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ScienceDirect
Estuarine, Coastal and Shelf Science 76 (2008) 14–20
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Gradients in coral reef communities exposed to muddy river discharge in Pohnpei, Micronesia

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Received 24 May 2007; accepted 14 June 2007
Available online 30 July 2007

Abstract

This study analyzed how coral communities change along a gradient of increasing exposure to a mud-discharging river in the Enipein Catchment, Pohnpei, Micronesia. Using video transects, we quantified benthic communities at five sites along a gradient moving away from the river mouth towards the barrier reef. The most river-impacted site was characterized by a high accumulation of mud, low coral cover and low coral diversity. Although coral cover leveled off at ~400 m from the river mouth to values found at the outer-most sites, coral diversity continued to increase with increasing distance, suggesting that the most distant site was still impacted by the river discharges. Fungiidae, *Pavona*, *Acropora*, *Pachyseris* and *Porites rus* all significantly increased in cover with distance from the river, while *Turbinaria* decreased. The combined presence and abundance of these six species groups, together with coral species richness, may help to indicate the effects of terrestrial runoff in similar runoff-exposed settings around Micronesia, whereas coral cover is not a sensitive indicator for river impact. Coral reefs are important resources for the people of Pohnpei. To prevent further degradation of this important resource, an integrated watershed approach is needed to control terrestrial activities.

Keywords: corals; coral reef; coral communities; coral diversity; sedimentation; terrestrial runoff; indicator species; Pohnpei; Micronesia

1. Introduction

Coral reefs are the most diverse marine ecosystems on earth (Reaka-Kudla, 1997) and provide essential resources to millions of people living in tropical and subtropical coastal areas (Moberg and Folke, 1999). Despite their importance and value, coral reefs have been declining at an alarming rate in the past few decades due to both natural and human impacts (Wolanski et al., 2003b). Natural disturbances such as storms, volcanic eruptions, river floods, and earthquakes have been shaping reefs for millions of years but reefs are able to recover when water and substratum quality are not degraded. Human impacts, on the other hand, are usually chronic and they degrade water and substratum quality, thus retarding recovery (Wolanski et al., 2003b).

Land clearing for construction and agriculture is continuing to increase worldwide, causing increased runoff and pollution on reefs and coastal marine environments (Fabricius, 2005). Runoff from land affects coral reefs in several ways; it increases the nutrient levels on reefs (both inorganic and particulate organic matter), decreases light levels due to increased turbidity, and increases rates of sedimentation in coral reef areas (Fabricius, 2005). A number of previous studies have addressed the issue of sedimentation effects on reefs (reviewed in Rogers, 1990; Fabricius, 2005). Most of these studies focused on extreme conditions at specific locations where several forms of disturbances may have co-occurred, and often

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doi:10.1016/j.ecss.2007.06.005

compared these with some form of control sites. Fabricius et al. (2007) observed species-specific mortality in coastal reef organisms during an acute sedimentation event in Micronesia, and predicted loss in coral diversity directly caused by the observed sedimentation event. In most cases, however, impacts are rarely directly observed, and data on the condition of coral reefs prior to intensifying land use are unavailable. Also, suitable reference sites often do not exist as few coastal fringing reefs are left in a near-pristine condition.

In the absence of historic data and valid reference sites, we analyzed changes in reef communities along an environmental gradient of decreasing exposure to river influences. This complements previous studies investigating gradients in coral reefs away from a source of terrestrial runoff. Two of these studies focused on regional-scale water quality gradients spanning over scales of tens to >100 km of reefs adjacent to the big land mass of Australia (van Woesik et al., 1999; Fabricius et al., 2005), while one investigated short (~1 km) gradients away from rivers in Okinawa where human population density and organic pollution (indicated by a high biological oxygen demand and suspended particulate matter) were severe (West and van Woesik, 2001).

This paper presents the results of a study to determine how coral reef communities change along a water quality gradient moving away from the mouth of a river in a small island setting in Micronesia. With the current rate of development taking place across most inhabited Indo-Pacific islands, sedimentation into coastal waters continues to increase at an alarming rate (Golbuu et al., 2003; Wolanski et al., 2003a; Victor et al., 2004, 2006). Information on how this development is impacting marine resources is needed to develop sound policy and management strategies. While several studies have demonstrated how improper land use has led to increased erosion and sedimentation around small islands (Golbuu et al., 2003; Wolanski et al., 2003a; Victor et al., 2004, 2006), to our knowledge none have analyzed in detail how, and at what scale, coral reef communities are being affected. Such gradient studies on small islands provide information that will contribute to our understanding of coral reef communities and their potential changes in response to increased terrestrial runoff.

2. Materials and methods

2.1. Study area

The Federated States of Micronesia (FSM) consists of 607 islands, and a long coastline (6112 km) compared with its 702 km^2 of land mass. Pohnpei is the largest and tallest of these islands, measuring about 21 km across with the highest peak reaching 790 m. With an average rainfall of 838 cm yr^{-1} at the highest point of the island, Pohnpei is one of the wettest places on earth. Over 40 rivers run through the forested steep upper mountain slopes down into the lagoon. Most of the nearly circular island is fringed by mangrove forest, while a barrier of coral reefs surrounds much of the lagoon at 2–4 km distance from the coast, with patch reefs found within the lagoon. The Enipein Watershed (Fig. 1), our study area, is approximately 27.2 km^2 area and is located in the southern part of the island. Due to the popularity of sakau (*Piper methysticum*) and the economic gains made by selling it, most of the native forests in this and other catchments of Pohnpei are being cleared for sakau plantations. This has contributed to an increase in sedimentation onto the reefs, with suspended sediment concentrations as high as 100 mg l^{-1} recorded around the reefs during a flood event (Victor et al., 2006).

A detailed physical description of the study area is given by Victor et al. (2006). That study showed that water circulation in the lagoon is complex due to the presence of many patch reefs. The current in the estuary was swift at 0.4 m s^{-1}, but slower in other areas (<0.08 m s^{-1}). Following flood events, freshwater plumes extended into the lagoon and took four days to clear, while sediments cleared within one day. This suggests that the sediments drop out of the freshwater plume onto the coral reef area, rather than being transported out and away from the reefs with the freshwater plumes. Suspended sediment concentrations reached 100 mg l^{-1} following flood events at our Site 3 but was only 5 mg l^{-1} outside of flood events. Victor et al. (2006) showed that rates of sedimentation range from 66 mg cm^{-2} d^{-1} near the river mouth to 35 mg cm^{-2} d^{-1} about 1 km away from the mouth. Since the lagoon is enclosed by a barrier reef, flushing is limited and much of the sediments remain in the lagoon.

2.2. Field sampling and methods

Five sites, each with three replicate stations, were established away from the river mouth. Site 1 was closest to the river mouth and Site 5 farthest away (Fig. 1). At Sites 2, 3 and 4, stations were slightly closer to each other than at Sites 1 and 5 due to the location of the patch reefs that were available along the gradient. However, benthic changes along the gradient away from the river mouth were so strong that the natural configuration of the sites did not obscure the patterns measured. At each station, five 20 m transects were laid on the reef at 3 m depth, with 2–3 m horizontal distance between transects. The substratum type was recorded with an underwater video camera while swimming about 60–70 cm above the transects at a speed of about 2 min per 20 m.

2.3. Data acquisition

In the lab, underwater videos were projected onto a television screen and 40 frames were sampled for each 20 m transect by stopping the video every 2–3 s and identifying benthos under the five fixed sample points on the screen. Cover for the following benthos categories was estimated from these 200 points for each of the 75 transects: abiotic substrata were recorded as carbonate (consolidated, including crustose coralline algae), mud, sand or rubble. The category ‘mud’ was only used if the mud layer was so thick that no other substratum was visible underneath, otherwise the substratum category underneath was recorded. Most hard corals (scleractinia) were distinguished at the genus level where

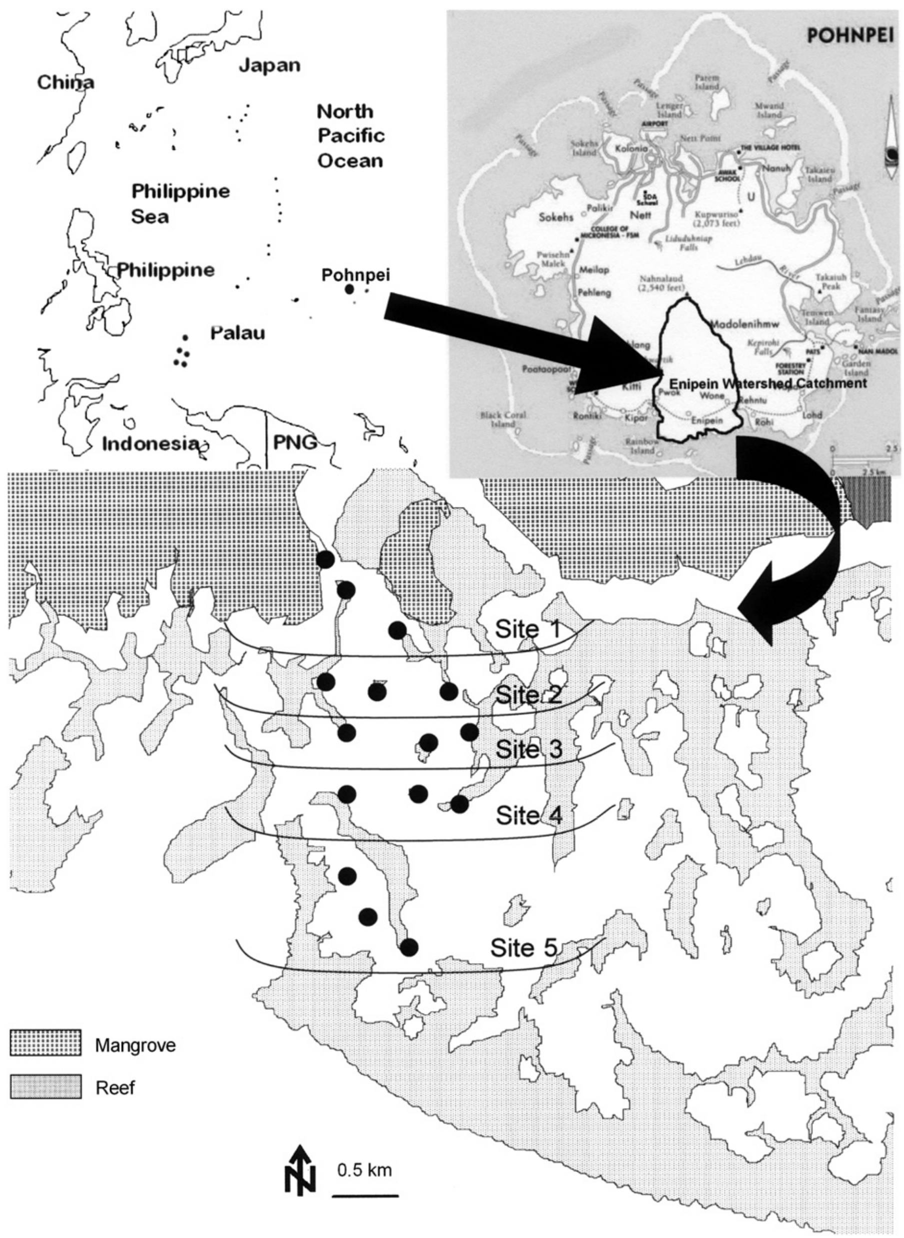

Fig. 1. Map showing location of Pohnpei, the Enipen Watershed, and the location of the study sites on the reef.

possible, while corals in the Faviidae and Fungiidae were recorded at the family level. Within the genus *Porites*, the three abundant taxa, *Porites* (massive), *Porites cylindrica*, and *Porites rus* were recorded separately. An additional separate category was created to record hard corals that were unidentifiable on the video tapes. Other benthic groups recorded were the calcareous green alga *Halimeda*, other macroalgae, soft corals, the calcareous hydrozoan *Millepora*, and sponges.

2.4. Statistical methods

Substratum cover data were averaged across the five transects within each of the 15 stations. Log–linear models were used to assess the changes in cover as a function of distance to the river mouth. Linear and quadratic effects of distance were included in the models and the latter were dropped from the model if non-significant ($P > 0.05$). Over-dispersion was present and thus all effects were assessed against the mean error (deviance). A constrained principal component analysis was used to relate the benthic biota (24 hard coral taxa, algae, soft corals, *Millepora* and sponges) to the environmental data (mud, carbonate, sand, rubble and distance to the river). Data were column standardized to the same maximum, and row standardized to the same mean, to remove variance due to differences in abundances between sites and taxa. Since the ecological gradient was long, extended dissimilarity based on the Manhattan metric was used (De'ath, 1999) rather than Euclidean dissimilarity. Permutation tests (ter Braak, 1992) were used to assess the statistical significance of the environmental variables. Indicator values for each species and each site were calculated based on Dufrene and Legendre (1997), as the product of the mean abundance of species i in the stations of site j compared with all sites, and the relative frequency of occurrence of species i within the stations of site j. Data analyses were conducted using the R statistical package (R Development Core Team, 2005) and S-Plus (Statistical Sciences, 1999).

3. Results

The amount of mud deposition was very high near the river. At Site 1, 56% (±8 SE) of the surface was covered with fine mud (Fig. 2a). At Site 2, mud cover averaged only 0.9% (±0.7 SE), and decreased further after Site 2, with no thick mud layer covering the substrata recorded at any of the stations at Sites 3–5. In contrast, the amount of consolidated carbonate substratum (the preferred settlement substratum of coral recruits) gradually increased from Site 1 (<4 ± 2%) to ∼12% at Sites 2 and 3, and 24–28% at Sites 4 and 5. Both macroalgae and sponges had high cover, but only at Site 5 (16 and 11%, respectively) (Fig. 2a), however, one station at Site 1 also had high sponge cover, with just two species represented.

Hard coral cover was low (7.2 ± 2%) within 400 m from the river mouth, and 30–35% farther away from the river

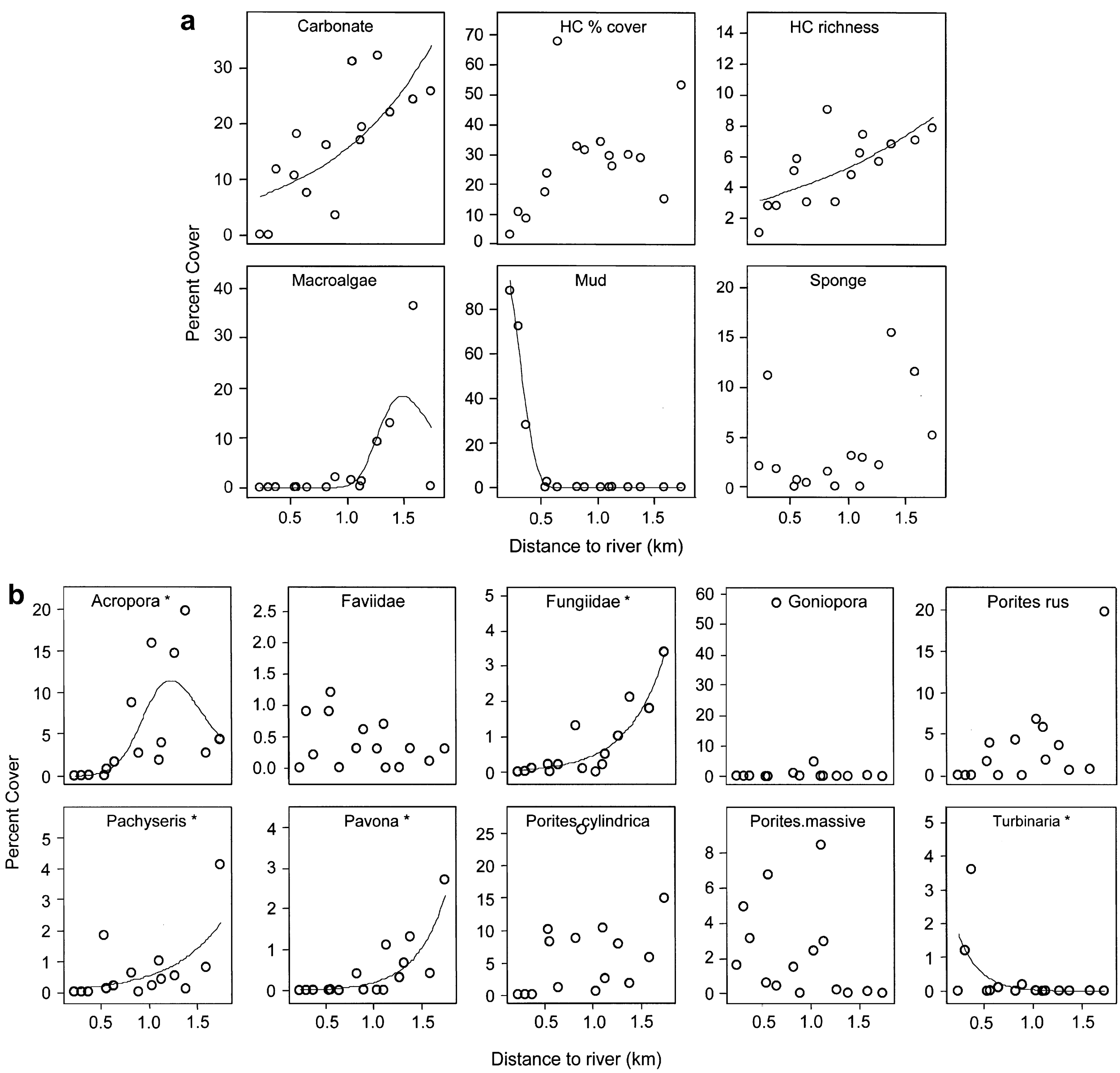

Fig. 2. (a) Percent cover of mud, carbonate, macroalgae, sponge, hard coral cover and hard coral richness plotted against distance to the river. Solid lines are log–linear or quadratic fits by general linear models. The asterisks mark significant correlations with distance to the river. These were significant for the following variables: carbonate ($z = 3.171$, $P = 0.0015$), mud ($z = -4.583$, $P < 0.0001$), $P = 0.0013$), macroalgae ($z = -2.634$, $P = 0.008$), and hard coral richness ($z = 3.487$, $P = 0.0005$). Changes in hard coral cover and sponges were not significant ($P > 0.05$). (b) Changes in the percent cover of selected coral species with increasing distance to the river mouth. Solid lines are log–linear fits (quadratic for *Acropora*) by general linear models. The asterisks mark significant correlations with distance to the river.

(Fig. 2a). There was a strong gradient in hard coral richness away from the river mouth: richness increased more than threefold, from 2.2 ± 0.4 taxa per station at Site 1 to 7.2 ± 0.4 taxa per station at Site 5 (Fig. 2a). Hard coral richness showed no sign of saturation 1.7 km from the river mouth, with no signs of leveling off at the outer end of this study site (Fig. 2a).

An investigation of the distribution of individual hard coral taxa showed that 13 of the 24 species groups had very low abundances at the most impacted sites. Log–linear models showed that of these, five taxa significantly declined in cover towards the river mouth (Fig. 2b). These were the following: *Acropora* spp. ($z_{linear} = 2.84$, $p = 0.004$, $z_{quadratic} = -2.72$, $p = 0.007$), Fungiidae ($z_{linear} = 5.25$, $p < 0.001$), *Pachyseris* spp. ($z_{linear} = 2.72$, $p = 0.007$), *Pavona* spp. ($z_{linear} = 4.24$, $p < 0.001$), and *Porites rus* ($z_{linear} = 2.88$, $p = 0.004$). Five other genera were missing at Sites 1–3, however, they were also uncommon or patchy at greater distances, and therefore changes in their cover were not significantly related to distance (these were the following: *Echinophyllia*, *Galaxea*, *Pectinia*, *Stylophora*, and *Symphyllia*). Furthermore, *Astreopora* and *Oxypora* were missing at Sites 1 and 2, while occurring in low abundances at Sites 3–5. The only taxon that increased in abundance towards the river mouth was *Turbinaria* spp. ($z_{linear} = -2.32$, $p = 0.021$), a genus that is known to be highly tolerant to sedimentation and turbidity. However, *Turbinaria* was found to occur patchily, with moderate cover encountered only at very few stations. Massive *Porites* and *Porites cylindrica* were abundant at many sites throughout the region, and their cover was unrelated to river distance (Fig. 2b). Similarly, the cover of the less common *Montipora*, *Hydnophora* and Faviidae was unrelated to distance from the river. Coral communities at Sites 1 and 2 were generally dominated by massive *Porites*, with some large colonies of *Goniopora*, some Faviidae, *Hydnophora* and *Turbinaria* co-occurring, and the usually common and framework building genera *Acropora*, *Pachyseris*, *Pavona* and *P. rus* were missing.

A constrained principal component analysis was used to display differences in reef communities across the sites (Fig. 3). The environmental vectors ‘mud’ (associated with Site 1), ‘carbonates’ and ‘distance to river’ (both associated with Site 5) all oriented near-parallel to the first axis that explained nearly 69% of the total variation in the data, with the second axis explaining a further 14.6% of the variation. The amount of variance explained by the five environmental variables was 63.13%. A permutation analysis confirmed that the differences in the communities were most strongly related to distance to river ($F_{(1,9)} = 6.60$, $p < 0.001$). The variables carbonate, mud and rubble also contributed to explaining differences in communities, with $F_{(1,9)}$ ratios ranging from 1.81 to 2.078, and p values from 0.044 to 0.048. Sand cover was unrelated to differences in the community structure ($F_{(1,9)} = 1.15$, Perm-$P = 0.31$). Communities at Site 1 (associated with high mud and short distance to the river) were clearly separated from those found at the remaining stations. None of the major species vectors were directed towards Site 1 except for a few colonies of *Pocillopora*, and the almost ubiquitous massive *Porites*. All the other species groups had

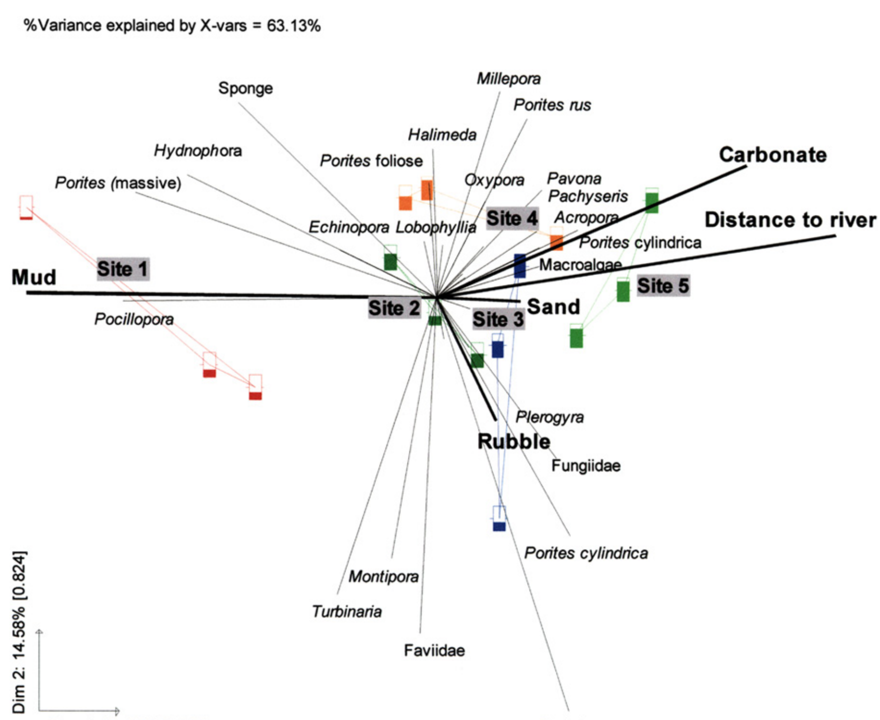

Fig. 3. Constrained principal component analysis biplot showing changes in reef communities on the 15 stations across 5 Sites that are located at increasing distances to the river mouth. Permutation tests showed that the environmental variables distance to river, percent mud, carbonate and rubble were significantly related to community structure. The amount of variance explained by the environmental variables is 63.13%. The fill of the ‘thermometer’ symbols represents relative hard coral richness at each station.

low representation at Site 1, they mostly occurred at the less river-influenced Sites 2–5. The communities of Sites 2, 3 and 4 were located in proximity to each other farther along axis 1, indicating that communities of these sites had similar species composition but continued to change away from the river. Stations of Site 5 were located at the outer most and opposite end of axis 1; these transects were characterized by high cover of *Acropora*, Fungiidae, *Pavona* and *Seriatopora*. Calculations of indicator values confirmed the patterns observed in the constrained principal component analysis. The strongest indicator species for Site 5 were Fungiidae, *Pavona*, *Acropora*, *Seriatopora* and *Pachyseris* while *Hydnophora* and *Porites cylindrica*, *Goniopora* and Faviidae were associated with Sites 4, 3, and 2, respectively (Table 1). No strong indicator species existed for Site 1, which was characterized by a sparsity of all species except for the slightly higher than expected abundance of the mud-tolerant genus *Turbinaria*, and high values of massive *Porites* (Table 1). *Pocillopora* was rare throughout, hence its indicator values were low despite an apparent higher than average occurrence at Site 1.

4. Discussion

This study provides the first detailed analysis of gradients in coral communities in Micronesia or similar small Pacific islands when exposed to a river discharging high loads of terrestrial sediments. Near the river mouth, we observed thick layers of mud, consistent with previous records of mean rates of sedimentation of 66 $\mathrm{mg\,cm^{-2}\,d^{-1}}$ at this site (Victor et al., 2006). Coral communities at this site had low diversity and many coral species groups were missing. Near Site 2, sedimentation rates averaged 38 $\mathrm{mg\,cm^{-2}\,d^{-1}}$, and near Site 3 it was 35 $\mathrm{mg\,cm^{-2}\,d^{-1}}$ (Victor et al., 2006), and at these sites, the coral community was still changing. Since the lagoon is enclosed by a barrier reef, there is very little flushing and much of the sediments remain in the lagoon (Victor et al., 2006). Because of this accumulation, the reef surfaces at Site 1, and to a lesser degree at Site 2, were found to be covered by mud. Mud deposits on the substrata also extended far beyond Site 2 (Victor et al., 2006, and personal observation). At Sites 3–5, there were no further changes in coral cover, but coral communities were still changing along the river gradient, as demonstrated by the observed linear increase in species richness, by continuing changes in community structure, and by low abundances of any forms of indicator species groups. The rapid deposition of coarser sediment near the river mouth (Victor et al., 2006), as well as increasing water motion farther away from land, are two possible reasons why mud deposits declined towards Site 5, although turbidity from fine suspended material was still high in the plume as observed at Site 5 during the surveys.

Data from this study showed declining macroalgal and sponge cover towards areas of high sedimentation, except for some high sponge cover at the muddy Site 1, mainly due to the dominance of two unidentified, yet apparently sediment-tolerant species. Other gradient studies demonstrated macroalgae abundance increasing towards areas with higher levels of nutrients and turbidity (van Woesik et al., 1999; Fabricius et al., 2005). However, these studies were placed in areas of lower levels of sedimentation. The sakau farmers in Pohnpei do not use fertilizers; therefore, the input of dissolved inorganic nutrients into Enipein is likely to be low, while soil-bound organic nutrients are likely to be carried into the system by sedimentation. Our results suggest that, as predicted conceptually (Fabricius, 2005), most types of macroalgae and sponges are quite sensitive to sedimentation, hence their abundance decreased towards the river mouth at Enipein. However, this pattern is also confounded with the greater water movement away from the river mouth, which promotes growth of both the filter-feeding sponges and the nutrient mass-transfer limited macroalgae. It is likely that both the disturbance by sedimentation and the lower flow towards the coast contributed to their decline from Site 5 to Site 2, with the high abundances at Site 1 attributable to a proliferation of certain extremely sediment-tolerant species.

Table 1
List of indicator values (Dufrene and Legendre, 1997) for the different coral species at the five sites along the water quality gradient. Bold font is used to highlight the best indicator species for each of the sites

	Site 1	Site 2	Site 3	Site 4	Site 5
Massive *Porites*	18.96	9.64	13.27	16.19	0.12
Turbinaria	**13.26**	0.75	3	0	0
Pocillopora	10.31	0	0.59	6.3	2.8
Faviid	8.84	**17.29**	12.4	0.29	3.91
Goniopora	0	**16.47**	1.76	2.54	0.4
P. cylindrica	0	18.72	**34.11**	13.67	19.09
Hydnophora	4.86	5.08	9.73	**17.92**	0
Fungiidae	0.18	0.85	10.17	3.73	**51.55**
Pavona	0	0	1.4	6.38	**48.1**
Acropora	0	2.08	10.48	28.38	**37.07**
Seriatopora	0	2.21	10.82	0	**27.2**
Pachyseris	0	2.47	14.08	10.33	**26.1**
Porites rus	0	13.6	13.25	**24.25**	**25.59**

5. Conclusion

This study demonstrates the benefits of examining changes along clearly defined environmental gradients, which allowed us to quantify changes in diversity and determine which species were the best indicators of environmental change. The results of this study showed that coral cover is not as sensitive as coral diversity as an indicator of river and sediment exposure. Based on coral cover data alone, one might conclude that only Site 1 reefs appear to be impacted by the river and its high discharge of sediments. In contrast, coral species richness continued to increase with increasing distance away from the river mouth, suggesting that the coral richness and the absence of the sensitive indicator species Fungiidae, *Pavona*, *Pachyseris* and *Acropora* are far better indicators of river impact on coral reef communities than coral cover. Even at Site 5, the slope of the species richness–river distance relationship had not leveled off (Fig. 2a), suggesting that the river impact extends beyond Site 5 at Enipein, i.e., the sediments and nutrients coming down this river affect reefs which are more than

1.7 km away from the river mouth. If similar conditions were to occur from the other ~40 rivers discharging into the lagoon of Pohnpei, a majority of the corals growing around the periphery of this island might be severely affected.

At Enipein, like other places around the world, soil loss from the land and the resultant increased rates of sediment and nutrient discharges into the marine environment are impacting coastal coral reefs. In addition to the dramatic impacts of smothering corals at Site 1, the remaining coral community in Enipein is being altered in terms of species richness and composition. At present, it is unknown how land-based changes affect the outer barrier reefs and fish stocks of Pohnpei. Because the people of Pohnpei depend on their coral reefs for food and as a source of income from dive tourism, it is an urgent mandate to take a holistic approach and implement integrated watershed management practices to mitigate land-based activities in order to prevent further destruction of adjacent coral reefs.

Acknowledgements

This study was supported by NOAA Coastal Oceans Program (CRES Grant NA160P2920), The Palau International Coral Reef Center, the Conservation Society of Pohnpei and JICA Technical Assistance (PICRC Strengthening Project). The authors gratefully acknowledge the statistical advice and analyses provided by Glenn De'ath, and the support and assistance of William Kostka, Eugene Joseph, Leinson Neth, Larko Mikel, Kirino Olpet, Benjamin Chen, Scottie Malakai and Eugene Eperiam and the people of Enipein Village. We also thank Charlene Mersai, Bill Raynor, Mark Tupper and Rob van Woesik for reviewing and providing insightful comments on the manuscript.

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