Sediment Stress, Water Turbidity, and Sewage Impacts on Threatened Elkhorn Coral (*Acropora palmata*) Stands at Vega Baja, Puerto Rico

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ABSTRACT

Poorly implemented beach renourishment activities and increasing raw sewage pollution from local storm sewers and other non-point sources have significantly impacted coral reef communities at the candidate Vega Baja Submarine Gardens Natural Reserve, Puerto Rico. There have been recurrent violations to legal water turbidity and microbiological water quality standards. Percent living cover of threatened Elkhorn coral (*Acropora palmata*) across six reefs declined by 29% within 1997 and 2008, for an annual mean loss of 2.65%. But mortality rocketed to 52% between December 2008 and June 2009 across the zone following beach renourishment and recurrent raw sewage spills. Mortality was lower at outer reefs with stronger oceanographic circulation (34-37%), in comparison to reefs located inside the shallow platform, closer to the shoreline (52-69%), or closer to polluted areas (81-97%). Massive coral mortality at Vega Baja produced a significant phase shift in community structure in many of the sites from dominance by *A. palmata* towards dominance by non-reef building benthic categories (i.e., algal turf, recently dead corals, and dead corals with algae). Recurrent sediment bedload from adjacent renourished beaches, as well as turbid and sewage-polluted runoff pulses, were devastating to Elkhorn coral stands. These violations to existing State and Federal regulations must be prevented in order to prevent further degradation of these highly vulnerable communities, as well as the continuous decline of its ecosystem resilience, functions and services. There is a need to designate the area as a Natural Reserve, and to develop and implement an integrated coastal-zone management plan with emphasis in protecting one of the largest remaining *A. palmata* stands in Puerto Rico and the northeastern Caribbean.

KEY WORDS: *Acropora palmata*, Puerto Rico, sediments, sewage, turbidity

Estrés Sedimentario, Turbidez del Agua e Impactos de Aguas Usadas sobre las Poblaciones del Coral Amenazado Cuerno de Alce (*Acropora palmata*) en Vega Baja, Puerto Rico

Las actividades pobremente implementadas de realimentación de playas y el incremento en la contaminación por aguas usadas crudas provenientes de puntos de descargas de escorrentías pluviales y de otras fuentes dispersas han impactado significativamente las comunidades de arrecifes de coral del área candidata a Reserva Natural de los Jardines Submarinos de Vega Baja, Puerto Rico. Se han documentado violaciones recurrentes a los límites legales para la turbidez del agua y para su calidad microbiológica. El porcentaje de cobertura del coral amenazado cuerno de alce (*Acropora palmata*) a través de seis arrecifes de coral disminuyó por una magnitud de 29% entre 1997 y 2008, para una pérdida promedio anual de 2.65%. Sin embargo, entre diciembre de 2008 y junio de 2009 la mortalidad de corales fue de 52% posterior a eventos de realimentación de playas, seguidos de eventos recurrentes de descargas de aguas crudas. La mortalidad fue menor en aquellos arrecifes más distantes de la costa, sujetos a una circulación oceanográfica más fuerte (34 - 37%), en comparación a aquellos arrecifes localizados dentro de la plataforma llana, más cercanos a la costa (52 - 69%), o aquellos más cercanos a las áreas contaminadas (81 - 97%). La mortandad masiva de corales en Vega Baja resultó en un cambio de fase significativo en la estructura de la comunidad en muchas de las localidades donde la dominancia por *A. palmata* cambió a una dominancia por categorías bénticas no constructoras de arrecifes (ej. céspedes de algas filamentosas, corales recién muertos, corales muertos cubiertos por algas). Los eventos recurrentes de corridas horizontales de sedimentos provenientes de playas realimentadas, así como aquellos de escorrentías turbias y contaminadas por aguas usadas resultaron devastadores para las poblaciones del coral cuerno de alce. Dichas violaciones a leyes estatales y federales deben prevenirse si se pretende prevenir una degradación adicional de estas comunidades altamente vulnerables, así como la pérdida continua de la resiliencia, funciones y servicios del ecosistema. Resulta necesaria la designación del área como una Reserva Natural, así como el desarrollo e implantación de un plan de manejo integrado de la zona costera, con énfasis en la protección de uno de los más grandes remanentes poblacionales de *A. palmata* en Puerto Rico y en el norestes del Caribe.

PALABRAS CLAVE: *Acropora palmata,* Puerto Rico, sedimentario, aguas usadas, turbidez

Les Activités de Construction de Digue Causent une Mortalité Massive Localisée du Corail Corne d'élan (*Acropora palmata*), Espèce Menacée, à Vega Baja, Puerto Rico

MOTS CLÉS: *Acropora palmata,* Puerto Rico, mortalité

INTRODUCTION

A wide variety of anthropogenic activities on coastal habitats or adjacent to these are frequently dismissed as having non-significant environmental impacts. Often many of them are also approved and implemented under supposed premises of emergency situations, often by-passing full analysis of environmental impacts and analysis of alternatives. These may typically include activities such as beach erosion control measures, the construction of storm sewers along the coast, water diversion projects near estuarine environments, filling and beach renourishment activities, among many others. In many of these instances, potential direct, indirect, acute, cumulative and long-term impacts on adjacent coral reef communities are rarely addressed or dismissed as minimal or non-existent. However, coral reef communities along the northern coast of Puerto Rico (PR) have witnessed extensive historical impacts from a significant number of human stressors (Hernández-Delgado 2000, 2005), including areas supporting Federal designated critical habitats (DCH) under the Endangered Species Act (ESA) of threatened Elkhorn coral, *Acropora palmata*, and Staghorn coral, *Acropora cervicornis*).

Vega Baja Beach is located at approximately 30 km west of San Juan, along the northern coast of PR (Figure 1). This area still supports outstanding high-energy coral reef formations dominated by linear coral reefs, colonized pavements with channels, colonized bedrock, and scattered coral rocks atop of extensive eolianite platforms intermingled with limited seagrass beds and sandy bottoms. These constitute a primary essential fish habitat for a myriad of commercially-important fish and invertebrate species. Also, reef bottoms down to the 20 m depth contour constitute part of the DCH for *A. palmata* and *A. cervicornis*. The most significant and unique natural feature of these high-energy northern coast reef communities is the presence of impressively dense thickets of *A. palmata* (Figure 2). However, Vega Baja Beach has been recently subjected to recurrent impacts by a sort of acute anthropogenic environmental stressors, including recurrent beach renourishment activities at nearby Playa Puerto Nuevo, illegal dumping of raw sewage along the coast, recurrent turbidity pulses from non-point source runoff, from flooding events from the nearby Cibuco River mouth, and from continuous sediment resuspension from wave action and its backwash impacting an adjacent rip-rap that was built to protect the shoreline from erosion.

Recurrent beach renourishment activities that commenced at the end of 2008 and extended at least towards February, 2009 resulted in substantial localized dredging and modification of the shoreline at Playa Puerto Nuevo, at the eastern end of Vega Baja Beach. There was an extensive operation of heavy machinery within the tidal and subtidal zones, without the mandatory implementation of management measures to prevent resuspended sediments and turbid waters to impact adjacent areas. Therefore, extensive sediment bedload and turbid water plumes moved downstream east to west impacting adjacent coral reefs. These types of impacts have had significant negative impacts on both coral reef benthic and fish communities elsewhere (Lindeman and Snyder 1999). Also, chronic raw sewage pollution from point and non-point sources occurred at Vega Baja at least during 2008 and 2009, as well a major illegal and intentional spill of an unknown volume of a mixture of raw sewage and mud at the end of 2008 associated to a sewage pipe reconstruction project along state road PR-686, which is located parallel to the shoreline. Sewage spills immediately reached adjacent reefs due to the prevalent east-west drift. Raw sewage has been largely acknowledged to produce severe impacts on reef communities, including contamination by poisonous or corrosive chemicals, detergents and degreasing agents, chlorine, solid material, and increased pathogenic microbial inputs (Barnes 1973). Sewage can also represent significant inputs of nutrients and partially degraded organic matter into receiving waters (Srinath and Pillan

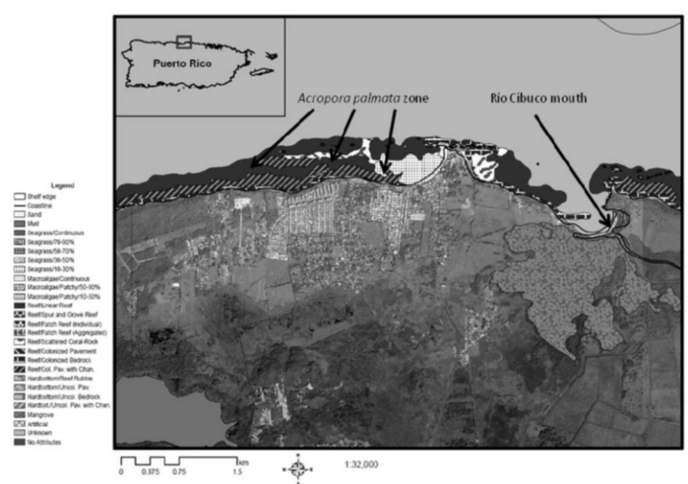

Figure 1. Study site at Vega Baja, PR.

1966), largely impacting coral reef communities (Walker and Ormond 1982, Pastorok and Bilyard 1985, Cloern 2001).

Beach erosion has also been a major chronic problem along some portions of the Vega Baja coast and has resulted in significant property destruction. As a result, during 2007 a rocky rip-rap was constructed at Puerto Nuevo beach to reduce increasing erosion threats to state road PR-686. However, this solution has triggered further *in situ* erosion problems, as well as along nearby shorelines. Backwash effects of crashing waves on the rip-rap have resulted in the net loss of sand due to increased benthic erosion effects and sediment bedload. It has also increased fine sediment resuspension, causing a nearly permanent state of very high turbidity, which has in turn increased impacts to adjacent reefs due to the east-west littoral drift, and has contributed to the resuspension and movement of sewage pollution towards adjacent coral reef ecosystems.

In spite of the importance of these coral reef habitats as fish nursery grounds, and as one of the few remnant source populations and key genetic link for the population connectivity of *A. palmata* across the northeastern Caribbean, there is very limited available information regarding their actual ecological conditions. This coral species has largely disappeared from many locations across PR and the wider Caribbean region (Weil et al. 2003). There is also a lack of known information regarding how much have local coral reefs been impacted by these activities through recent time. The objectives of this study were to:

i) Determine if there were significant signs of sediment stress, turbidity and sewage pollution along the Vega Baja coast during 2009; and
ii) Determine if there was any significant temporal change in coral reef conditions at Vega Baja between 1997 and 2009 that could have been associated to any localized anthropogenic stressor.

METHODS

Study Sites

This study was carried out along six *A. palmata*-dominated coral reef patches along the 250 m-wide shallow -water eolianite platform along the Vega Baja coast (Figure 1). These included two offshore sites: Tractores east (TRA-E) and Hawaii thicket (HI-TH); two mid-platform sites: El Eco (ECO) and Tractores west (TRA-W), and two inshore sites: Las Pozas (POZAS) and Afropoint (AF-FR). Water quality studies (Figure 3) were conducted at 8 sites, with six of those at Vega Baja: Cibuco River (CIB), Playa Puerto Nuevo east (BAL-E) and west (BAL-W), El Malecón (MAL), Las Pozas (POZ), and El Eco (ECO), and two control sites at Manatí: Los Tubos (TUB) and Mar Chiquita (MCH). These were located west of Vega Baja.

Water Quality Sampling

Water turbidity was measured twice (February, May 2009) in triplicates in 20 mL vials at approximately 15 - 18 random points across a distance gradient from known point sources of pollution located east of the coral reef system located between AFR-FR and TRAC-W. Polluted control samples were also collected at MAL and close to Plaza de Los Pescadores (PPE). Samples were measured using a LaMotte 2020e portable turbidimeter. Data was expressed in nephelometric turbidity units (NTU). A baseline characterization of water physical and microbiological quality was also conducted during October and November 2009 at six locations to determine if there were signs of any water quality stress gradient at Vega Baja. Data were

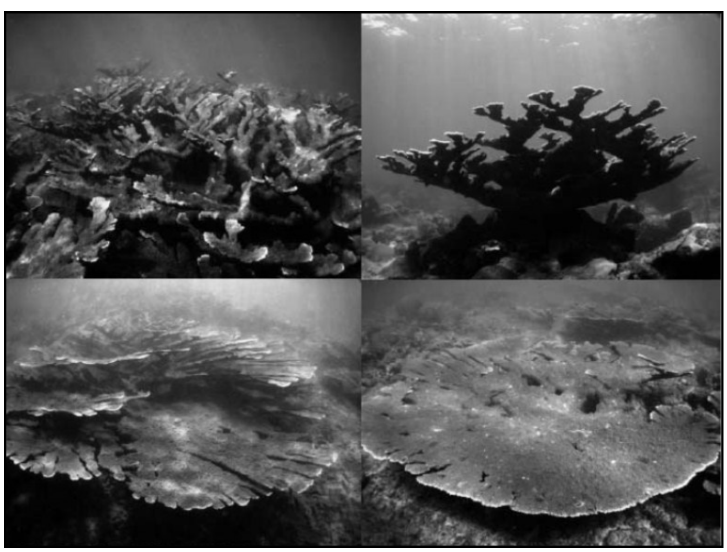

FIGURE 2. Typical stands of threatened Elkhorn coral (*Acropora palmata*) from Vega Baja.

compared to two control sites at Manatí. A YSI 650 MDS multi-parameter was used to document water temperature, pH, salinity, conductivity, dissolved oxygen concentration (data not shown), and turbidity. Microbiological water quality analysis was focused in fecal coliforms (FC) and enterococci (ENT), and followed U.S. Gelogical Survey's Standard Method 9230C (Britton and Geeson 1987). FC were incubated in m-FC at 44.5°C/24 hours and ENT in m-Enterococcus at 41°C/48 hours. Other qualitative documentation of potential impacts to coral reef communities was made by means of pivot diver random swims and high-resolution digital photography during all visits to study sites.

Temporal Patterns of Benthic Coral Reef Community Structure

The null hypothesis of no significant temporal patterns in coral reef benthic community structure was tested by conducting a quantitative survey at five sites in Vega Baja during 1997, and at six sites during 2002, 2008, and 2009. A total of 26 replicate transects were surveyed in 1997 and 32 in 2002 using 25 m-long point count transects. A total of 36 replicate point-count transects were surveyed in 2008 and 56 point-count video-transects in 2009. Each video-transect took roughly 1 minute and was filmed in a planar view, at a rough distance of 75 cm from the reef bottom, parallel to the shoreline, to the reef patch or following depth contours. Five replicate digital images were randomly selected from each transect and analyzed for benthic component cover by projecting 10 randomly-generated dots per image using CPCE v3.5 (Kohler and Gill 2006). This provided a quantitative estimate of percentage cover of all major epibenthic components (i.e., corals, algal functional groups, sponges, zoanthids, dead corals with algae, others). Temporal pattern data was analyzed using combined univariate and multivariate statistical approaches. The null hypotheses of no significant difference in selected benthic community parameters among time and study sites were tested using a one-way analysis of variance (ANOVA) on Statistix 9 (Analytical Software), following Zar (1984). Barlett's test of equal variances was used to test for homosedasticity and the Shapiro-Wilk test was used to test for normality. Data on proportions were transformed to arcsine ($\sqrt{X}$), as described by Zar (1984). Data was subdivided as follows: *Time* (1997, 2002, 2008, 2009), and *Sites*. Replicate transects per sampled site were used as the error term. No interaction analysis was carried out due to the unbalanced nature of the sampling design.

A community matrix was also compiled and imported into PRIMER 6.1 ecological statistics software package (PRIMER-E, Ltd.). Raw proportional cover values were fourth root-transformed in order to appropriately weight the less abundant benthic categories (Clarke and Warwick 2001). Mean data from each site was classified with hierarchical clustering using the Bray-Curtis group average

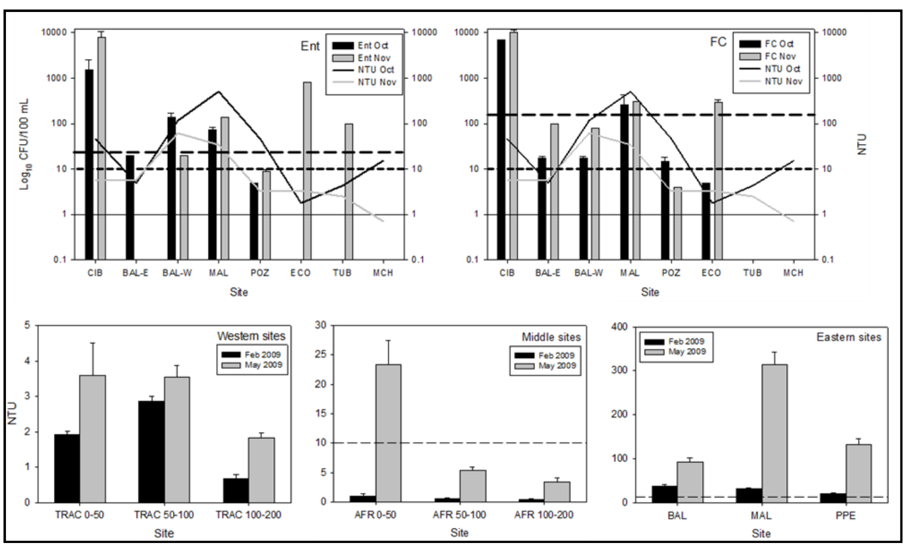

Figure 3. Water quality stress gradients at Vega Baja. From top left: A) Enterococci (ENT) concentrations and water turbidity (NTU); B) Fecal coliform (FC) concentrations and water turbidity; and C, D and E) Water turbidity across a west-east distance gradient along the coastline, from coral reefs at Playa Tractores (Western sites), coral reefs at Afropoint (Middle sites), to Eastern Sites (BAL= Playa Puerto Nuevo bathing zone; MAL=Malecón or rip-rap zone; PPE= Plazoleta de los Pescadores). Long dashed line in Fig. 3a represents ENT standard of 35 CFU/100 mL. Long dashed line in Fig. 3b represents FC standard of 200 CFU/100 mL. Short dashed line represents water turbidity standard of 10 CFU.

linkage method and then ordinated using non-metric multidimensional scaling (MDS). Temporal and site effects were tested using a two-way permutational multivariate analysis of variance or PERMANOVA (Anderson et al. 2008). A pairwise 1-way PERMANOVA was used to test the null hypotheses that there were no differences in the structure of benthic communities between different pairs of years or pairs of sites. Interaction effects between time and sites were also tested. All tests were based on 9,999 permutations and had no built in assumptions about the data distribution. The key taxa responsible for spatial patterns in benthic community structure were determined using a Principal Component Ordination (PCO) (Anderson et al. 2008).

RESULTS

Water Turbidity and Sewage Stress Gradient

There was a strong east-west gradient of sewage pollution along the Vega Baja coast. ENT at CIB reached 1,500 CFU/100 mL during October, followed by BAL-W with 140 CFU/100 mL, and MAL with 73 CFU/100 mL (Figure 3a). ENT rocketed to 8,000 CFU/100 mL at CIB during November, followed by ECO with 800 CFU/100 mL and MAL with 140 CFU/100 mL. ENT standard for coastal waters is 35 CFU/100 mL. Most other samples complied with ENT standards. FC at CIB reached 7,000 CFU/100 mL during October, followed by MAL with 253 CFU/100 mL (Figure 3b). FC averaged 10,350 CFU/100 mL during November, followed by MAL with 300 CFU/100 mL, and ECO with 290 CFU/100 mL. FC standard for coastal waters is 200 CFU/100 mL. Other samples complied with FC standards. These results reflected the presence of a laminar flow of turbid, sewage-polluted water along the east-west littoral drift that crossed out nearly the entire Acroporid coral reef system. Fecal pollution gradient is also consistent with the observed water turbidity gradient. There was a strong east-west gradient of very high turbidity at BAL, MAL and PPE, many of them exceeding by as much as 10 to 50-fold the 10 NTU legal standard for coastal waters in PR (Figures 3c -e). AFR showed moderate to high water turbidity values, with the inshore zone showing a turbidity value in May more than 1-fold higher than the current turbidity standard. Water turbidity at TRAC-E never exceeded legal standards, but mean level exceeded 3 NTU, which, if chronic could be detrimental to corals. These factors impacted reefs also in combination with increased sediment bedload stress that smothered corals, particularly along the inshore zone.

Temporal and Spatial Changes in Coral Reef Communities

Percent living coral cover showed a nearly stable condition between 1997 and 2002 across most sites, with a minor decline detected at 2008, possibly as a result of the unprecedented sea surface warming and massive coral bleaching event in 2005, or possibly as a result of previous undocumented impacts associated to sewage pollution and chronic water turbidity following the construction of the rip-rap at El Malecón in 2007 (Figure 4a). But % coral cover showed a significant decline during 2009 across most sites (Table 1). Living coral cover declined from 1997 to 2009 by a magnitude of 40% at Tra-E, 30% at Hi-Th, 72% at Eco, 51% at Tra-W, 80% at Poz, and 77% at Afr-Fr (2002 - 2009). But, % living coral cover only declined from 1997 to 2008 by a magnitude of 10% at Tra-E, 9% at Hi-Th, 26% at Eco, 25% at Tra-W, and 29% at Poz. Between 2002 and 2008 living coral cover declined by 78% at Afr-Fr. Percent coral cover decline, however, was highly significant between 2008 and 2009, dropping by a magnitude of 33% at Tra-E, 23% at Hi-Th, 62% at Eco, 34% at Tra-W, and 71% at Poz within less than a year following the acute sediment bedload and sewage pollution pulse events. Coral cover at Afr-Fr increased by 5% at Afr -Fr possibly as a result of random variation in the abundance of disturbance-resistance coral species and random variation in transect location. Percent *Acropora palmata* cover also declined from 1997 to 2009 by a magnitude of 37% at Tra-E, 34% at Hi-Th, 69% at Eco, 59% at Tra-W, 81% at Poz, and 97% at Afr-Fr (2002-2009) (Figure 4b). But, % living *A. palmata* cover only declined from 1997 to 2008 by a magnitude of 8% at Tra-E, 9% at Hi-Th, 20% at Eco, 30% at Tra-W, and 28% at Poz. *Acropora palmata* cover, however, declined by 79% at Afr-Fr between 2002 and 2008. Percent *A. palmata* decline, however, was highly significant between 2008 and 2009, dropping by a magnitude of 31% at Tra-E, 27% at Hi-Th, 61% at Eco, 42% at Tra-W, 73% at Poz, and 86% at Afr-Fr. Most of the *A. palmata* mortality resulted from patchy necrosis-like and white pox-like conditions that impacted local reefs following anthropogenic disturbances.

Algal communities also showed significant changes through time. Algal cover in 1997 was low and seasonally dominated by limited green macroalgae and filamentous algal turfs (Figure 4c). By 2002 algal turf dominance increased significantly (Figure 4d). There was also presence for the first time of old dead coral stands with algae (often turf), cyanobacteria and crustose coralline algae (CCA). The presence of old dead corals with algae, cyanobacteria and turf increased significantly by 2008 (Figure 4e). But major changes did occur between 2008 and 2009, with increased dominance by algal turfs, recently dead corals, dead corals with algae, and cyanobacteria (Figure 4f).

Multivariate analysis showed that benthic community structure showed progressive significant variation through time (Table 2) and across sites (Table 3). Elkhorn coral-dominated benthic communities at TRAC-W, TRAC-E, and HI-TH were significantly different from other sites (Table 4). This difference was consistent through time, but temporal changes reflected largely across a distance gradient from the shore, and across a east-west gradient. Principal Component Ordination showed three clustering patterns following a 50% community similarity level: one grouping all reefs from 1997, and most from 2002 and 2008; a second group with part of 2008 and 2009 reefs; and a final cluster composed of highly degraded reefs in 2009 (Figure 5). Benthic communities were dominated in 1997, 2002 and in a large extent during 2008 by *A. palmata*. However, the AFR-FR benthic community was large dominated even since 2002 by macroalgae and turf, suggesting impacts earlier than 2002. With few exceptions, benthic communities following the acute sediment bedload and sewage pollution pulse disturbances between 2008 and 2009 were dominated by old dead coral and recently dead coral stands, cyanobacteria, turfs, and open pavement. This suggests a highly significant phase shift as a result of anthropogenic disturbances.

DISCUSSION

Coral reefs along the Vega Baja coast showed no signs of significant anthropogenic stress between 1997 and 2002, showed minor stress during 2008, but showed substantial impacts and a significant community phase shift during 2009. These changes were coincident with known coral stressing factors such as:

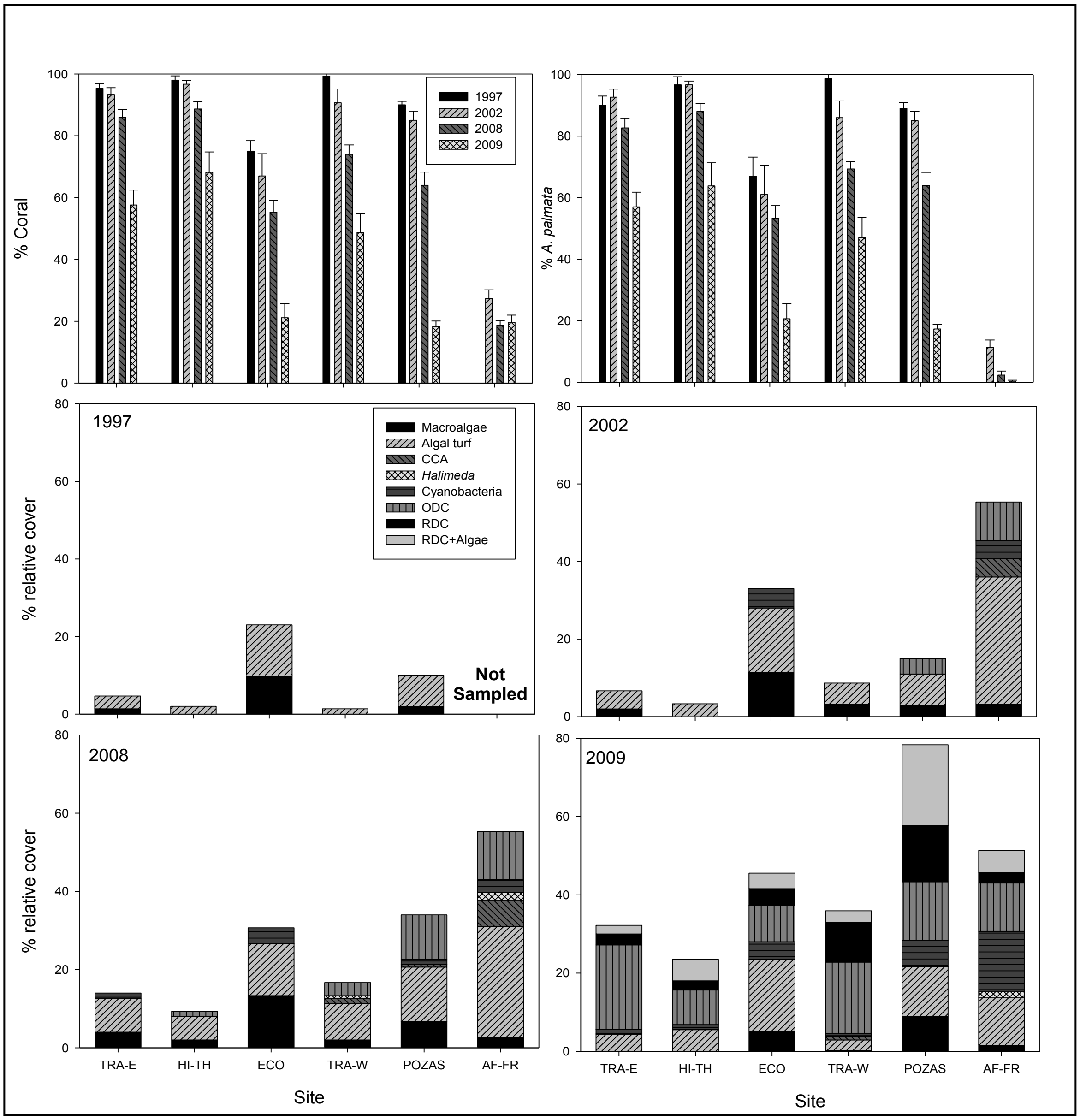

Figure 4. Temporal change in benthic communities. From top left: A) Percent coral cover (mean ± one standard error); B) Percent *Acropora palamta* cover (mean ± one standard error); and percent algal cover through time: C) 1997; D) 2002; E) 2008; and F) 2009; 2008; and F) 2009.

TABLE 1. One-way ANOVA of temporal patterns of benthic community parameters.

Parameter	Time (df = 3,146)	Site (df = 5,144)
% Coral	F=94.64; *p*<0.0001	F=57.43; *p*<0.0001
% *Acropora palmata*	F=80.46; *p*<0.0001	F=84.73; *p*<0.0001
% Total algae	F=6.61; *p*=0.0003	F=32.63; *p*<0.0001
% Macroalgae	F=6.50; *p*=0.0004	F=24.68; *p*<0.0001
% Turf	F=6.47; *p*=0.0004	F=24.00; *p*<0.0001
% Crustose coralline algae	F=1.55; *p*=0.2045 (NS)	F=8.87; *p*<0.0001
% *Halimeda*	F=1.80; *p*=0.1503 (NS)	F=7.12; *p*<0.0001
% Cyanobacteria	F=5.04; *p*=0.0024	F=13.72; *p*<0.0001
% Recently dead coral + algae	F=19.33; *p*<0.0001	F=3.57; *p*=0.0045
% RDC	F=59.55; *p*<0.0001	F=9.23; *p*<0.0001
% Old dead coral	F=59.28; *p*<0.0001	F=3.91; *p*=0.0024

NS= Not significant (*p*>0.05).

i) Local increases in sediment bedload and turbidity associated to recurrent beach renourishment activities at Playa Puerto Nuevo public beach between 2008 and 2009;

ii) Sediment resuspension and increased water turbidity associated to backwash effects from a rip-rap at El Malecón built in 2007;

iii) Local increases in sewage-polluted, nutrient-loaded and sediment-laden turbid runoff pulses from different point and non-point sources; and 4) chronic sewage-polluted pulses from the highly turbid Cibuco River mouth.

There is a nearly continuous strong east-west gradient of highly turbid waters and sediment bedload smothering corals, particularly along coral reefs adjacent to the shoreline. This is continuously maintained due to prevalent littoral drift along the Vega Baja coast and due to continuous wave backwash and sediment resuspension along the existing rip-rap area adjacent to coral reefs. But it was significantly enhanced during recurrent beach renourishment activities at Puerto Nuevo Beach. Sediment deposition might be minimal or high-energy habitats such as Vega Baja's reefs. But sediment bedload abrasive

Table 2. PERMANOVA of coral reef benthic community structure variation through time and across sites.

Parameters	d.f.	Pseudo-F	*p*
Time	3,146	24.42	<0.0001
Site	5,144	14.65	<0.0001
Time x Site	22,127	14.02	<0.0001
Pairwise analysis			
1997 vs. 2002		t= 2.07	0.0150
1997 vs. 2008		t= 4.29	<0.0001
1997 vs. 2009		t= 7.34	<0.0001
2002 vs. 2008		t= 2.08	0.0141
2002 vs. 2009		t= 5.73	<0.0001
2008 vs. 2009		t= 4.77	<0.0001

TABLE 3. PERMANOVA of coral reef benthic community structure spatial patterns through time.

Parameters	d.f.	Pseudo-F	*p*
Sites within 1997	4,21	4.81	0.0003
Site within 2002	5,26	9.59	<0.0001
Site within 2008	5,30	12.42	<0.0001
Site within 2009	5,50	8.58	<0.0001

Table 4. Pairwise PERMANOVA of coral reef benthic community structure spatial patterns across time.

Site	TRA-E	HI-TH	ECO	TRA-W	POZ
TRA-E	-				
HI-TH	NS*	-			
ECO	<0.0001	<0.0001	-		
TRA-W	NS	NS	<0.0001	-	
POZ	0.0038	0.0002	0.0050	0.0012	-
AFR-FR	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

*NS= Not significant (*p*>0.05).

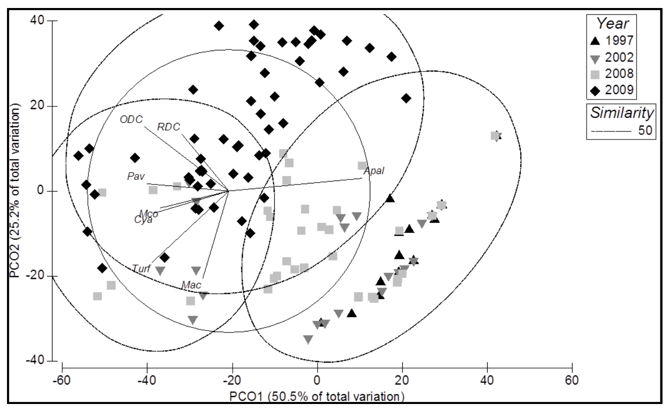

Figure 5. Principal component ordination (PCO) of temporal variation of benthic community structure explains 76% of variation (solution based on correlation factor >0.60). Clustering pattern (dashed ellipsoids) based on 50% similarity level. Apal= *Acropora palmata*, Mac= Macroalgae; Turf= Filamentous algal turf, Cya= Cyanobacteria, Mco= *Millepora complanata*, Pav= Pavement, ODC= Old dead coral, RDC= Recently dead coral.

effects can be substantial and deleterious to corals. There is also a particular concern for potential pollutant resuspension under such conditions. Sediments can have a long-term influence on the structure of coral reef benthic communities (Roy and Smith 1971, Hubbard 1986, Yoshioka and Yoshioka 1989), may smother reef organisms, and reduce light available for photosynthesis (Brown 1997). But sedimentation effects can be highly variable depending on the taxa (Brown and Howard 1985, Rogers 1990), on the local oceanographic conditions, topographic complexity, and on the spatial and temporal scales of impacts. So is the ability of coral reefs to survive and recover from sediment and turbidity stress. Sediment pulses are often discrete events in time and space that can become chronic and/or widespread depending on their frequency and severity. Deforestation, poor land use patterns, coastal development, engineering projects, dredging, construction of rip-raps, beach renourishment and other sort of anthropogenic activities can produce a significant chronic increase in sedimentation rates and/or bedload on coral reefs adjacent to the coast (Loya 1976, Bak 1978, Cortés and Risk 1984). This can result in a widespread increase in the frequency, duration and/or severity of stressful events for corals, and in a reduced time span for coral reefs to recover from recurrent disturbances, therefore resulting in a net long-term phase shift in community structure favoring non reef-building taxa similarly to what has occurred at Vega Baja under a status of nearly continuous sediment bedload stress, increased water turbidity and recurrent sewage pollution.

There was also a similar gradient of raw sewage pollution impacting coral reefs. Local non-point source sewage pollution sources across the Playa Puerto Nuevo area were numerous and included sewage spills from illegal pipes that empty at the beach, illegal connections from private properties to stormwater sewers, broken sewage pipes along road PR-686 by corrosion or by beach erosion, overloaded septic tanks at nearly sea level, and illegal dumping of sewage from septic tank cleaning trucks. Further, the Vega Baja sewage treatment plant effluents empty at Caño Cabo Caribe, which in turns empties to the east at Cibuco River. Caño Cabo Caribe also connects to the west to a system of wetlands that includes Laguna Tortuguero, which is a Natural Reserve. The Vega Baja municipal landfill is also located in the eastern bank of the Cibuco River alluvial plain, further polluting river waters. These also create a chronic stress to local reef systems. Sewage pollution has been shown to potentially extend across large geographic areas across the shelf (Bonkosky et al. 2009), negatively impacting extensive coral reef communities (Hernández-Delgado et al. 2010). Impacts are often associated to eutrophication and turbidity (Pastorok and Bilyard 1985, Cloern 2001), to altered coral-associated microbial community composition (Sekar et al. 2008), to an increased prevalence of Black Band Disease and White Plague-Type II in coral colonies (Kaczmarsky et al. 2005), and to declining coral survival rates (McKenna et al. 2001) and skeletal extension rates (Tomascik and Sander 1985). Sewage impacts often result in a combination of system- and species-specific responses, as well as cascading direct and indirect effects that could result in major long-term phase shifts in benthic community structure, favoring dominance by fleshy macroalgae and non reef-building taxa similar to those observed by Hernández-Delgado et al. (2010) and to those documented in this study. Such phase shifts could be irreversible in long-term scales (Knowlton 1992, Hughes 1994). Sewage-associated eutrophication impacts can also result in an accelerated reef decline often due to a combination of synergistic impacts, mostly from sediments and turbidity (Meesters et al. 1998, Szmant 2002). This combination of factors may explain why some local coral reefs at Vega Baja showed such a rapid phase shift.

CONCLUSIONS

Recurrent pulses of highly turbid, nutrient-loaded, sediment-laden and raw sewage-polluted runoff have unequivocally impacted extensive stands of threatened Elkhorn coral, *Acropora palmata*, as well as sporadic colonies of Staghorn coral, *A. cervicornis* across the Vega Baja coast. These impacts have caused extensive coral physiological stress and massive localized outbreaks of patchy necrosis-like and white pox-like conditions that resulted in extensive coral colony mortalities and physiological colony fragmentation of ESA-protected corals. Also, this resulted in major benthic community phase shifts in designated critical habitats for both coral species. There were recurrent turbidity and pollution impacts from other sources mostly through illegal discharges of raw sewage to the public beach. There were also other pollution sources outside the Puerto Nuevo area, including the Vega Baja sewage treatment plant, the Vega Baja landfield, and other non-point sources that were not addressed as part of this study. These conditions resulted in a major decline of one of the largest and most dense populations of threatened Elkhorn corals across the northeastern Caribbean. This situation requires immediate action from regulatory agencies to prevent further damage to these unprecedented resources. Further, sewage pollution represents a threat to recreational users and deserves immediate attention and further studies.

Recommendations include:

i) Implement mandatory erosion-sedimentation controls on any soil removal and/or beach renourishment activity;

ii) Instead of recurrent beach renourishment or beach destruction by rip-raps, explore the alternative of using semi-artificial reef technology to reduce or modify wave action and/or littoral drift to reduce beach erosion rates;

iii) Cease all illegal sewage dumping from septic tank effluents and other non-point sources at Puerto Nuevo Public Beach;

iv) Prepare an inventory of septic tanks, illegal connections to storm sewers and other illegal discharges. This will be paramount to develop a rapid plan to eliminate all local raw sewage discharges through storm sewers;

v) Review and improve the status of the Vega Baja sewage treatment facilities;

vi) Develop a permanent long-term ecological monitoring program for *A. palmata*, as well as a water quality monitoring program to test for physico-chemical variables and microbiological water quality;

vii) Develop a community-based low-tech coral aquaculture and reef restoration program aimed at propagating *A. palmata* and reintroducing the species at nearby potentially depleted reefs;

viii) Designate the entire area of Vega Baja and at least some areas of Manatí as a Natural Reserves;

ix) Explore alternatives to reduce or eliminate pollution at the Cibuco River watershed; and

x) Develop a community outreach and an educational program for all local and regional technical personnel and decision-makers from government agencies regarding the importance of local coral reef ecosystems.

There is no time to waste and remedial actions are immediately required at Vega Baja if we are up to conserve and restore one of the most significant and beautiful remnant living Acroporid coral reefs in the northeastern Caribbean. Failing to do so may represent an irreparable loss of a significant population of an already severely depleted species through the entire Atlantic. Further, this would be unacceptable in face of current and forecasted climate change impacts. The combination of climate-related effects and uncontrolled local anthropogenic stressors would be devastating for these coral reefs in the near future.

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