Baseline characterization of bio-optical oceanographic properties and their relation to the diversity and health of coral reef communities

FINAL REPORT

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Introduction

Coral reefs are highly productive and diverse ecosystems that play an important role in the economy of many tropical islands and coastal areas throughout the world. Maximum development of coral reefs occurs in oligotrophic areas away from terrestrial inputs. They are affected by high transport of organic and inorganic matter and nutrients (Muscatine and Porter, 1977). In Indonesia, the greatest coral reef development occurs in areas characterized by clear water free from suspended sediments and excessive freshwater runoffs (Tomascik et al., 1993).

Reefs are affected by anthropogenic factors which have accelerated their demise in the last 30 to 40 years. Suspended organic and inorganic matter in the water column reduces light penetration which in turn affects photosynthetic benthic organisms including zooxanthellate corals. Increasing turbidity is an important environmental factor determining the structure and health of coral reef communities (Loya 1976; Rogers 1979). Van Den Hoek and Breeman (1978) established the lower limit of growth for hermatypic corals and crustose coralline algae as occurring at the depth of 0.2% of surface incident radiation. Water transparency, indeed, is a key environmental factor affecting the vertical distribution of corals as well as the maximum depth of a functional coral community (Tomascik et al., 1993).

Increasing turbidity directly affects photosynthesis-respiration rates causing the organisms to become more susceptible to other factors that may arise, such as algae proliferation and diseases (Goenaga et al., 1989; Gleason and Wellington 1993; Reaka-Kuella et al., 1993). Both algae proliferation and diseases, such as black band disease have been well documented and related to problems with water transparency (Maragos, 1972; Smith et al., 1981; Marszaleck, 1981; Bell, 1982; Williams and Bunkley-Williams, 1990; Porter and Meier, 1992; Peter, 1993). Suspended sediments in the water column add to the negative effects of turbidity in coral reef systems by potentially reducing reef fish abundance and diversity (Amesbury 1981), and by modifying the trophic structure of fish communities (Harmelin-Vivien 1992).

There is little information on the relationship between the incident spectral flux and the diversity, community composition, rugosity, and health of coral reefs. There is a need to ascertain how gradual or drastic increases in turbidity, as defined by the water attenuation coefficients of photosynthetic active radiation ($K_{d\,(PAR)}$), can serve as precursors for change for these communities. This coefficient, K_d, expresses logarithmically the rate of change of the downwelling irradiance with variations in depth (Kirk, 1983).

The purpose of this research was to develop an empirical model relating the attenuation coefficient of PAR to the diversity and percent cover of living corals at selected sites off southern and western Puerto Rico while taking into consideration depth and substrate factors. The objective of the reef fish community component was to extend this model to include analysis of reef fish community structure and to determine the relationship between the reef icthyofauna and coral reef condition.

Methodology

A total of 24 stations were selected between Mona Island, Mayagüez Bay, Parguera, and Guayanilla and Ponce bay areas. Only well-defined coral reefs (i.e. no hardground areas) were included in this study. Reef sites were selected at a fixed depth of 10 m, to control for exponential light absorption due to variable bathymetry, and were located in areas of differing water quality: 1) Mona Island, characterized by oceanic clear waters, 2) La Parguera, with waters of low to intermediate turbidity, and 3) Guayanilla and Ponce, characterized by relatively high turbidity.

Profiles of downwelling irradiance of PAR ($E_{d\,(PAR)}$) were measured *in situ* using a submersible radiometer (Model LI-1400 from Licor) with a cosine-corrected underwater quantum sensor (Licor LI-192SA). E_d underwater values were normalized by using a surface Ed (Licor LI-190SA) sensor. Corrected values of E_d were used to calculate the attenuation coefficient, K_d, using the slope of the log-transformed linear regression of $E_{d\,PAR}$ vs. depth. K_d values were also calculated after Kirk (1983) using:

$$K_d = 1/(z_2 - z_1) * \text{Ln } Ed_1/Ed_2 \qquad (1)$$

Regression analysis was used to relate $K_{d\,(PAR)}$ to the coral reef parameters of interest, such as percent living coral cover, species richness, index of evenness and index of diversity. Percent coral cover, defined as the total bottom area occupied by living coral colonies was estimated using photoquadrats (1.0 m^2 area) following the method described by Bohnsack (1979) and Weinberg (1981). Due to the high turbidity at some of the sites, the photoquadrats were further divided into four areas of 0.5 m^2 in order to reduce the camera to subject distance and obtain higher quality digital images. In summary, four photos were obtained per quadrat for a total of fifteen photoquadrats and 60 photos per site.

At each site, three 10 meter transects that were parallel to the depth contours, were used (Kershaw, 1964). Identification of the coral species present within the photoquadrats was performed *in situ* in order to facilitate the coral identification during the image analysis. These images were enhanced using Photoshop 7.0 and the percent coral cover determined by the Deneba Canvas 8.0 area measuring tool. All data were entered into an Excel spreadsheet where coral cover, rugosity, index of evenness, and diversity index were calculated. Three sets of rugosity measurements were obtained using a 10m brass chain.

Study Sites

Mayagüez Bay

Mayagüez Bay, with an approximate area of 100 km^2, has an insular shelf from 2 to 6 km wide with an average shelf edge depth of 15 to 25 m (Morelock et al., 1983). Coral reefs occur sparsely within this bay. The reefs are under heavy siltation pressure and have declined significantly during the past decades (Goenaga, 1988). Three rivers, the Guanajibo, Yagüez and Añasco drain into the bay.

Two sites were sampled in Mayaguez Bay: Manchas Interiores and Escollo Rodríguez. Escollo Rodríguez is located approximately 2 km offshore and at its shallowest point the reef may reach the surface during low tide. This reef is highly influenced by terrigenous sediments from the Guanajibo and Yagüez rivers and because of the high turbidity most of the living coral cover is presently confined to the uppermost 10 meters. Resuspension of fine sediments occur during the winter months with the arrival of cold fronts from the northwest.

La Parguera

The southwest coast of Puerto Rico has the best development of emergent and submerged coral reefs in the island. The absence of rivers in La Parguera creates ideal conditions for coral development. This platform extends approximately 15 km offshore, and possesses emergent fringing reefs, bank-barrier reefs and submerged patch reefs (Morelock et al. 2001). This reef system began to develop between 6,000 and 9,000 ybp, although the modern "coral carpet" is only one to two hundred years old (Vicente 1993; Torres and Morelock 2002). Eustatic sea level rise, relatively shallow water, and suitable substrates allowed the development of extensive coral reefs along the insular shelf.

Even though the coral reefs of this area has been described as having high diversity, abundance and cover, the area is now confronting multiple stressors from both natural and anthropogenic sources. Coral diseases, hurricanes, and sedimentation have caused significant changes including local extinctions, competitive displacements of hermatypic corals by sponges and macroalgae, and coral bleaching resulting in a decrease in coral cover and an increase in algal biomass (Vicente, 1993). The water transparency in La Parguera is usually high, particularly at the shelf edge. However, rapid urbanization and nutrient loading from runoff appear to be an increasing problem in this area (Morelock et al., 2002). Decreasing water transparency could be a precursor of change at this and other coral reef areas throughout Puerto Rico.

A total of eleven sites were characterized in La Parguera with a relatively wide range of water optics (e.g. Kd) and coral cover. The selected reefs included Caracoles, Mario, Enrique, Laurel, San Cristobal, El Palo, Media Luna, El Corral, Turrumote, Turrumote II and Pinaculos.

Guayanilla Bay

The reefs of Guayanilla Bay have been subjected to high levels of sedimentation and in many places are severely impacted. The source of fine sediments is the interior of the bay or from Tallaboa Bay, where petrochemical industries were built in the late 1970's. The Tallaboa and Guayanilla rivers discharge directly into the bay and ship traffic is active in this area causing resuspension of bottom sediments (Morelock et al. 2001). The substrate at these reefs is mostly composed by terrigenous muds. Coral cover can be described as ranging from few massive coral colonies at the top of the reef in 10m depth to mostly hardground areas dominated by gorgonians. Three sites were sampled in theis bay: 1) Boya Verde, 2) Fanduco reef, and 3) Cayo Caribe.

Ponce Bay

Three reef sites were characterized in this area west and east of the Ponce harbour: Bajo Tasmania, Cayo Cardona and Cayo Ratones. Throughout the Ponce basin sediment plumes are frequently formed by wave action resuspension of fine bottom sediments. These sediment plumes drifts westward reaching both Bajo Tasmania and Cayo Cardona and less frequently, Cayo Ratones.

Results

Benthic Community Analysis

The locations and coordinates of the 19 stations visited in Mayagüez, La Parguera, Guayanilla and Ponce are presented in Table 1. The names and locations of the twelve stations sampled in La Parguera, are shown in Figure 1. A total of six stations were sampled in the south coast, three in Guayanilla Bay area and three in Ponce Bay (Figure 2). Two additional stations were sampled in Mayagüez Bay (Figure 3). Water quality in these areas is highly influenced by the local hydrography, as in the case of Mayagüez Bay, due to the influence of the Guanajibo and Añasco rivers.

Downwelling irradiance (E_d) profiles of PAR were obtained at all stations with a minimum of two profiles per station to a maximum of six at different times of the year. Stations in La Parguera were the most visited followed by Mayagüez Bay because of accessibility and logistics. In La Parguera, a total of 49 visits to twelve stations were conducted to obtain profiles of downwelling irradiance. Irradiance profiles for Mayagüez Bay were obtained at two stations with seven visits in total. The average number of visits to Manchas Interiores was four and three for Escollo Rodríguez. A total of eight visits were conducted in Guayanilla and Ponce for Ed measurements. In these bays, three visits were conducted to all sites except Boya Verde in Guayanilla and Cayo Ratones in Ponce where only two visits per station were possible.

Site	Code	Latitude	Longitude	Distance (km)
Boya Verde	**G**	17° 58.062'	66° 45.912'	1.38
Tasmania	**Po**	17° 56.513'	66° 37.692'	2.76
Cardona	**Po**	17° 57.260'	66° 37.990'	3.55
Escollo Rodríguez	**M**	18° 11.378'	67° 11.528'	2.63
El Corral	**Pa**	17° 56.817'	67° 01.162'	2.66
Cayo Caribe	**G**	17° 57.904'	66° 44.180'	3.06
Fanduco	**G**	17° 57.925'	66° 45.663'	1.91
Mario	**Pa**	17° 57.071'	67° 03.356'	2.87
Ratones	**Po**	17° 56.733'	66° 40.224'	2.96
Enrique	**Pa**	17° 57.197'	67° 02.928'	2.96
Caracoles	**Pa**	17° 57.694'	67° 02.091'	1.26
El Palo	**Pa**	17° 55.826'	67° 05.435'	3.59
Manchas Interiores	**M**	18° 13.448'	67° 11.883'	3.64
San Cristobal	**Pa**	17° 56.362'	67° 04.575'	3.79
Laurel	**Pa**	17° 56.379'	67° 03.529'	4.15
Pináculos	**Pa**	17° 55.920'	67° 00.763'	4.21
Turrumote	**Pa**	17° 56.039'	67° 01.087'	4.06
Turrumote II	**Pa**	17° 55.726'	66° 58.497'	2.83
Turrumote III	**Pa**	17° 56.064'	67° 02.056'	4.45

Table 1. Study sites location and distance from the shore. Codes refer to locations: (**G**): Guayanilla Bay, (**Po**): Ponce Bay, (**Pa**):Parguera, (**M**): Mayagüez Bay

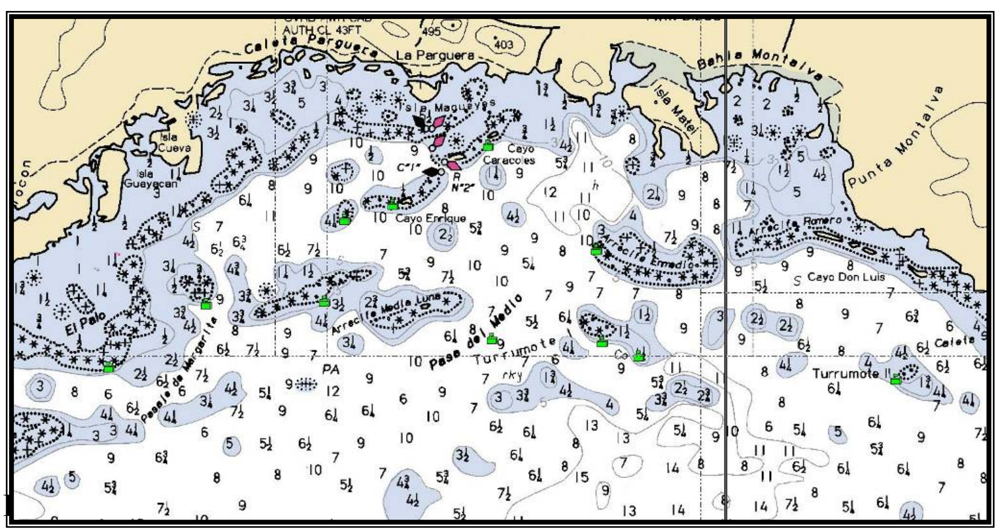

Figure 1. Sites off La Parguera.

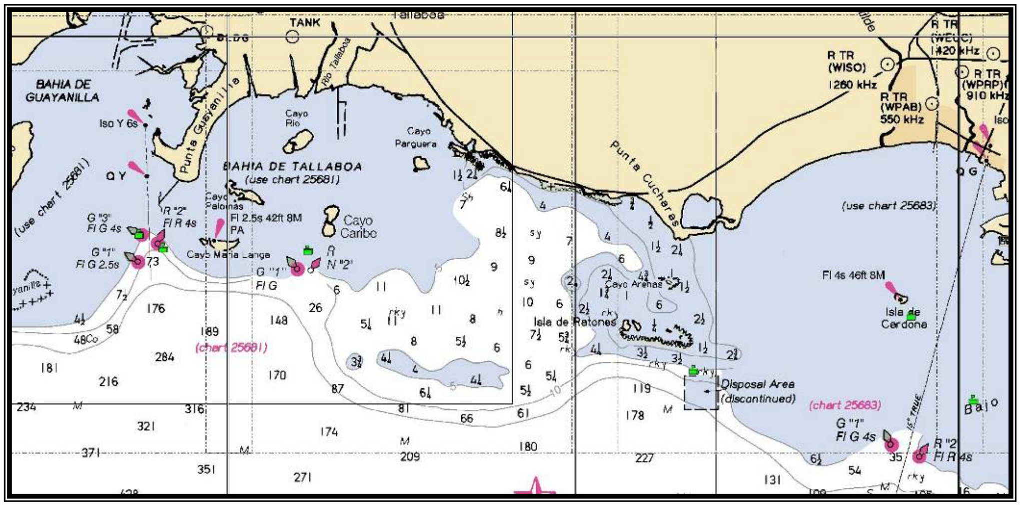

Figure 2. Sites off Guayanilla and Ponce Bay.

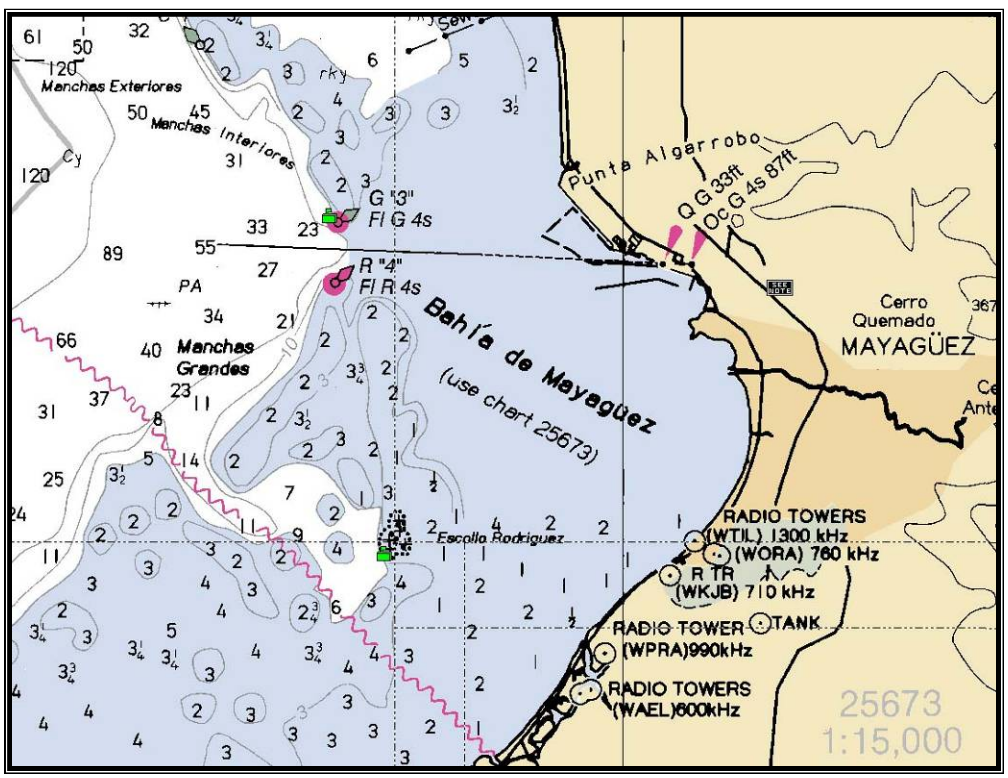

Figure 3. Sites off Mayagüez Bay.

Vertical attenuation coefficients (K_d) were calculated from the downwelling irradiance profiles. In some cases K_d values varied considerably depending on the season and/or weather conditions encountered. Throughout this study, the wet and dry seasons were recognized as the most important factors affecting the variability of K_d. An average K_d value per reef site was used in the regression analysis (Table 2).

The most abundant species at Ponce and Guayanilla were *Montastrea cavernosa, Montastrea annularis*, *Siderastrea siderea*, *Porites astreoides*, and *Agaricia sp.*. In the Mayagüez Bay area these species were also dominant together with *Colpohyllia natans* and *Porites porites*. In La Parguera all of these species were abundant in addition to *Montastrea franksi*, *Montastrea faveolata*, *Diploria strigosa*, *Diploria clivosa*, and *Acropora cervicornis*.

Site	Diversity Index	Evenness Index	Species Richness
Boya Verde	1.56	0.795367	10
Tasmania	1.48	0.868038	7
Cardona	1.56	0.847462	11
Escollo Rodríguez	1.49	0.86224	8
El Corral	2.18	0.878762	21
Cayo Caribe	1.58	0.704401	14
Fanduco	1.95	0.850831	14
Mario	2.26	0.849165	21
Ratones	1.58	0.676697	13
Enrique	2.09	0.819446	18
Caracoles	2.07	0.825307	18
El Palo	2.09	0.824834	19
Manchas Interiores	2.07	0.84295	16
San Cristobal	2.17	0.811483	21
Laurel	1.89	0.845487	14
Pináculos	1.49	0.752966	10
Turrumote	1.92	0.817888	16
Turrumote II	2.08	0.843976	21
Turrumote III	2.04	0.79474	20

Table 2. Mean diversity, evenness, and species richness at all stations.

Species richness (n) was highest at Turrumote II, El Corral, Mario, and San Cristobal reefs in La Parguera (n=21) and lowest for Tasmania in Ponce (n=7). K_d values ranged from a maximum of 0.319 at Boya Verde in Guayanilla to a minimum of 0.142 at Turrumote III in La Parguera (Table 3). The corresponding percent living coral cover at these sites were 4.55 and 61.43, respectively (Table 4). The maximum K_d value at La Parguera was in El Corral with a value of 0.22 and 16.91% live coral cover. The minimum K_d value was Turrumote III with 0.142 and a maximum live coral cover of 61.43%, the highest for all stations. In Guayanilla the maximum K_d value was at Boya Verde with 0.319 and a live coral cover of 4.55%, while the minimum K_d value recorded was 0.211 for Fanduco station with a live coral cover of 23.6%. In Ponce Bay, the maximum K_d value was for Bajo Tasmania station with 0.268 and live coral cover of 5.46% and the minimum for Cayo Ratones with a K_d value 0.206 and a live coral cover of 26.03%. Finally, Mayagüez Bay presented a maximum K_d value of 0.229 and a 8.12% of live coral cover for Escollo Rodríguez while a K_d of 0.17 and a live coral cover of 29.52% described Manchas Interiores.

Sites	K_d PAR	K_d Range (Min-Max)
Turrumote III	0.142	0.085-0.240
Turrumote II	0.143	0.051-0.219
Turrumote	0.144	0.110-0.190
Pináculos	0.147	0.110-0.172
Laurel	0.158	0.099-0.220
San Cristobal	0.159	0.110-0.200
Manchas Interiores	0.170	0.103-0.237
El Palo	0.174	0.110-0.247
Caracoles	0.197	0.130-0.279
Enrique	0.205	0.131-0.352
Ratones	0.206	0.177-0.225
Mario	0.209	0.138-0.299
Fanduco	0.211	0.121-0.266
Cayo Caribe	0.219	0.115-0.344
El Corral	0.220	0.114-0.420
Escollo Rodríguez	0.229	0.131-0.280
Cardona	0.253	0.227-0.319
Tasmania	0.268	0.223-0.307
Boya Verde	0.319	0.246-0.389

Table 3. K_d values (above) and Table 4. Coral reef parameters (below)

Data for all the stations showed a non-linear inverse relationship between the K_d values and the percent coral cover (R^2= 0.92, p<0.0001) (Figure 4).

The relationship shown in Figure 4 could be used to predict the condition of Caribbean coral reefs, using percent living coral cover as the main ecologically-relevant parameter, as a function of the average vertical attenuation coefficient of PAR. Notice that coral cover of less than 15% is associated with Kd values of 0.23 or more. A wider range of coral cover values (30 to >60%) are associated with Kd values of less than 0.18. Intermediate range Kd values (0.18-0.23) are associated with a relatively narrow range of coral cover (15-30%).

An inverse relationship was found (R^2 =0.43, p<0.0001) between K_d values and distance from shore. As expected, K_d values decreased as the distance to shore increased. This relationship was more evident in La Parguera, where a larger number of stations at a wider range of distance from shore were present.

Site	Live coral	Octo-corals	Sponge	Macroalgae	Turf	Invertebrates	Bare substrate
Boya Verde	4.55	25.00	21.25	0.76	2.38	0.05	46.01
Tasmania	5.46	24.90	7.46	0.49	3.29	0.44	58.23
Cardona	7.42	21.93	8.46	1.05	6.67	1.28	52.31
Escollo Rodriguez	8.12	3.47	18.07	1.50	19.17	0.16	49.51
El Corral	16.91	22.07	4.62	2.01	11.54	0.05	40.90
Cayo Caribe	19.65	21.47	15.19	1.11	3.35	0.00	39.23
Fanduco	23.60	12.00	10.08	2.97	2.75	0.08	48.32
Mario	24.76	14.47	3.98	1.14	0.48	0.05	54.50
Ratones	26.03	23.13	7.16	4.31	7.43	1.60	30.06
Enrique	26.36	22.47	7.82	8.80	7.50	4.26	22.79
Caracoles	27.35	11.00	5.45	20.98	3.37	2.11	26.66
El Palo	28.97	4.87	3.56	9.08	4.29	0.00	39.45
Manchas Interiores	29.52	6.60	6.15	4.21	0.00	0.18	53.35
San Cristobal	44.79	11.04	4.82	4.49	0.00	3.11	21.17
Laurel	46.10	9.20	6.08	2.97	8.80	0.38	11.58
Pinaculos	51.69	5.87	2.97	6.68	4.91	1.16	13.45
Turrumote	59.30	7.60	1.70	7.42	9.32	0.00	6.37
Turrumote II	59.34	6.40	4.19	9.56	4.87	1.03	12.72
Turrumote III	61.43	8.67	3.55	0.42	4.14	0.90	11.30

Table 4. Percent of reef components at each study site. Bare substrate includes rubble.

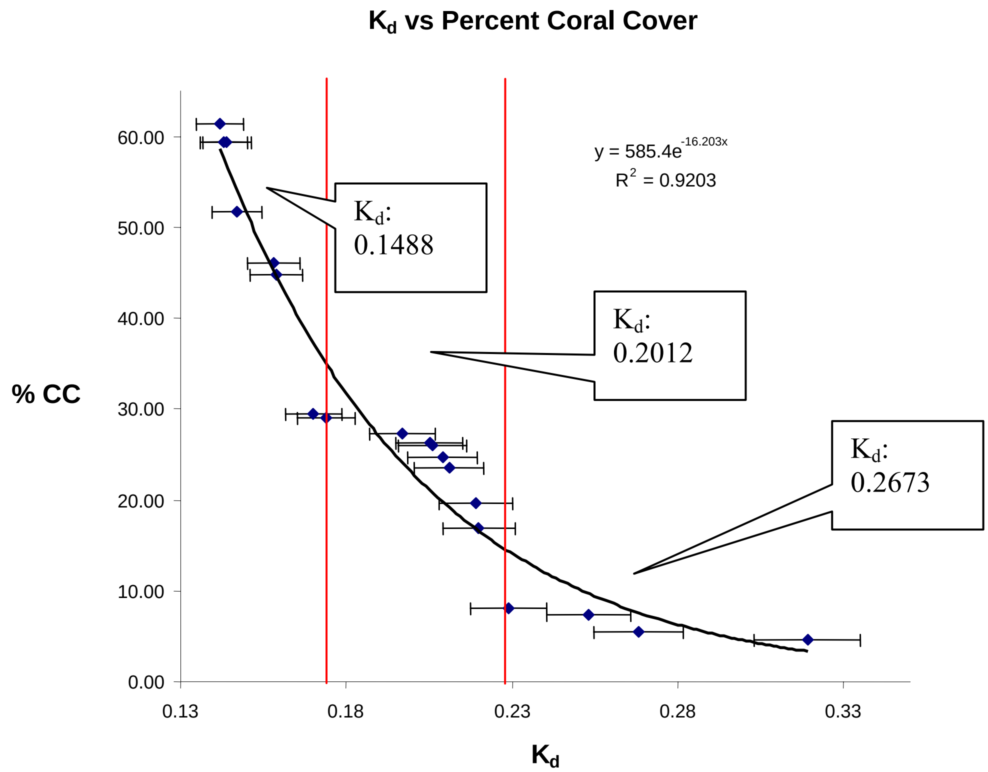

Figure 4. Relationship between the vertical attenuation coefficient (K_d) and percent live coral cover.

A negative correlation was found between the diversity index and the K_d values. The minimum diversity index was recorded for Bajo Tasmania at 1.48 while a maximum value of 2.26 was observed for Mario Reef in La Parguera (Table 2). The lowest value for the evenness index was for Cayo Ratones at 0.677 and the highest for El Corral at 0.879 (Table 2).

Quantitative data on the percent of octocorals, sponges, macroalgae, turf and bare substrate were also obtained from the digital photography analysis (Table 4). Escollo Rodríguez in Mayagüez Bay presented the lowest percent of octocorals (3.47%) while Boya Verde had the highest value at 25% (Table 4). Boya Verde had the highest percent of sponges (21.25%), while the minimum was observed for Turrumote at 1.7%. Macroalgae was highest in Caracoles at 20.98% and lowest in Turrumote III at 0.42%. Turf algae was highest at Escollo Rodríguez at 19.17% while it was undetectable from the digital photography taken at both Manchas Interiores and San Cristobal (Table 4).

Reef Fish Community Analysis

A total of 6,400 fishes from 101 species and 37 families were observed at the study sites. Significant differences were found among sites in mean values of fish density, species richness, biomass, and diversity index (H') (Table 5). Higher fish densities were found at Mona Island, varying from 44 to 118 fish/30m^2. In La Parguera densities varied from 16 to 48 fish/30m^2. Guayanilla and Ponce sites had densities ranging from 32 to 55 fish/30m^2. Maximum fish species richness (16) occurred in La Parguera, at San Cristobal and in Guayanilla, while the lowest number of species were recorded in La Parguera at Romero and eastern La Parguera. Fish biomass at one of the Mona Island sites (12,713g) was almost twice that observed at any other site; high values were also observed in La Parguera at Margarita (7027g) and San Cristobal (6646g), while the lowest values occurred at Guayanilla (510g) and Ponce (661g).

There were significant differences among sites in mean densities of herbivores, planktivores, omnivores and sessile invertebrate feeders, while densities of mobile invertebrate-piscivorous feeders and piscivores among sites were not significantly different (Table 5). The highest mean densities of herbivorous (34/30m^2) and planktivorous fishes (43/30m^2) were recorded at Mona Island, whereas the lowest herbivore densities (5/30m^2) were found at Romero in La Parguera.

Parameter	**F**	**p**
Kd $_{(PAR)}$	4.74	<0.0001
Rugosity	27.45	<0.0001
Fish species richness	2.23	0.0005
Fish density	3.19	<0.0001
Herbivorous fish density	3.00	<0.0001
Mobile invertebrate fish feeders density	3.47	<0.0001
Mobile invertebrate-piscivorous fish density	1.26	0.1725
Omnivorous fish density	1.52	0.0445
Piscivorous fish density	1.02	0.4452
Sessile invertebrate fish feeders density	1.67	0.0187
Planktivorous fish density	3.95	<0.0001
Fish diversity index (H')	5.08	<0.0001
Fish biomass	2.20	<0.0001

Table 5. Results of analysis of variance on transformed parameters compared among study sites.

The relationships between water turbidity and mean fish density and mean fish biomass (Figures 5 and 6) were significant but were driven by the extreme values at the Mona Island sites. Even when excluding Mona Island and other hardground sites, a trend of decreasing fish abundance and biomass with increasing turbidity was observed, but the regressions were not statistically significant.

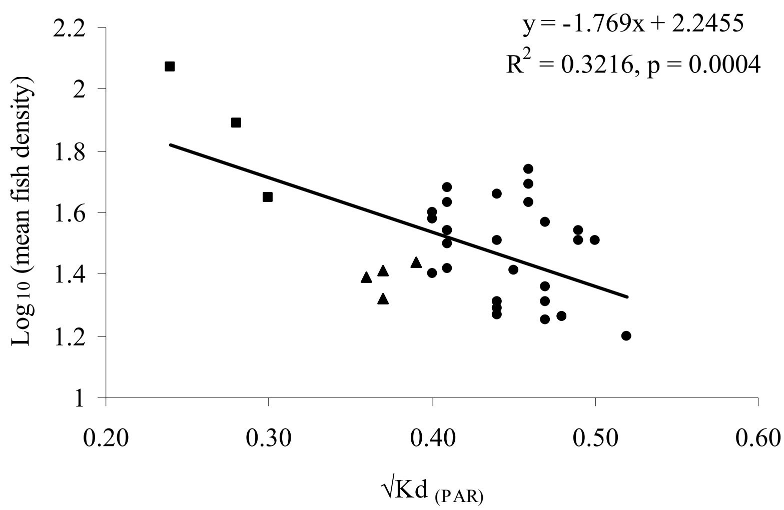

Figure 5. Regression between the vertical attenuation coefficient of PAR and mean fish density. Squares represent Mona Island sites, triangles are hardground sites, and circles represent all other sites.

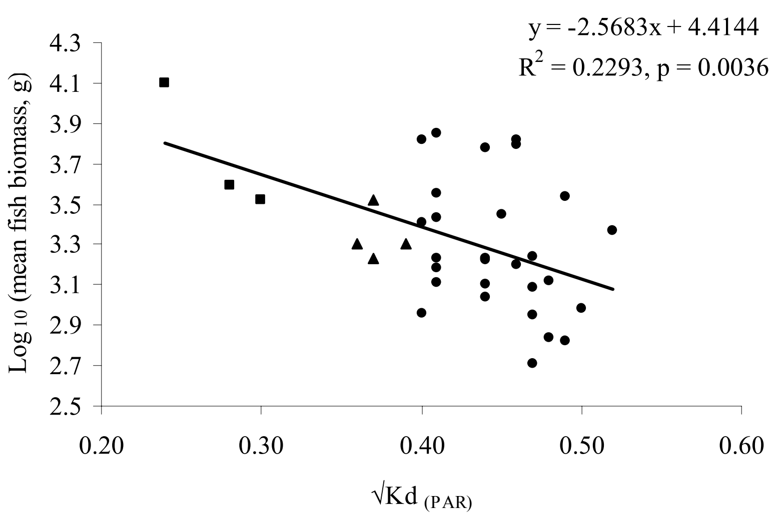

Figure 6. Regression between the vertical attenuation coefficient of PAR and mean fish biomass. Squares represent Mona Island sites, triangles are hardground sites, and circles represent all other sites.

Mean abundance of herbivores was negatively correlated with turbidity when using all sites (Figure 7) and when Mona Island and the hardground sites were excluded (Figure 8).

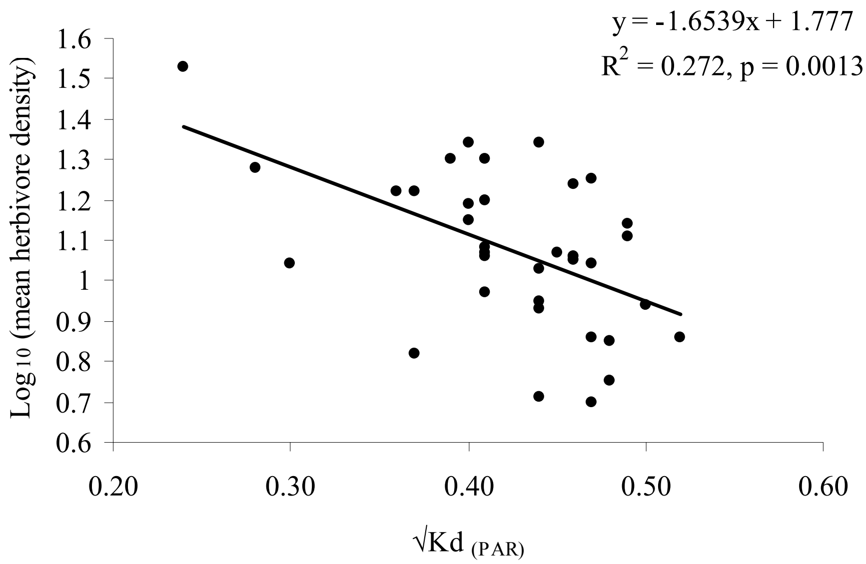

Figure 7. For all sites, regression between the vertical attenuation coefficient of PAR and mean fish density.

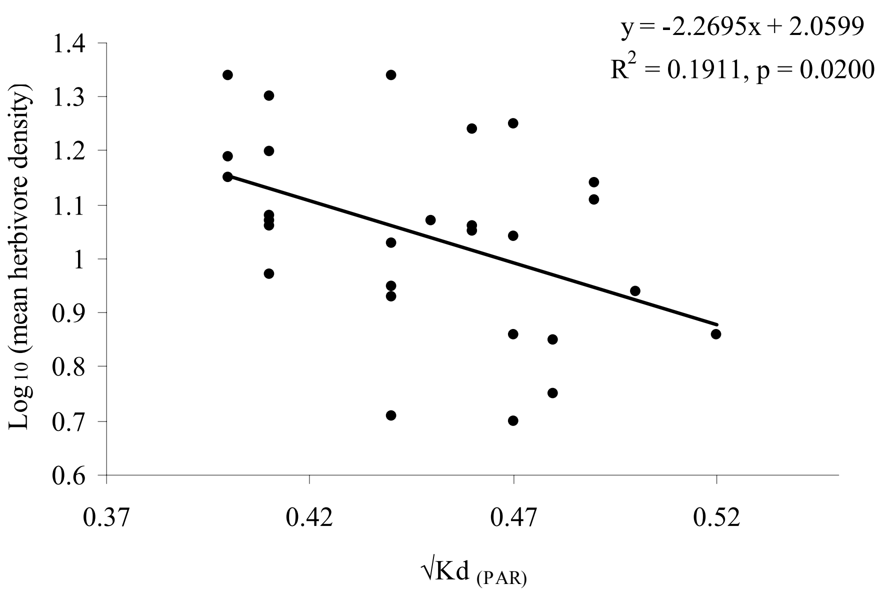

Figure 8. Regression between the vertical attenuation coefficient of PAR and mean fish density, excluding Mona Island and hardground sites.

Conclusions

This study provided valuable insights into the relationships between water optical properties and coral reef and fish community parameters. The attenuation coefficient of PAR, an apparent optical property, was used to estimate the percent living coral cover and the diversity and evenness indices of coral reefs. Depth and substrate factors were taken in consideration to reduce the variability in the relationship. As expected, the percent living coral cover is related to higher turbidity (i.e. higher K_d values) in a non-linear inverse relationship. As the attenuation coefficients can be easily measured from boats and even satellites (e.g. MODIS $K_{d\ 490}$ product), this relationship can be used to monitor changes in water quality as a precursor of change in coral reef communities. The reef fish community component extended this model to include analysis of reef fish community structure and the relationship between the reef icthyofauna and coral reef condition. K_d PAR was also inversely related to reef fish density, biomass, and herbivore abundance.

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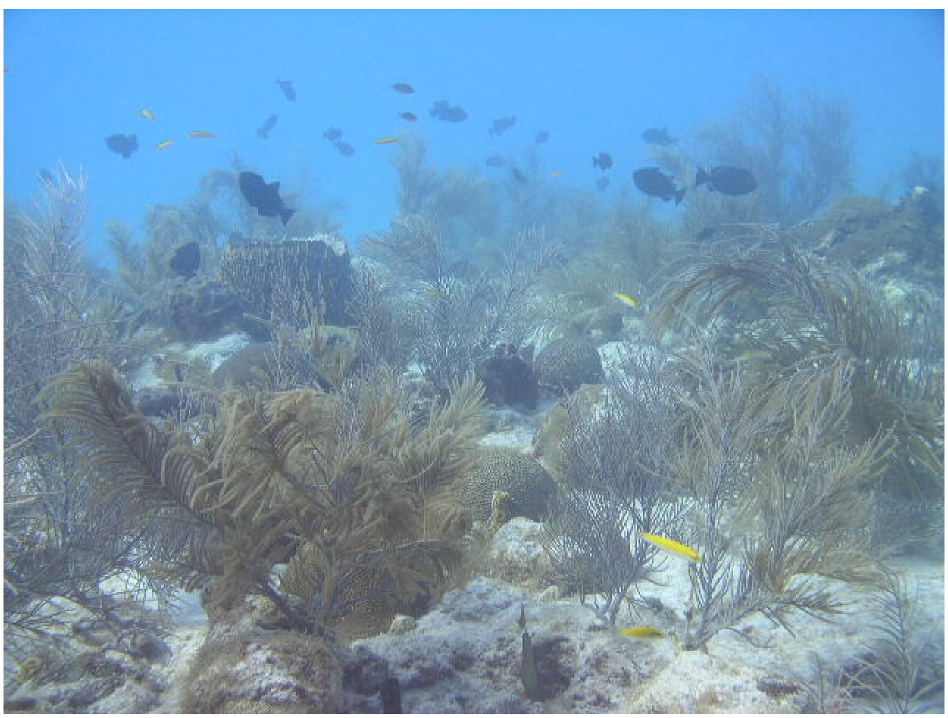
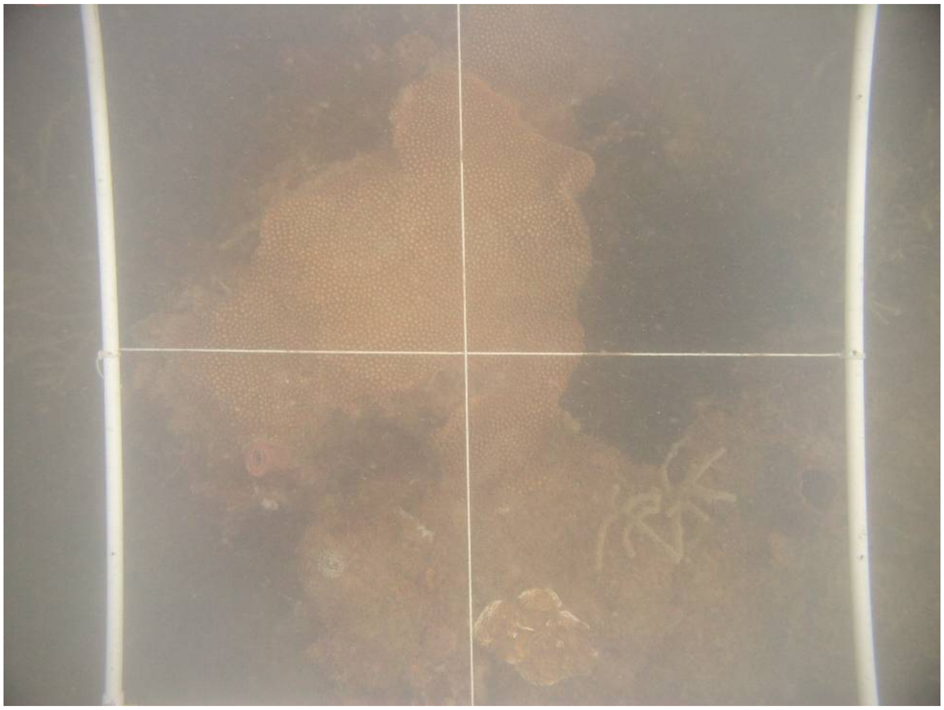
Appendix: Representative underwater photography from some of the study sites.

Rugosity measurements in Mona Island



Hardground in Mona Island

Manchas Interiores



Rodriguez Reef

Fanduco Reef

Boya Verde

Cardona

Tasmania