized perceived rugosity and habitat variability along the shelf (Figure 2.1). Within each site, comparisons were made between the reef top area that leads up to the drop off associated with shelf edge reefs, and the reef slope itself. The in-site comparisons did not vary in depth by more than 5m at any of the study sites. Among sites, data were collected from 17m to 29m, depending on the topography of the site. All transects were conducted along a broad depth contour, either on the reef top or along the slope.

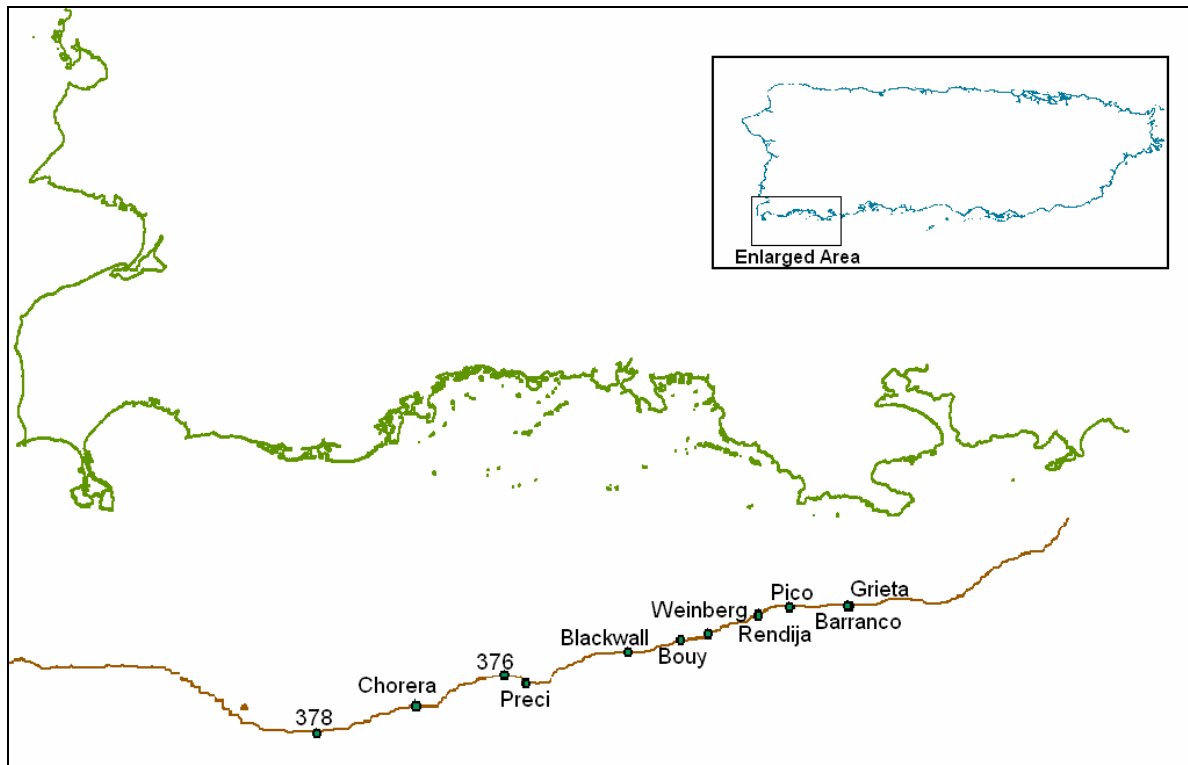


Fig. 2.1. Study sites situated along the shelf break of southwestern Puerto Rico.

#### *Visual Census Transects*

The four most common parrotfishes to Puerto Rican shelf edge reefs were counted for this study, two from each genus: *Scarus taeniopterus*, *Scarus iseri*, *Sparisoma viride* and *Sparisoma aurofrenatum*. Eight 25 x 4-m belt transects were performed at each site (4 reef top, 4 slope) to determine parrotfish community composition (Brock 1954). Fish were identified at the species level and total length estimated to the nearest 1 cm (Colvocoresses and Acosta 2007). Sampling occurred from February 24 through December 9, 2008.

#### *Benthic Transects*

Point intercept transects were employed to determine the benthic composition along each transect (Watson and Quinn 1997). Two transects were run horizontally along the reef top while the other two ran along the reef slope. Points were recorded every 25cm along a 10-m transect line. Hard corals were classified to the species level, algae was classified to the genus level whenever possible, while all other benthos was classified at the order level. Statistical analysis concentrated on differences among orders.

### *In situ Rugosity Measurements*

Integral Rugosity measurements were taken in the field as this method was formed to be advantageous over classical chain rugosity measurements (Chapter 1). Integral rugosity is defined as the variance of distance measurements from the reef to a fixed plane that is parallel to the substratum (i.e., distances were measured perpendicular to the substratum). Details of the method are described in Chapter 1.

### *Remote Sensing Measurements*

High resolution LiDAR (4-m) and multibeam (3-m) bathymetries were obtained via the National Oceanic and Atmospheric Administration's Seafloor Characterization Program ([http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi\\_nps.html](http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi_nps.html)). Multibeam values typically were not available for areas shallower than 18 meters, while LiDAR values did not exceed 20 meters at most sites. In this study, most remote sensing calculations were made using multibeam data. In a few instances, LiDAR data were used where multibeam data did not exist.

ArcGIS 9.2 software was used to determine several factors for each study site. Original site positions were selected based on multibeam bathymetry data. The eleven sites chosen for this study are meant to provide a broad representation of all features of the shelf edge environment. Using the spatial analyst extension, slope was calculated using neighborhood statistics on a 3x3 pixel grid centered on single pixel as determined by GPS waypoints.

A measure of remote sensing rugosity utilized in this study was Slope Neutral (SN) Rugosity. This form of rugosity measurement is a more useful technique in high sloping environments, such as those encountered in this study. Details of this method are described in Chapter 1.

### *Statistical Analysis*

All abundance data were compared to habitat descriptors via regression analyses. Abundances were calculated as the total observations over all transects conducted. Benthic

site characteristics were used as input variables for an Empirical Orthogonal Function (EOF) analysis (Weare and Nasstrom 1982). The EOF was programmed and run using MATLAB version 7.5. The modes associated with this analysis are responsible for the variability seen in the input data. All modes presented in this study are accompanied by a percent variability explained. Mode values at each study site were plotted against scarid abundances to determine positive or negative correlations.

A paired T-test was used to differentiate between means of individual species distributions within sites. In addition, a Friedman repeated measures Analysis of Variance on ranks test was used to analyze the variation of these same distributions among the four targeted scarid species. Both statistical tests were run on SigmaStat 3.1 software.

## Results

### *Parrotfish Abundance*

Over all transects conducted, a total of 972 individuals of the four target parrotfish species were observed. Of these, *S. taeniopterus* was the most abundant (N = 450), representing 46.3% of the total (Table 2.1).

Table 2.1. Total numbers of individuals of scarid species observed at 11 shelf-edge reef top and slope locations off La Parguera, PR from a total of 88 visual transects.

Species	Abundance (#)	% of Total Scarids
<i>S. taeniopterus</i>	450	46.30
<i>S. aurofrenatum</i>	256	26.34
<i>S. viride</i>	102	10.49
<i>S. iseri</i>	164	16.87
Total	972	100

Scarid abundance varied between 56 and 133 individuals among sites. ‘La Boya’ represented the site with the highest parrotfish abundance, while ‘Barranco’ had the fewest of any site (Figure 2.2). *Scarus taeniopterus* was the most abundant species at 9 of the 11 study sites. At the other two sites *S. iseri* was the most abundant species. At 9 of 11 sites all four species were present. At ‘Chorera’ no *S. iseri* were observed, while at ‘Point 376’ no *S. viride* were recorded.

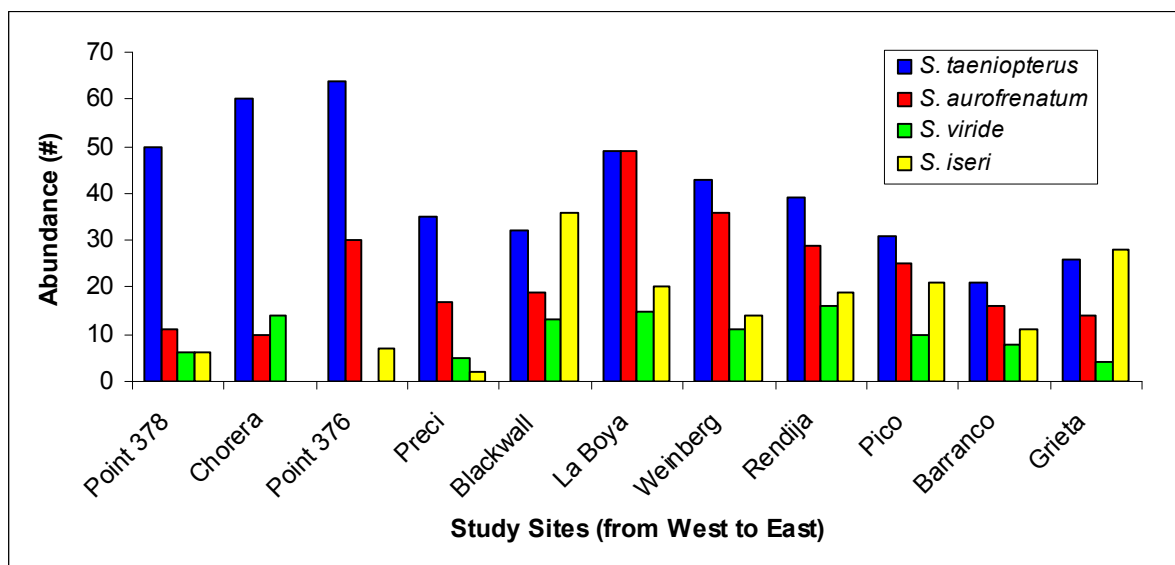


Fig. 2.2. Cumulative abundance of scarid species observed at each study site.

Relative abundances of the two species in the *Scarus* genus, were negatively correlated, with  $r = 0.82$ ;  $p = 0.002$  (Figure 2.3). No other significant correlations were found among species.

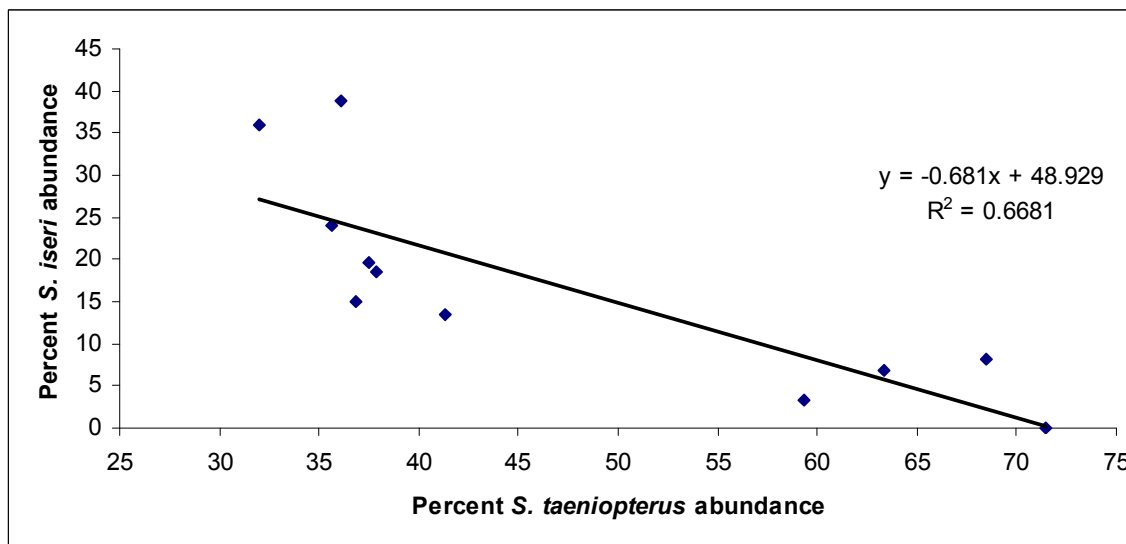


Fig. 2.3. Relative abundances of *S. iseri* plotted against those of *S. taeniopterus* at each of 11 study sites.

### Benthos

Overall, benthic composition at the sites sampled consisted of 67% algae, 16% hard coral, 9% sponge, 6% soft coral and <1% of both sand and rubble. Coral cover among sites varied from 26.88% at 'Rendija' to 3.13% at 'Point 376'. Algae cover over the same sites



varied from 90.63% at ‘Point 376’ to 55% at ‘Rendija’ (Figure 2.4). A strong negative correlation existed between percent coral cover and percent algal cover over the 11 study sites (Figure 2.5).

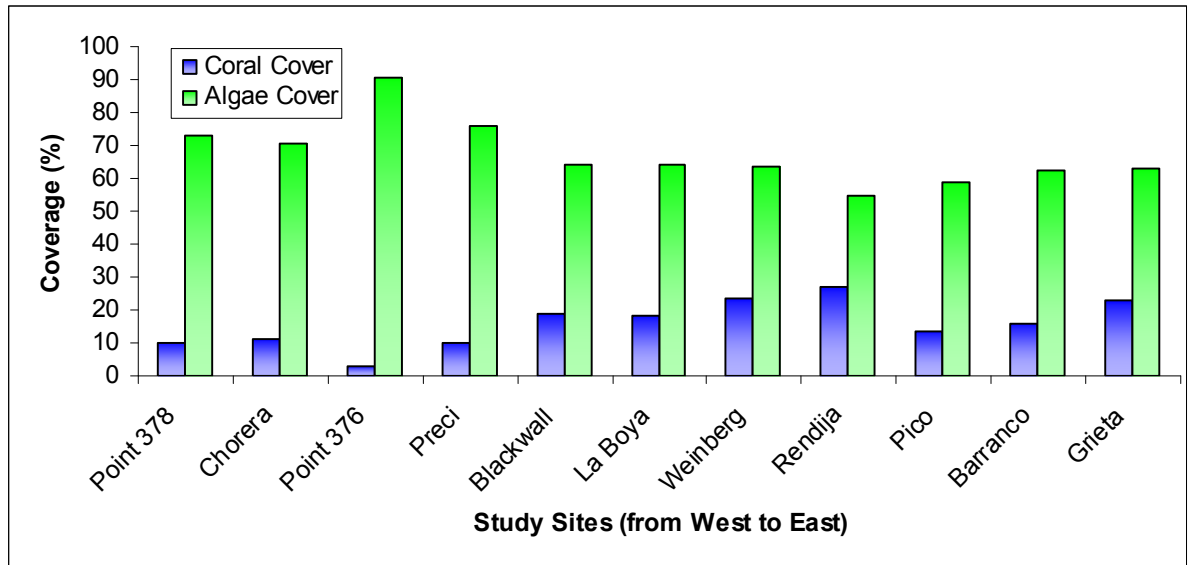


Fig. 2.4. Percent coverage by the two most dominant benthic classes observed for each site.

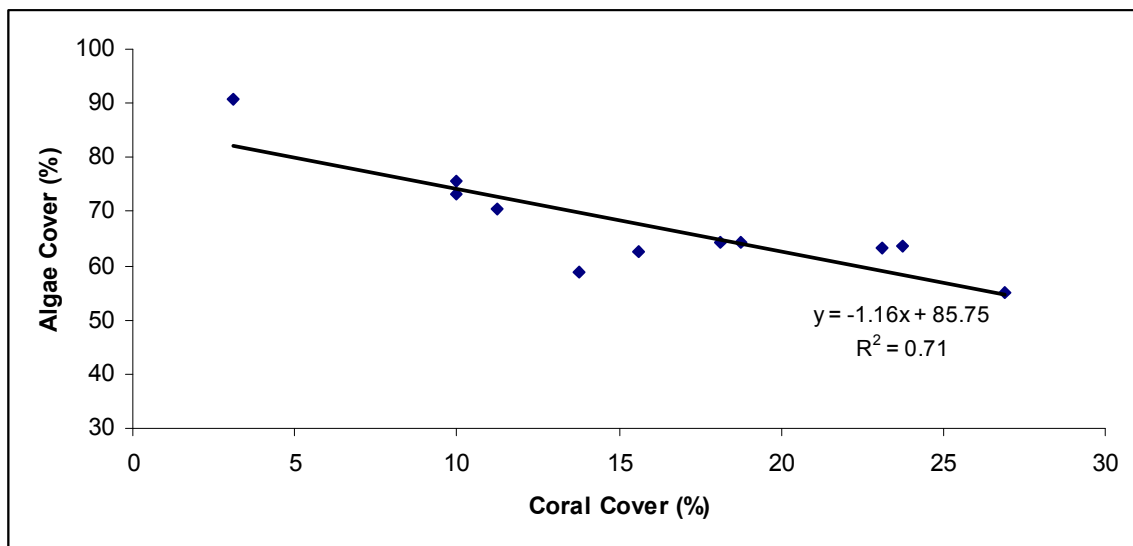


Fig. 2.5. Values of coral cover plotted against values of algae cover for each study site.

### Reef Location

All scarid species observed in this study were more abundant along the flat reef top at each site than on the adjacent reef slope. While this trend held true for all species, *S.*

*taeniopterus* showed a relatively higher percent abundance on slopes compared to the other species (Table 2.2). Paired T-tests were run among the four species and confirmed a statistically significant difference between means of each species, with P values  $\leq 0.01$ . Paired T-tests used abundance data during analysis.

Table 2.2. Comparison of scarid species abundance on reef tops and slopes over 11 shelf edge locations.

Scarid Sp.	reef top	Slope	% observed on Slope
<i>S. taeniopterus</i>	270	180	40.00
<i>S. aurofrenatum</i>	180	76	29.69
<i>S. viride</i>	69	32	31.68
<i>S. iseri</i>	116	48	29.27
<b>Total</b>	<b>635</b>	<b>336</b>	<b>34.60</b>

Each scarid species had a unique pattern of abundance across sites and locations within sites (Figure 2.6). A Friedman repeated measures Analysis of Variance on ranks (data were not normally distributed,  $p < 0.05$ ) confirmed the significant differences among median abundances ( $P < 0.001$ ).

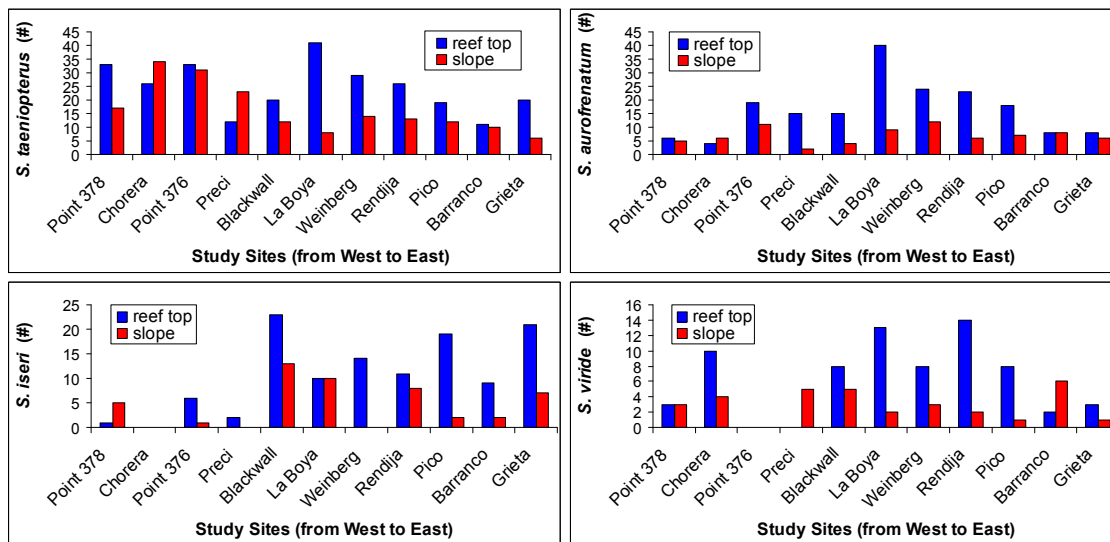


Fig. 2.6. Total number of individuals found each species in each reef location within sites

### Site Characteristics

The first mode of the EOF analysis, accounting for 36% of the variability in the data (Figure 2.7), showed a positive correlation to measures related to benthic structure, i.e. rugosity and habitat types providing vertical relief (hard coral, sponge, and soft coral coverage). Algal coverage, indicative of low structure, had a strong negative correlation to the mode.

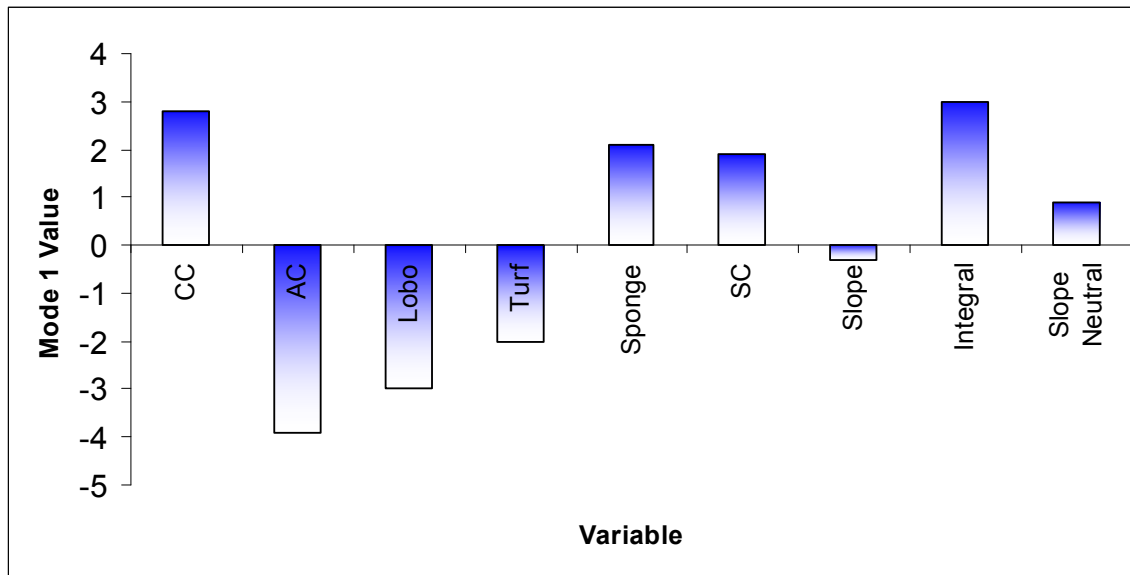


Fig. 2.7. The primary mode of an EOF analysis for site characteristics across the 11 study sites. Values with the same numerical sign are positively correlated, while those with opposite signs are negatively correlated. CC = Coral Coverage; AC = Algal Coverage; Lobo = *Lobophora* Coverage; Turf = Turf Algae Coverage; Sponge = Sponge Coverage; SC = Soft Coral Coverage; Slope = Slope of drop off; Integral = Integral Rugosity measurements; Slope Neutral = Slope Neutral Rugosity Measurements.

The second and third modes of the EOF analysis accounted for 25% and 16% of the variability, respectively (Figure 2.8). The second mode is driven largely by slope and slope neutral rugosity, but a negative association with sponge cover is also important. The third mode emphasizes a negative correlation between *Lobophora* and turf algae coverage, with slope also being important.

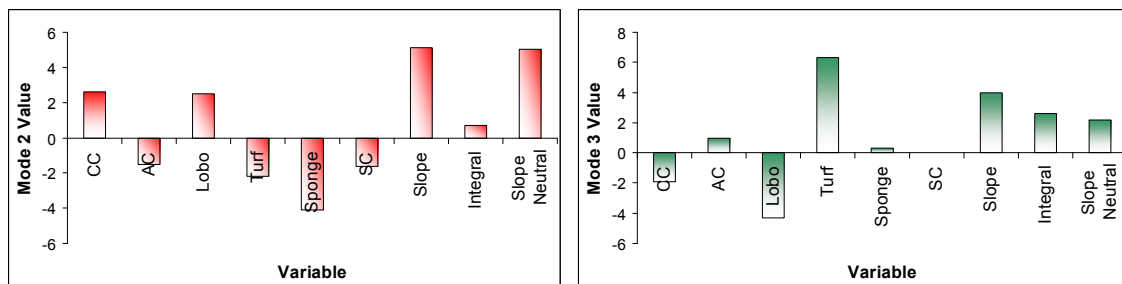


Fig. 2.8. The second (left) and third (right) modes of an EOF analysis conducted using site characteristics as input variables. Values with the same numerical sign are positively correlated, while those with opposite numerical signs are negatively correlated.

### Structural Preferences

Values for Mode 1 at each site were plotted against scarid abundance (Figure 2.9) and linear regressions calculated. No trend was present for *S. iseri* and *S. aurofrenatum*. For *S.*

*taeniopterus*, there was a significant negative correlation ( $r = -0.64$ ;  $P = 0.03$ ). While for *S. viride* the correlation was similar but positive ( $r = 0.68$ ;  $P = 0.02$ ).

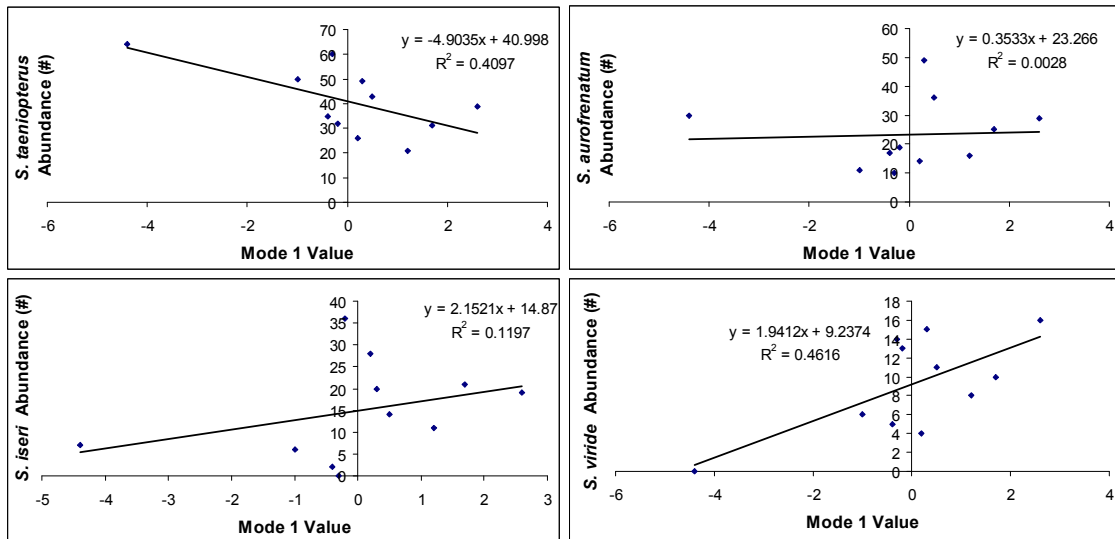


Fig. 2.9. Mode 1 values at each study site plotted against individual species abundance.

Scarid abundance was also plotted against values for Mode 2 of the EOF analysis at each site (Figure 2.10). Similar trends exist between this mode and the first in that mode 2 values positively associate with all scarid species other than *S. taeniopterus*. The only significant correlation to mode 2 values was for *S. iseri* abundances ( $r = 0.78$ ;  $P = 0.005$ ).

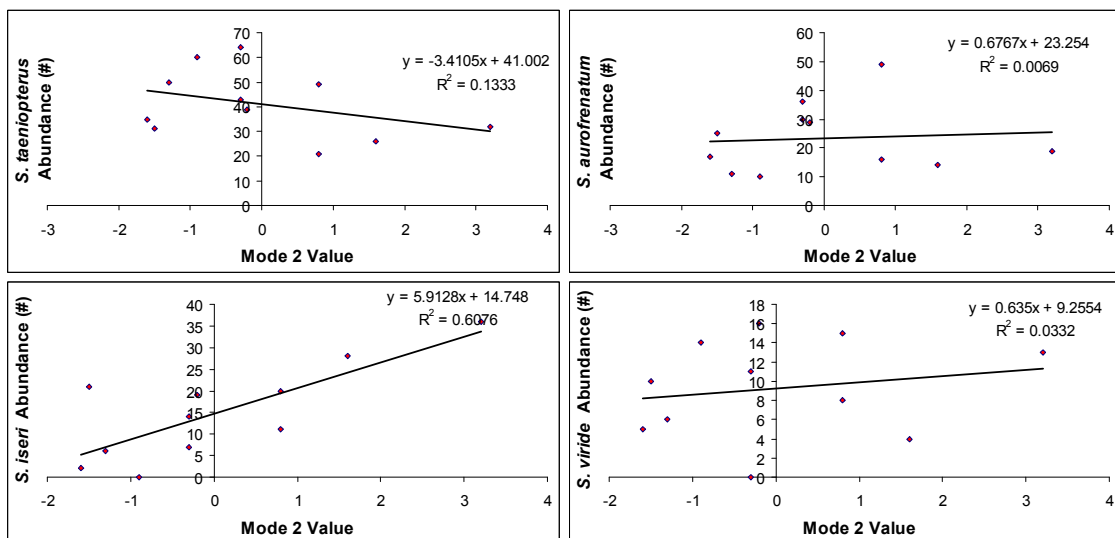


Fig. 2.10. Mode 2 values at each study site plotted against individual species abundance.

### Large Scale Site Characteristics

A second EOF analysis was conducted in response to the output data received from the first EOF. The second analysis yielded a first mode that accounted for 42% of the overall variability in the data (Figure 2.11). This second EOF separated reef top from slope locations in the raw data. In order to avoid bias due to slope in the SN rugosity measurements, only sites with less than 35° inclinations were included. This first mode shows a positive correlation to large scale structural features (Coral cover, sponge cover, soft coral cover, slope and SN rugosity), and a strong negative association with algal cover.

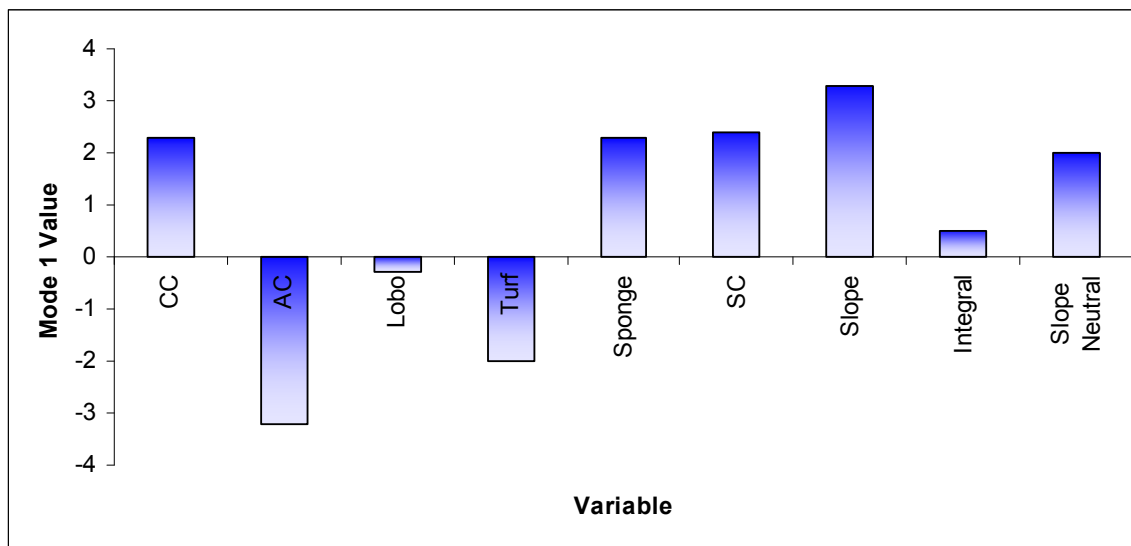


Fig. 2.11. The first mode of a second EOF analysis that separated reef top from slope locations that were less than 35°.

A second and third mode of the same EOF analysis accounted for 24% and 15% of the variability in the data respectively (Figure 2.12). Both the second and third modes show inverse relationships between *Lobophora* coverage and Turf algae coverage. The second mode is dominated by both measurements of rugosity (Integral and SN) which are positively correlated to the mode. The third mode of this analysis yields positive associations to coral cover, *Lobophora* coverage and both types of rugosity.

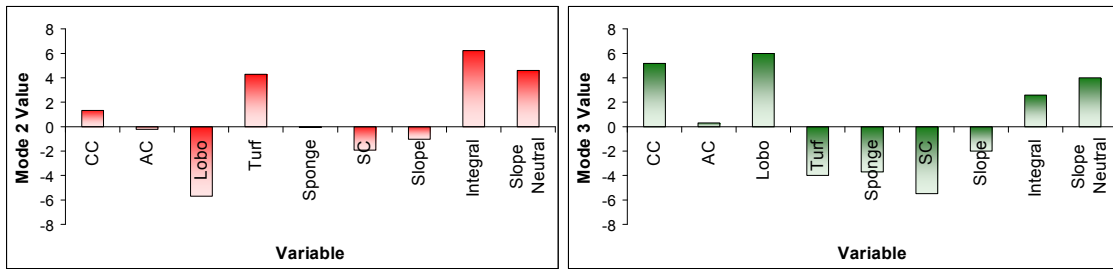


Fig. 2.12. The second (left) and third (right) modes of the EOF analysis that separated reef top from slope locations less than 35°.

### Reef Location Preferences

No significant correlations were observed when scarid abundances were plotted against mode 1 values for this second EOF analysis (Figure 2.13). While no statistically significant correlations are found among this mode and scarid abundances, most reef top locations have a negative association with the mode.

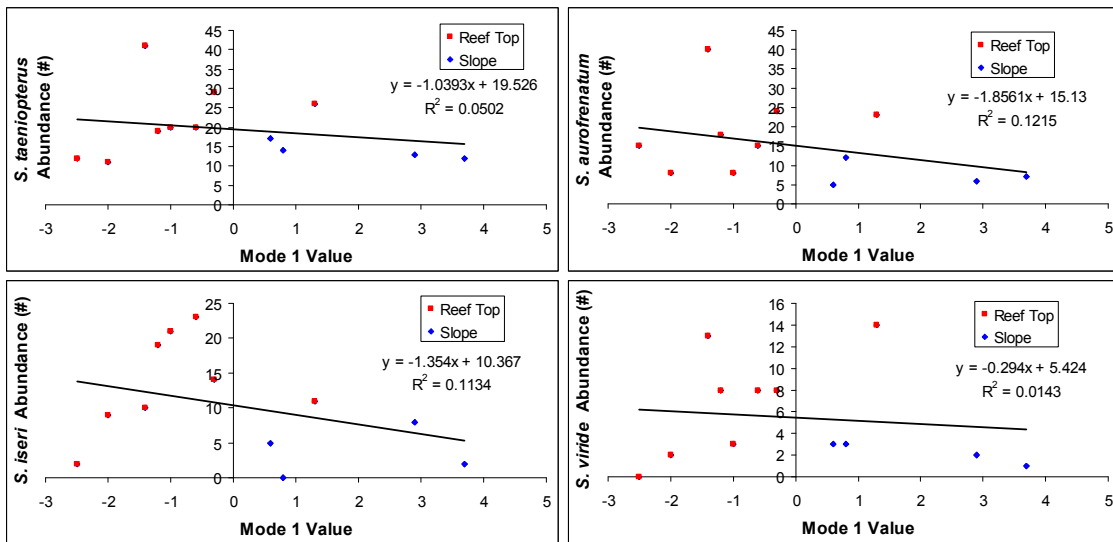


Fig. 2.13. Scarid abundances plotted against Mode 1 values of a second EOF analysis. Reef location (Reef Top v. Slope) has been separated.

Scarid abundances were not significantly correlated with either the second or third modes of the second EOF analysis.

### Scarus Size Frequency Distributions

The size frequency distribution of *S. taeniopterus* reveals a large contingency of early juvenile phase individuals on the shelf edge (Figure 2.14). Over 34% of all *S. taeniopterus* individuals recorded had a total length of less than 5cm.

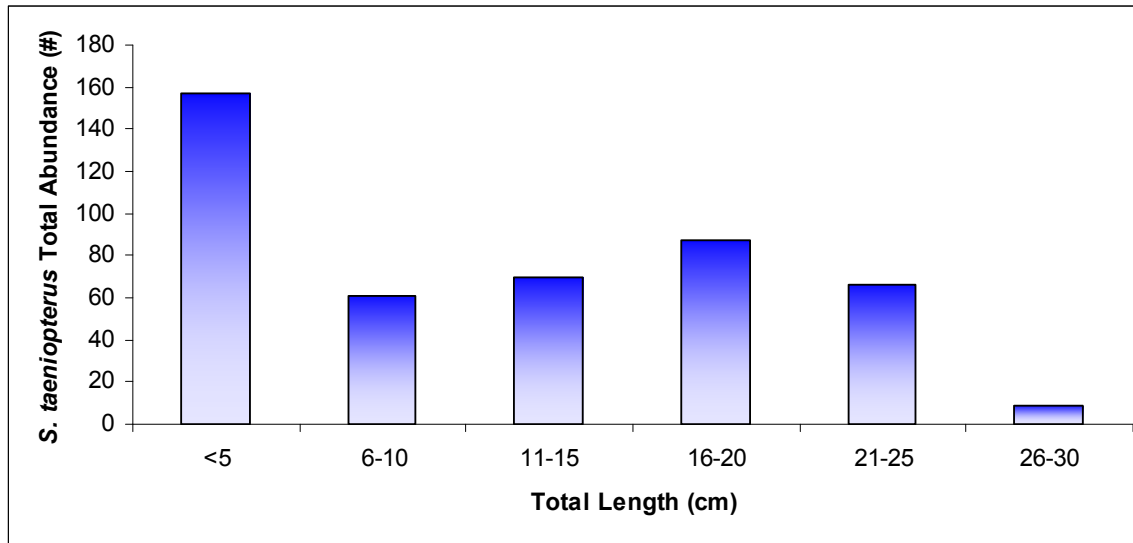


Fig. 2.14. Size frequency distribution for a total of 450 *S. taeniopterus* individuals observed during visual census transects.

In contrast, the size frequency distribution of *S. iseri* presents a different distribution. Less than 15% of all *S. iseri* observed had total lengths less than 5cm (Figure 2.15). This suggests that for *S. iseri* full recruitment of juveniles to the shelf edge is occurring at a larger size. Additionally, overall, far fewer *S. iseri* individuals are present at shelf edge reefs than *S. taeniopterus*.

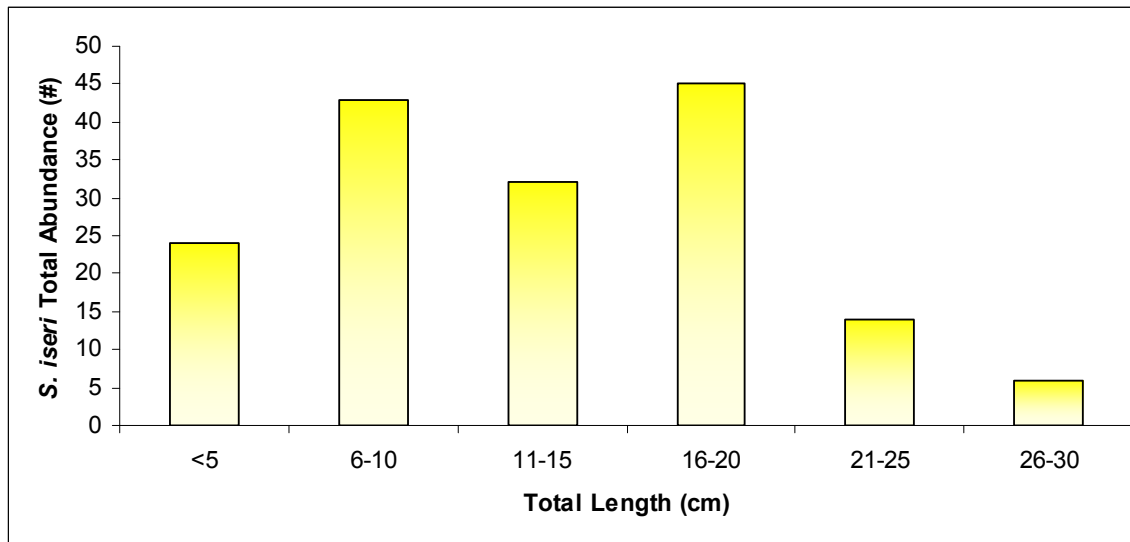


Fig. 2.15. Size frequency distribution for a total of 164 *S. iseri* individuals that were observed during visual census transects.

#### *Sparisoma* Size Frequency Distributions

The size-frequency distribution for *S. aurofrenatum* reveals extremely high relative abundances of early juveniles and adults (Figure 2.16). Juvenile and young adult abundances are relatively low compared to distributions of other species.

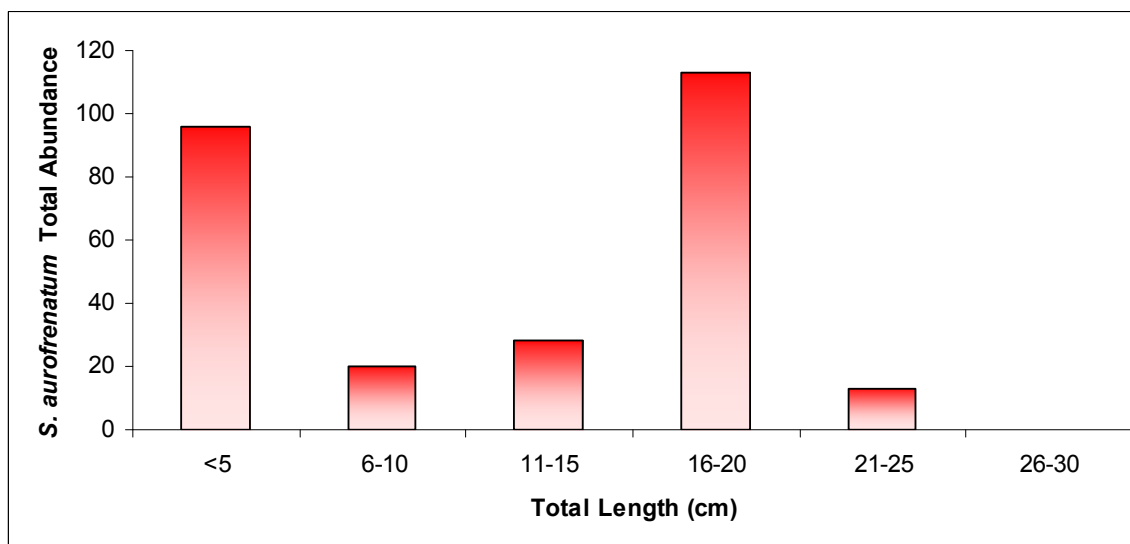


Fig. 2.16. Size frequency distribution for a total of 256 *S. aurofrenatum* that were observed in visual census transects at shelf edge sites off southwest Puerto Rico .



The population size structure of *S. viride* on the shelf edge shows (Figure 2.17) very few juveniles relative to the total number of individuals, indicating a lack of direct recruitment to the shelf edge population.

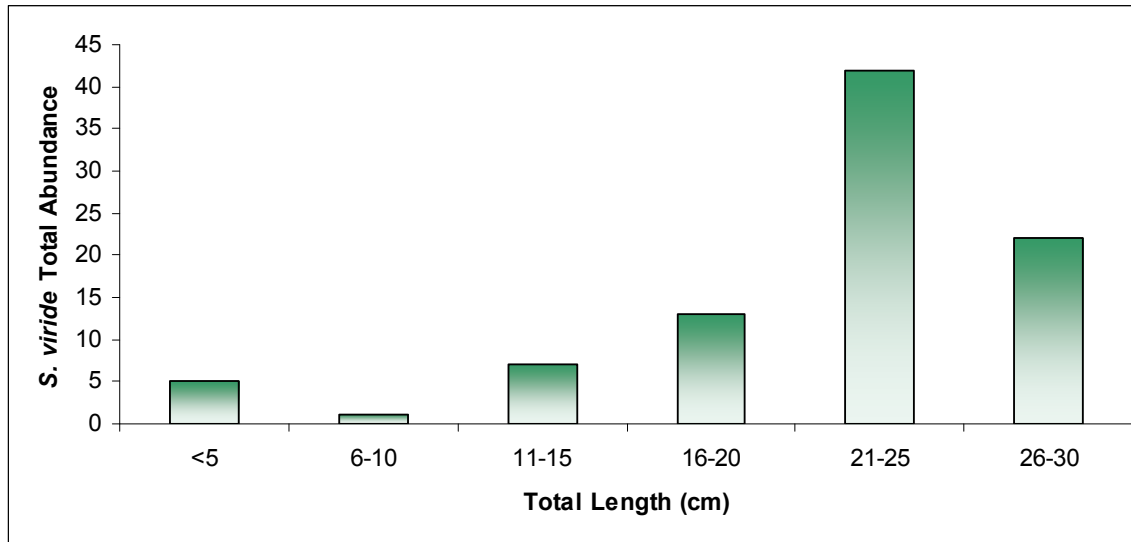


Fig. 2.17. Size frequency distribution for a total of 102 *S. viride* individuals that were observed during visual census transects.

## Discussion

Scarid community composition differed significantly between study sites due to altered species distributions. Each species shows unique distribution patterns and can be found in abundance at certain sites over others. Broad relationships are apparent in spatial distributions, which can further be broken down by site characteristics. While *S. taeniopterus* is the most abundant scarid species along the shelf edge reef, proportionally more individuals were observed at the western most study sites. Similarly, fewer individuals of both *S. viride* and *S. iseri* were observed at these same western sites. *S. aurofrenatum* was the most spatially generalized species observed and was present at every study site. The species composition may have direct links to habitat characteristics, as similar patterns can be observed via site classification. A clear gradient is represented by decreasing coral cover and increasing algae cover from the eastern most sites towards the western most ones.

An association of scarid abundance with the first set of EOF modes revealed that three out of four scarid species were found to associate positively with the first mode of the EOF analysis, indicating that reef structure was an important variable accounting for scarid

abundance. One such correlation was statistically significant (*S. viride*). Highly rugose areas provide shelter from predators for most scarids, as well as ideal conditions during inactivity at night, at which time Scarids have been known to sleep in mucus cocoons (Shephard 1994). Only *S. taeniopterus* differed with respect to reef structure, being significantly and negatively correlated to Mode 1 while showing a clear preference for areas dominated by algae. These observations generally agree with previous studies in that most scarids, especially *S. iseri* have a positive relationship between abundance and structure (Mumby and Wabnitz 2002, Kendall et al. 2004). The different preferences of individual species may be due to a tradeoff between habitat structure and food availability (i.e. algae cover).

The second EOF analysis confirmed that scarid population distribution is ultimately dependent on reef location. The first mode of this analysis was highly influential in accounting for the variability in the benthic data (42% explained). This first mode was representative of large scale structure at each study site with positive correlations among such variables (Coral cover, sponge cover, soft coral cover, slope and SN rugosity). While no scarid abundances were significantly correlated with the mode, reef top and slope locations were clearly separated in figure 2.13 as being negatively and positively associated to the mode, respectively.

Scarid species in the Caribbean have evolved to utilize the resources available to them via excavating and scraping feeding methods (Streelman et al. 2002). Species distribution reflects this resource utilization as each species has the capability to specialize within an environment where other scarids are present (McAfee and Morgan 1996). In such environments, resource partitioning has been observed among scarids throughout the Caribbean basin (Bruggeman et al. 1996; McAfee and Morgan 1996). No such observations were made between the two species belonging to the genus *Sparisoma* in this study. One of the target species, *S. viride*, has shown evidence of resource partitioning against the distribution of *Scarus vetula*, which was not included in this study (Bruggeman et al. 1994). Due to relatively low abundances of *S. vetula* in the reefs of La Parguera such speculation was outside the scope of this study.

The distribution patterns of *S. taeniopterus* and *S. iseri* are negatively correlated and appear spatially distinct. While *S. taeniopterus* was the most abundant scarid observed at 9

out of 11 study sites, *S. iseri* dominated the scarid community at the other two. The significantly positive correlation with Mode 2 of the EOF analysis suggests that *S. iseri* individuals were observed more frequently among highly rugose habitats with high coral cover and relatively low algae cover. In contrast *S. taeniopterus* populations were abundant in non-rugose habitats with high algae cover. Within these areas *S. taeniopterus* was found more often in areas with low *Lobophora* algae coverage while *S. iseri* was recorded where *Lobophora* coverage dominated the algal community. In addition, the size frequency distributions of the two species suggest that *S. taeniopterus* spends its entire life history at the shelf edge, while *S. iseri* may spend its early juvenile phase elsewhere and only mature individuals make it out as far as the shelf edge. The distribution of the size classes of *S. taeniopterus* is indicative of an entire fish population, while the division of the size classes for *S. iseri* suggests that there are juvenile populations, and possibly many more individuals elsewhere. The population distribution of *S. iseri* along the shelf edge reef is consistent with previous studies that suggest ontogenetic migrations of this species over the entire shelf platform (Aguilar-Perera 2004; Cervený 2006). In contrast to the shelf edge ecosystem, *S. iseri* is the most dominant scarid on more inner shelf fore-reefs while *S. taeniopterus* is rarely observed in those same locations (Nemeth and Appeldoorn 2010).

## Conclusions

Differences in species distribution patterns are apparent within the Scaridae family. Scarid abundance is heavily influenced by the physical characteristics of the habitats they occupy. General trends indicate that scarids prefer rugose habitats with high coral cover. The lower amounts of algae found at these same sites may be an effect of the heavy grazing by scarids or may be due to the successful coral colonization of available substrate. The systems invariably benefit from each others presence, yet the mutual advantages do not imply causality among fish or benthic organisms.

The unique case of *S. taeniopterus* warrants further investigation. The positive correlation to non-rugose, high algae sites is distinctive among the scarids in this study. Future studies should concentrate on *S. taeniopterus* feeding and behavior as the unusual positive association with turf algae suggests that they may be feeding on different algal

matter than other scarids within the community. The distribution patterns found between *S. taeniopterus* and *S. iseri* on the shelf edge are indicative of resource partitioning. The size frequency distributions clearly demonstrate the different population structure that is apparent at the shelf edge between these two species. Further investigation is needed to compare the diets, behavior and feeding techniques in order to determine sympatry.

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