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Impacts of non-point source sewage pollution on Elkhorn coral, *Acropora palmata* (Lamarck), assemblages of the southwestern Puerto Rico shelf

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Abstract. Non-point source sewage pollution represents a major threat to coral reefs. Impacts are typically associated with chronic eutrophication, water turbidity, and microbes potentially pathogenic to corals. Sewage pollution can produce variable system- and species-specific responses, as well as cascading direct and indirect effects, that could result in major long-term phase shifts in coral reef benthic community structure. This study was aimed at characterizing the ecological condition of eight shallow-water (<5 m) Elkhorn coral (*Acropora palmata*) assemblages located across a non-point source sewage pollution gradient along the southwestern Puerto Rico shelf. Non-point source pollution was a key stressor structuring local coral reef communities. Long-term phase shifts have favored dominance by macroalgae and non reef-building taxa at inshore locations under chronic pollution. Non reef-building taxa correlated with fecal pollution indicators. *Acropora palmata* and crustose coralline algae (CCA) are dominant at offshore remote reefs. Coral reef degradation is already beyond the point of recovery at most inshore habitats. Coral reef communities within local Marine Protected Areas were also undergoing significant degradation as a result of variable impacts, including non-point source sewage pollution. There is a paramount need to implement adequate management measures to prevent further water quality degradation across the region.

Key words: *Acropora palmata*, Coral reefs, Non-point source sewage pollution, Puerto Rico

Introduction

Marine non-point source sewage pollution is a major cause of concern in coral reef communities. Negative sewage impacts have been mostly associated to eutrophication and turbidity (Pastorok and Bilyard 1985; Cloern 2001). Kaczmarsky et al. (2005) also documented a high prevalence of Black Band Disease and White Plague-Type II in coral colonies exposed to sewage. Coral survival rates (McKenna et al., 2001), as well as reef-building activity (i.e., skeletal extension rates), are highly susceptible to sewage impacts, although effects seem to be species-specific (Tomascik and Sander 1985; Spencer-Davies 1990). 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. 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 sedimentation and turbidity (Meesters et al. 1998; Szmant 2002), as well as to recurrent pulses of increased biological oxygen demand and declining dissolved oxygen concentration that can create a hypoxic condition in coastal waters (Desa et al. 2005).

Sewage impacts can produce a major decline in the socio-economic value of coral reefs and associated communities due to the loss of ecological services (i.e., coastal protection, sinkhole of greenhouse gases, food-protein production, source of bio-active compounds), and reef aesthetics (i.e., SCUBA, snorkeling, educational excursions). Declining reefs may also represent a permanent phase shift to fisher community livelihoods and a loss of cultural heritage. Sewage has been previously implicated in coral reef degradation in Puerto Rico (Goenaga and Boulon 1992; Hernández-Delgado 2000, 2005). In spite of that, there is very limited information regarding the impact of non-point source sewage pollution in benthic community structure in coral reefs, particularly in highly susceptible species such as Elkhorn coral, *Acropora palmata*.

This study aimed at characterizing the ecological condition of eight shallow-water (<5 m) *A. palmata* assemblages located across a non-point source sewage pollution gradient along the southwestern Puerto Rico shelf. This species constitutes one of the most significant reef-builders in the Atlantic, but their populations have declined by an estimated 97% during recent decades through the region, including Puerto Rico, due to a combination of natural and anthropogenic factors (Hernández-Delgado 2000; Weil et al. 2003). Elkhorn coral was designated in May 2006 as a threatened species under Endangered Species Act 4d rule.

Materials and methods

Studies were conducted at eight coral reefs located along a non-point source sewage pollution gradient across the southwestern Puerto Rico shelf (Fig. 1). Sampling was limited to shallow reef assemblages (<5 m).

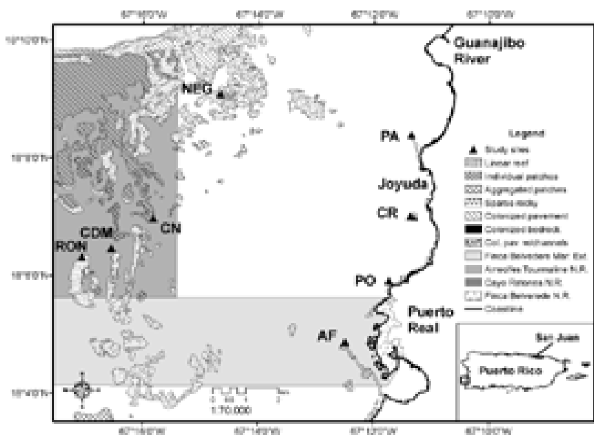

Figure 1. Coral reef study sites: Arrecife Fanduco (AF), Punta Ostiones (PO), Cayo Ratones (CR), Punta Arenas (PA), Arrecife El Ron (RON), Cayo del Medio (CDM), Corona del Norte (CN), and El Negro (NEG).

Sites were arranged into two different geographic regions (inshore, offshore). Inshore reefs (<0.5 km) included AF, PO, CR, and PA (see Fig. 1 for acronyms). Offshore sites (>0.5 km) included RON, CDM, CN, and NEG. Sites were further arranged within two management categories (MPA, non-MPA controls). MPA sites included RON, CDM, CN, CR, and AF. The first three lie within the Tourmaline Natural Reserve. Cayo Ratones is located within the Cayo Ratones and Adjacent Waters Natural Reserve, while Arrecife Fanduco is located within the Finca Belvedere Natural Reserve Marine Extension. These are managed by the PR Department of Natural and Environmental Resources (DNER). Non-MPA control sites included NEG, PO, and PA.

Six replicate 10 m-long linear transects were haphazardously sampled at each site in February 2006. Five replicate non-overlapping 1 m^2 quadrats were haphazardously photographed along each transect using digital photography. Images were corrected for brightness and contrast, and analyzed using CPCE 3.4 software (CPCe, Kohler and Gill 2006), FL. Twenty replicate randomly-generated counting points were projected over each image and used to quantify the proportion of benthic categories. Hard coral (scleractinian + hydrocoral) data was also used to calculate coral species diversity index (H'n) and evenness (J'n).

Community parameter data were analyzed by means of one-way analysis of variance (ANOVA) to test the null hypotheses of no significant site, geographic location, and management regime effects in coral reef benthic community parameters. Significant differences were identified using Tukey's test for comparisons of means. Relationships between benthic community parameter data and data about water microbiological and physical quality obtained from Bonkosky et al. (2008) were analyzed by means of a Pearson correlation analysis. Data on coral species richness and colony abundance were √-transformed, and data on the proportion of % benthic components cover were *arcsin*-√-transformed to reduce variance (Zar 1984).

Community matrices were analysed in PRIMER 6.0 (Clarke and Warwick 2001). Hierarchical clustering usin the Bray-Curtis similarity and group average linkage method (Bray and Curtis 1957) as well as non-metric multidimensional scaling (MDS) and principal components analysis (PCA) were used. Spatial variation was tested using one-way ANOSIM (analysis of similarities). Interaction effects were tested using a two-way crossed ANOSIM. Key taxa responsible for spatial variation were determined using SIMPER and PCA.

Results

Site effects

Mean coral species richness per transect was significantly higher (p=0.0035) at CN (Table 1; Fig. 2). Significantly lower coral species richness occurred at reefs subjected to hurricane disturbance and macroalgal overgrowth due to Guanajibo River influences (i.e., RON), and at inshore reefs subjected to frequent pulses of non-point source pollution. Colony abundance showed a highly significant (p<0.0001) gradient that followed non-point source pollution influences, with a mean higher abundance at offshore sites (Fig. 2). Percent hard coral cover and % *A. palmata* also followed a similarly significant trend (p=0.0004; p<0.0001) (Fig. 3). Percent cover of threatened Elkhorn coral, *A. palmata*, followed a similar trend with a highly significant ($p<0.0001$) abundance at offshore remote sites. Living elkhorn corals were completely absent from PA, PO, and AF. These locations were subjected to chronic pulses of non-point pollution and high turbidity.

Table 1. Summary results of one-way ANOVA analysis of coral reef community parameters among sites (d.f.= 7, 33), between geographic locations (d.f.= 1, 39), and between management regimes (d.f.= 1, 39). NS= not significant

Parameter	Sites *p*	Loc. *p*	Management *p*
Species richness	0.0035	NS	NS
Colony abundance	<0.0001	<0.0001	NS
% Coral	0.0004	0.0001	NS
% *A. palmata*	<0.0001	0.0001	0.0462
H'n	NS	NS	NS
J'n	NS	NS	NS
% Octocoral	<0.0001	0.0012	NS
% Sponges	0.0123	0.0012	NS
% Zoanthids	<0.0001	NS	0.0475
% Macroalgae	<0.0001	<0.0001	NS
% CCA	<0.0001	<0.0001	NS
% Cyanobacteria	<0.0001	NS	<0.0001
% SPR	0.0003	0.0194	NS

Percent octocoral cover resulted significantly higher ($p<0.0001$) at AF and PO, and significantly lower at CDM and NEG. There was a major difference in species composition among sites, with *Pseudopterogorgia* spp., and *Plexaura* spp. being dominant at inshore polluted sites, and *Gorgonia* spp. being more abundant at offshore sites. Sponges were significantly ($p=0.0123$) more abundant at CDM. Zoanthid *Palythoa caribbaeorum* showed a wide geographic distribution, but at low benthic dominance. *Zoanthus sociatus* was significantly dominant at PA ($p<0.0001$).

Percent macroalgal cover showed a highly significant ($p<0.0001$) % cover under turbid and hypertrophic conditions at CR and PO (Fig. 4). Offshore reefs exhibited moderate abundance of macroalgae possibly as a combination of occasional

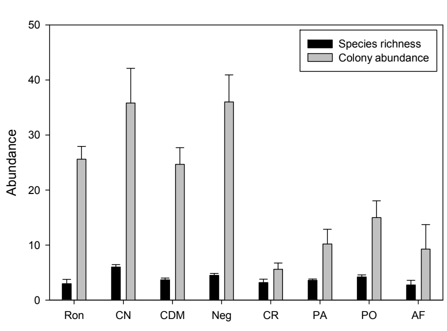

Figure 2. Hard coral species richness and colony abundance.

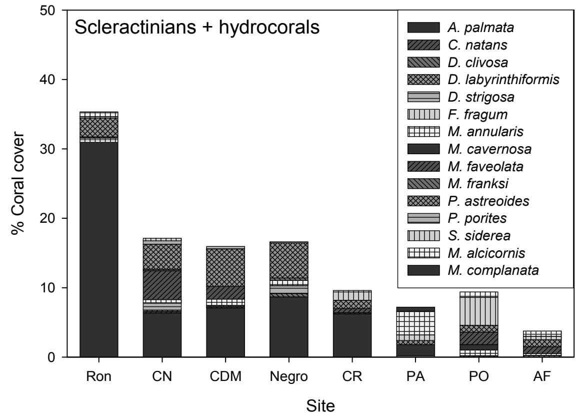

Figure 3. Percent scleractinian and hydrocoral cover.

pulse impacts by Guanajibo River plume and overfishing that has partially depleted large herbivore fish guilds (Hernández-Delgado, pers. obs.). Percent CCA cover was significantly higher ($p<0.0001$) at offshore remote sites. Mean lower CCA values coincided with dominance by macroalgae and other non reef-building taxa and were observed at inshore polluted sites. Percent cyanobacterial cover resulted significantly higher ($p<0.0001$) at NEG (Fig. 4), suggesting potential eutrophication pulses associated to the Guanajibo River plume and tidal flushing from polluted Mayagüez Bay. Recently dead corals (RDC) consistently accounted for 3-4% of benthic percent cover of non-living categories at offshore sites, and fluctuated from 1 to 5% at inshore reefs. RDC were largely attributed to the 2005 Caribbean-wide mass coral bleaching event that was followed by extensive coral mortalities until at least mid-summer of 2006 (Hernández-Delgado et al., unpub. data). About 50% of the sampled sites still showed bleached coral colonies at the moment of sampling, including AF (6%), CN (8%), CR (15%), and PO (17%). Further, 5% of the coral colonies at PO and AF were infected by white plague-like disease/syndrome conditions similar to the one that caused massive mortalities across the northeastern Caribbean reefs.

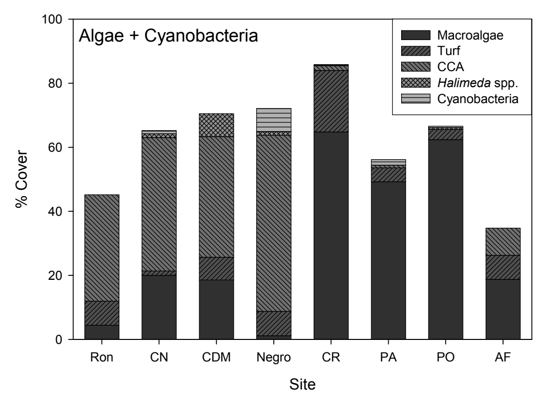

Figure 4: Percent algal and cyanobacterial cover.

Spatial patterns among sites

Two basic clustering patterns of the benthic community structure emerged from MDS analysis at the 50% community similarity cutoff level between inshore and offshore sites (Fig. 5). Four clusters emerged at the 60% cutoff level. Such patterns resulted from macroalgal, octocoral and zoanthid dominance at inshore reefs, and from coral and CCA dominance at the offshore reefs. Spatial patterns of benthic community structure were significantly different among sites (p=0.0002) (Table 2). CCA explained most of the spatial variation among sites (28.6%), closely followed by macroalgae (25%). *A. palmata* explained 14.3% of the variation,

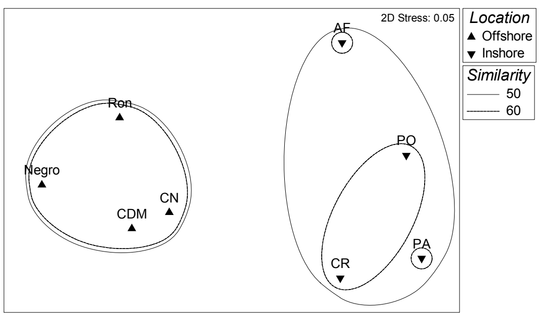

Figure. 5. MDS analysis of the community structure of shallow-water coral reef benthic communities among sites.

while *Pseudopterogorgia* spp. and *Zoanthus sociatus* explained 10.7% of the variation, each one. Spatial patterns were further suggested through PCA analysis, with *A. palmata* and CCA explaining most of the variation at offshore sites. Macroalgae and *Zoanthus sociatus* explained most of the variation at inshore sites, while *Pseudopterogorgia* spp. explained most of the variation at AF.

Spatial patterns between geographic locations

Offshore coral reefs showed significantly higher coral colony abundance (p<0.0001), % coral cover (p=0.0001), and % cover of *A. palmata* (p=0.0001)

Table 2. Results of ANOSIM test for significant differences of coral reef epibenthic community structure. Data was √x-transformed. Based on 5,000 permutations. NS= not significant.

Parameter	Global R	*P* value
One way ANOSIM		
Site	0.725	0.0002
Geographic location	0.875	0.0269
Management regime	0.052	0.3710 NS
Two way crossed ANOSIM		
Site x Location	0.512	0.0012
Site x Management	0.480	0.3333 NS
Location x Management	0.097	0.1300 NS

(Table 2). Also, sponges (p=0.0012), CCA (p<0.0001) and Sand/Pavement/Rubble (SPR) (p=0.0194) were significantly higher in offshore reefs. Octocorals (p=0.0012) and macroalgae (p<0.0001) were significantly higher at pooled inshore locations. Coral reef benthic community structure was significantly different (p=0.0269) between geographic locations (Table 2). CCA explained 14.3% of the variation between locations, followed by macroalgae (10.9%), *A. palmata* (7.5%), *Pseudopterogorgia* spp. (6%), and *Plexaura* spp. (4%). There was a significant site x location interaction (p=0.0012).

Spatial patterns between management regimes

Most parameters showed no significant differences between MPAs and non-MPA sites (Table 2). One exception was % cover in *Acropora palmata* that showed significantly higher % cover within MPA sites (p=0.0462), particularly, within Tourmaline Natural Reserve. Percent zoanthid cover (p=0.0475) and % cyanobacteria (p<0.0001) resulted higher within non-MPA control sites. Coral reef benthic community structure showed no significant difference between management regimes (Table 2). CCA explained 11.2% of the variation in benthic community structure between management regimes, followed by macroalgae (9%), *A. palmata* (8.6%), *Pseudopterogorgia* spp. (6%), and *Zoanthus sociatus* (4%). These results revealed that impacts of non-point source pollution have not discriminated between management regimes, further implying that pollution pulses can potentially affect widespread geographic areas and that current management measures have had no impact on water quality.

Relationship of coral reef community parameters and non-point source fecal pollution

A Pearson correlation analysis revealed several significant correlation patterns with microbial parameters obtained from a simultaneous study by Bonkosky et al. (2008). Zoanthids and cyanobacteria (r>0.95, p<0.01) were strongly correlated with enterococci counts, suggesting their dominance under hypertrophic, fecal-polluted conditions. Macroalgal cover was significantly correlated (r=0.94, p<0.02) to the frequency of *Bacteroides* GB32 molecular marker. *Bacteroides* is an anaerobic microorganism that grows in human and other warm-blooded animals gut. Therefore, its presence in environmental samples reveals a recent fecal pollution event. Macroalgae showed a marginally significant relationship (r=0.87, p=0.053) with *Bacteroides* molecular marker HF183. This probe is specific for human-derived fecal pollution. This suggests that inshore coral reefs were subjected to non-point source sewage pollution, mostly from human sources.

Discussion

There is unequivocal evidence that coral reefs along a significant portion of the southwestern Puerto Rico shelf are being significantly impacted by non-point source sewage pollution, mostly from human origin (Bonkosky et al. 2008). The historical combined and cumulative impact of natural factors (i.e., hurricanes), with long-term pollution pulses, and other potential anthropogenic reef degrading factors, such as sedimentation pulses and overfishing, have contributed to a dramatic phase shift in coral reef community structure. They have favored dominance by macroalgae and non reef-building taxa. Current MPA management activities have had no significant impact on the status of coral reef benthic communities. The spatial extent of non-point source sewage pollution can be frequently underestimated due to failure to detect fecal pollution or due to the lack of water quality monitoring. But recurrent pulses can be a major long-term threat to coral reefs in face of climate change and need to be addressed.

Conclusions

Most inshore coral reefs along the southwestern Puerto Rico shelf have significantly degraded at such a magnitude that recovery may never occur in a human time scale. Stronger efforts are needed to prevent further degradation of remote reefs through the region. There is an immediate need to implement a sound management strategy to reduce and/or prevent non-point source sewage pollution impacts in coral reefs before we witness an ecological and socio-economic collapse. Controlling and managing pollution will require a definite strong political will and commitment in the government of Puerto Rico aimed at establishing stringent controls over land use patterns and over land-based pollution. Failing to recognize and manage non-point source sewage pollution may result in further loss of remote reef systems along the Puerto Rico shelf that are already showing the early signs of degradation.

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