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Linking sewage pollution and water quality to spatial patterns of *Porites lobata* growth anomalies in Puako, Hawaii

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ABSTRACT

Sewage pollution threatens the health of coastal populations and ecosystems, including coral reefs. We investigated spatial patterns of sewage pollution in Puako, Hawaii using enterococci concentrations and $\delta^{15}N$ *Ulva fasciata* macroalgal bioassays to assess relationships with the coral disease *Porites lobata* growth anomalies (PGAs). PGA severity and enterococci concentrations were high, spatially variable, and positively related. Bioassay algal $\delta^{15}N$ showed low sewage pollution at the reef edge while high values of resident algae indicated sewage pollution nearshore. Neither $\delta^{15}N$ metric predicted PGA measures, though bioassay $\delta^{15}N$ was negatively related to coral cover. Furthermore, PGA prevalence was much higher than previously recorded in Hawaii and the greater Indo-Pacific, highlighting Puako as an area of concern. Although further work is needed to resolve the relationship between sewage pollution and coral cover and disease, these results implicate sewage pollution as a contributor to diminished reef health.

1. Introduction

Coral disease is a significant factor in declining coral health throughout the world (Ruiz-Moreno et al., 2012), and is often exacerbated by global and local stressors, such as increasing water temperature and sedimentation (rev. in Harvell et al., 2007). One widespread anthropogenic stressor impacting coral reef ecosystems is sewage pollution. Sewage pollution is not a single, simple stressor; rather, it is complex and can introduce diverse pollutants, including nutrients (especially nitrogen and phosphorous), microbial pathogens, and chemical contaminants that themselves can impact coral reefs (Wear and Vega Thurber, 2015).

One component of sewage, nutrient pollution, can be an important facilitator of coral disease. Couch et al. (2008) suggest that nutrient enrichment may favor growth of coral microbial associates, which indirectly modifies host coral immunity by requiring an elevated immune response. Increases in nutrient loading can increase the severity and prevalence of coral disease, possibly by favoring pathogen growth or inhibiting resistance (Bruno et al., 2003; Voss and Richardson, 2006; Harvell et al., 2007; Vega Thurber et al., 2014). It is important to note that there are several sources of nutrient influx to coral reefs, which include runoff (Fabricius, 2005), fish farm effluents (García-Sanz et al., 2011), and other natural terrestrial and atmospheric contributions (Szmant, 2002). Sewage pollution can also introduce pathogens, as is the case with the human gut microbe, *Serratia marcescens*. This microbe has been considered responsible for white pox disease in the Caribbean and the resulting decimation of the now endangered *Acropora palmata* corals (Sutherland et al., 2010), though this relationship is disputed (Lesser and Jarett, 2014). A third possible contribution of sewage pollution to coral disease is chemical contaminants such as endocrine disruptors, heavy metals, and other toxins (rev. in Wear and Vega Thurber, 2015).

Other human gut bacteria can also enter the marine environment through sewage pollution. While not necessarily pathogenic, these bacteria are of interest as indicators of untreated sewage entering coral reef ecosystems. The gram-positive *Enterococcus* spp. bacteria are used by the US Environmental Protection Agency (EPA) as a water quality metric and to assess the degree of sewage pollution. Naturally found as facultative anaerobes in human and animal guts, enterococci are relatively persistent bacteria and are able to tolerate both fresh and saline water.

Compared to typical seawater, sewage-polluted water is enriched in ^{15}N relative to ^{14}N, and therefore, has a highly positive $\delta^{15}N$ value (>10 ‰), which distinguishes it from other nitrogen sources such as fertilizers or N_2-fixing plants (~0‰) (Heaton, 1986; Derse et al., 2007; Risk et al., 2009; Dailer et al., 2010). The enrichment of ^{15}N in the environment is reflected in macroalgae and other biological tissues, allowing bioassays to be used to detect enrichment of ^{15}N and thus indicate sewage pollution (Risk et al., 2009). There is a large range of $\delta^{15}N$ values that

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could indicate sewage pollution in macroalgae (3 to >10‰), but levels typically decrease with increasing distance from the pollution source (Heaton, 1986; Costanzo et al., 2001; Risk et al., 2009). In Dailer et al. (2011), the alga *Ulva fasciata* was grown in waters off West Hawaii to produce a sample that integrated levels of nitrogen over a 1-week period. Dailer et al. (2010) also used $\delta^{15}N$ analysis on resident algae to map sewage pollution in Maui, Hawaii. Similar studies have been performed in both temperate and tropical environments; for example, bioassays of the oyster *Crassostrea virginica* and macroalga *Gracilaria* sp. were used to detect sewage and animal waste pollution in coastal Maryland, USA (Fertig et al., 2009) and Moynihan et al. (2012) used a combination of enterococci concentration measurements and $\delta^{15}N$ analysis of seagrass, scleractinian corals, sponges, and macroalgae in Zanzibar, Tanzania.

In Puako, Hawaii, untreated sewage pollution can enter the coral reef ecosystem through the combination of old cesspool systems, highly porous volcanic bedrock, and close proximity to the shore via submarine groundwater discharge (SGD) (Street et al., 2008; Knee et al., 2010). This region of the leeward coast of Hawaii Island (West Hawaii) has particularly well-developed reefs. However, as with many other coastal regions of Hawaii, the Puako region has experienced increased pressures from fishing, land-based pollution, recreational use, development, and likely climate change in recent decades. The consequences of these compounding impacts likely explain the dramatic decline of Puako marine resources over the long term. Data compiled by The Nature Conservancy and the Hawaii State Division of Aquatic Resources show a decrease in fish abundance over a 40-year span (Minton et al., 2012; Walsh, 2013). Coral cover also declined dramatically in Puako, dropping from 80% in the 1970s to 32% in 2010 (Walsh, 2013). Additionally, Couch et al. (2014) identified Puako as one of four regions in West Hawaii warranting special concern based on a 12% reduction in coral cover between 2003 and 2011. While there are likely many contributing factors in this decline, it is important to consider the role of coastal pollution in facilitating coral disease and death. Community concern primarily focuses on sewage pollution; however, other pollutants and sources of nutrient inputs may include animal wastes from upland regions, and fertilizers and pesticides used in the area. The nitrogen-fixing tree *Prosopis pallida* is common in the area, but work in anchialine pools elsewhere suggests that its contribution to nitrogen inputs is minimal (Dudley et al., 2014).

Puako reefs are dominated by *Porites lobata* corals, which are also the most vulnerable to disease (Friedlander et al., 2008; Aeby et al., 2011b; Couch et al., 2014). The most prevalent of these diseases is *P. lobata* growth anomalies (PGAs), which are identified as gross lesions of tumor-like tissue with lighter pigmentation, raised tissue, and enlarged or variable polyp (calyx) size (Fig. 1). The lighter pigmentation of PGAs is the result of lower densities of symbiotic dinoflagellates in PGA tissue. As a result, PGAs are likely unable to produce enough energy to sustain themselves and must rely on resources of healthy portions of the host to grow (Yasuda et al., 2012). As sinks for their colonies' resources and sites of decreased reproductive function, PGAs have the potential to decrease the reproductive ability and immunity of the whole colony (see Burns and Takabayashi, 2011 for *Montipora capitata* growth anomaly impact). Although a viral microbial agent has been investigated (Vega Thurber and Correa, 2011), the causative agent remains unknown and could even include somatic mutation (Irikawa et al., 2011).

Our study examines the relationships between PGAs, enterococci concentrations, and macroalgal $\delta^{15}N$ across 10 sites in Puako to test the hypothesis that coral disease is higher in areas of sewage inputs. Because host properties can also influence disease in addition to environmental pollution, we also investigated the role of colony size in patterns of PGAs.

2. Methods

2.1. The Puako region and study sites

The Puako region is located along the leeward, Kohala Coast of Hawaii Island, Hawaii. The adjacent community is comprised of one hundred sixty-three (163) houses. Cesspools and septic tanks provide the majority of wastewater treatment for the community, except for the condominium which uses an ejection well for primary treated sewage (Minton et al., 2012). The greater census-designated place has 772 residents and 2326 housing units, which includes hotels and condominiums in the resort area nearby to the community of interest (US Census Bureau, 2010).

Ten study sites ranging from Waialea Bay to Paniau Bay were selected to capture variation in coral health and sewage pollution along 3 km of the Puako coast (Fig. 2). Where possible, study sites were selected at shoreline access (SA) locations. SA sites (SA40, SA80, SA88, SA100, SA136, SA152), Condos, and Waialea were all located adjacent to residences. The road through the community hugs the shoreline such that most of the residences are immediately adjacent or across the road (inland) from the shoreline, forming a consistent strip two-houses deep along the SA sites. Paniau and Waialea are both public beaches, PBR is a launching site for small boats, and Condos is near the condominiums complex in the community.

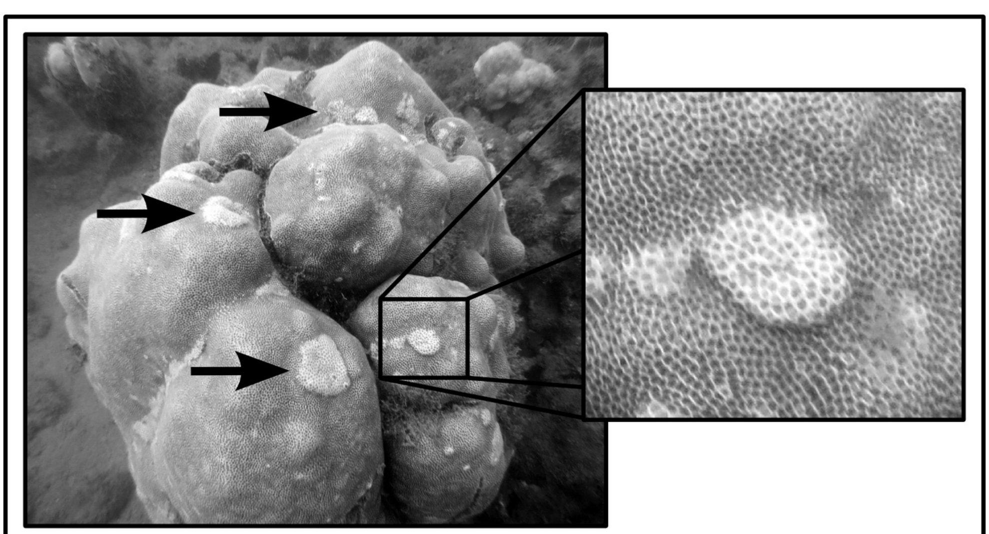

Fig. 1. *Porites* growth anomalies (PGAs) on *Porites lobata*. Arrows indicate several conspicuous PGAs. Note lighter pigmentation, raised surface, and enlarged polyps of PGA as shown in inset.