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Coral reef health response to chronic and acute changes in water quality in St. Thomas, United States Virgin Islands

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ABSTRACT

It is suspected that land cover alteration on the southern coast of St. Thomas, USVI has increased runoff, degrading nearshore water quality and coral reef health. Chronic and acute changes in water quality, sediment deposition, and coral health metrics were assessed in three zones based upon perceived degree of human influence. Chlorophyll ($p < 0.0001$) and turbidity ($p = 0.0113$) were significantly higher in nearshore zones and in the high impact zone during heavy precipitation. Net sediment deposition and terrigenous content increased in nearshore zones during periods of greater precipitation and port activity. Macroalgae overgrowth significantly increased along a gradient of decreasing water quality ($p < 0.0001$). Coral bleaching in all zones peaked in November with a regional thermal stress event ($p < 0.0001$). However, mean bleaching prevalence was significantly greater in the most impacted zone compared to the offshore zone ($p = 0.0396$), suggesting a link between declining water quality and bleaching severity.

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1. Introduction

Coral reefs form the foundation of one of the most diverse marine ecosystems on the planet (Hoegh-Guldberg, 1999; Guerra-García and Koonjul, 2005; Larsen and Webb, 2009). They are an invaluable element in the economies of small, tropical and subtropical island nations, as the tourism and recreational activities associated with coral reefs can account for up to 80% of total island income (Hoegh-Guldberg, 1999; Jeffrey et al., 2005; Carbery et al., 2006). However, increased runoff associated with development and land-use changes in the coastal zone has degraded nearshore water quality, threatening the health and persistence of coral reefs (Mora, 2008; Haapkylä et al., 2011; Maina et al., 2011; Dadhich and Nadaoka, 2012).

Sediment and nutrients are arguably the most influential components of runoff and have been shown to have largely negative impacts on coral reef ecosystems. Direct deposition of sediment on corals can cause burial, smothering, and mortality (Rogers, 1990; Dubinsky and Stambler, 1996; Nemeth and Nowlis, 2001). Land-based sediment particles can also act as vectors for coral disease agents (Larsen and Webb, 2009; Haapkylä et al., 2011), while nutrient enrichment in the coastal environment can intensify disease impacts (Dubinsky and Stambler, 1996; Bruno et al., 2003). Light reduction due to suspended sediment particles or nutrient-induced eutrophication and phytoplankton growth in the water column increases turbidity, preventing sufficient light from reaching photosynthetic benthic organisms (Hallock and Schlager, 1996; Fabricius, 2005; Anthony, 2006; Haynes et al., 2007; Larsen and Webb, 2009). Elevated nutrient concentrations can also favor the competitive ability of macroalgae over corals, leading to overgrowth and community shifts from coral to macroalgae dominance (Szmant, 2002; Fabricius, 2005; Haynes et al., 2007; Silverman et al., 2007; De'Ath and Fabricius, 2010). Increased sediment and nutrient loading may also be associated with a higher prevalence of coral bleaching (Nemeth and Nowlis, 2001). However, it has also been suggested that sediment and nutrients may have positive effects on coral growth and resistance to stress (Fabricius, 2005) and that some corals can exhibit heterotrophic plasticity to utilize excess sediment particles as an additional source of energy (Anthony and Fabricius, 2000; Anthony, 2006; Larsen and Webb, 2009).

Both the amount of development in the coastal zone and the volume of pollutants entering the nearshore environment can influence the severity of the impacts of increased runoff. Recently-developed watersheds are a source of elevated turbidity, total suspended solids, and chlorophyll *a* concentrations in nearshore waters, but these variables tend to decrease with lessening human influence in watersheds (Hertler et al., 2009). In the United States Virgin Islands (USVI), Oliver et al. (2011) demonstrated that distance from human activity was associated with healthier coral reef communities, as coral colony size, density, and species richness were negatively correlated with watershed landscape development around the island of St. Croix. Additionally, sedimentation rates and coral bleaching prevalence have been found to be

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higher in nearshore environments of the USVI compared to offshore areas and to decrease with distance from shore (Smith et al., 2008).

These findings refer to chronic impacts of low-level sedimentation or nutrient input over extended periods of time; however, acute impacts of heavy sedimentation or nutrient input on water quality and coral reef health have been less frequently documented. In tropical regions, acute events are natural phenomena that occur on a regular basis in association with seasonal storm activity. However, more intense, frequent storms may be likely due to global climate change (Webster et al., 2005; Knutson et al., 2010), potentially making the impacts of acute events more relevant to coral reef health in the near future. Immediately following a disturbance event, like a large influx of sediment, phytoplankton in the water column can achieve maximal growth rates (Furnas et al., 2005), leading to light reduction to the benthic environment. In laboratory experiments, zooxanthellae within corals exposed to short-term, large volumes of sediment, exhibited photosynthetic stress (Philipp and Fabricius, 2003). Additionally, it has been suggested that while some coral species may be more tolerant of low-level, chronic water quality impacts, others could exhibit greater stress under short-term influxes of large volumes of runoff (Philipp and Fabricius, 2003). However, field studies of the impacts of acute events on coral reef health are not well documented, and individual species responses to impacts of acute events have tended to be highly variable (Bythell et al., 1993).

In the USVI, water quality is declining, most likely due to rapid development in recent years and poor land-use planning and management (Nemeth and Nowlis, 2001; Brooks et al., 2007; Rothenberger et al., 2008). The economy of the territory was approximately 70% tourism based in 2005, increased to 80% in 2010, and development is likely to increase as this industry continues to expand (Jeffrey et al., 2005; van Beukering et al., 2011). Additionally, almost half of surveyed visitors claimed their reason for visiting the USVI was related to coral reefs and the majority would return if the reefs remained at their current status; however, the percent of return visitors drops by almost half if coral reef quality declines (van Beukering et al., 2011). Therefore, it is essential to assess the impacts of declining water quality on the coral reefs of the USVI because their loss would severely hurt the territory's main source of income. The USVI are also subject to tropical cyclone activity for about five months out of the year (July–November), which could substantially increase the amount of runoff entering the nearshore environment as acute pulses (Rothenberger et al., 2008). A better understanding of the impacts of development and storm activity on coral reef ecosystems is of particular concern in St. Thomas, the most populous of the three islands (U.S. Census Bureau, 2011), as it is the most heavily visited.

The southwestern region of St. Thomas contains two, extensively-altered areas where major port activities related to shipping, tourism, and chandlery are concentrated. Additionally, this area has the highest percentage of urban land cover and, historically, had one of the greatest rates of increase in urban cover in St. Thomas (The Cadmus Group, 2011). Therefore, this region was targeted to investigate potential impacts of both chronic and acute changes in water quality on coral reef communities across varying levels of human impact. In this study, chronic changes refer to low-level, continuous influxes of runoff whereas acute changes refer to high-volume, transient events on the order of days often associated with tropical storm activity. We hypothesized that acute terrestrial runoff events and chronic impacts from port activities are having negative impacts on coral reefs in this region. Specifically, we hypothesized that sediment loading and nutrient concentrations would be chronically higher in developed nearshore areas and would experience more dramatic increases during acute runoff events, compared to the offshore region. Additionally, we hypothesized that coral health parameters, such as disease, bleaching, and mortality, in nearshore waters would be more prevalent during both chronic and acute time frames, compared to the offshore area. The results of this study are applicable to other areas in the USVI, in addition to many other areas in the Caribbean, and could potentially aid in the formation or refinement of management actions regarding land-based pollution and port activities.

2. Methods

2.1. Study location

Shallow water coral reefs (<30 m) in the USVI most commonly form fringing or patch reefs, accounting for about 60% of shallow water substrates (Rothenberger et al., 2008). The most populous area of St. Thomas ($83\ km^2$) is the Charlotte Amalie subdistrict (18,481 residents) on the south-central coast ($20.1\ km^2$ – density of ~920 people/km^2; Fig. 1; Jeffrey et al., 2005; U.S. Census Bureau, 2011). This area also encompasses the primary ports of St. Thomas, located in Crown Bay and Charlotte Amalie Harbor. The coastal waters adjacent to this sub-district are most likely experiencing the greatest pressure from land-based and marine-based activities on all of St. Thomas due to this context. Therefore, this study includes the nearshore waters associated with this subdistrict, extending south to Flat Cay, Saba Island, and Frenchmans Reef, to examine how gradients in water quality affect coral reef community health (Fig. 1).

Within the study area, three zones containing six sites each were established based upon perceived level of anthropogenic impact (Fig. 1). Perceived level of impact was determined based upon aerial images of the island to locate coastal areas with large amounts of development in addition to personal knowledge of port activities within both the Charlotte Amalie Harbor and Crown Bay. Of the six sites within a zone, four sites were associated with coral reef or coral communities on hardbottom and two sites were located in open water to represent the remaining zone area not associated with targeted reef habitat. The majority of coral monitoring sites were known because of their previous or continued use in other studies. The remaining coral monitoring sites were located by snorkeling areas that appeared to be coral habitat from both aerial imagery and benthic habitat maps (see Fig. 1), and areas were deemed acceptable if estimated coral density was a minimum of 7–8 colonies per square meter between 5 and 10 m depth. Zone I was a nearshore, heavily-impacted pair of embayments encompassing both the Charlotte Amalie Harbor and Crown Bay. Zone II was an intermediately-impacted nearshore zone that included the embayments of Brewers and Perseverance Bay. Zone III was a lower impact zone located immediately offshore of Zones I and II, but on the insular shelf (Fig. 1).

Each zone was sampled for both water quality and coral community parameters from August 2013 to February 2014 with sampling done on August 5–23, September 19–October 1, November 13–16, December 2–14, and February 4–20. Sampling in November and December coincided with acute rain events, defined in this study as an accumulation of at least 2.5 cm of rain within a 24-hour period. Rainfall accumulation was recorded by a weather station at the Cyril E. King Airport, St. Thomas, USVI (NOAA National Centers for Environmental Information). Water quality and coral reef sampling began within one week after each acute event.

2.2. Water quality sampling

Water quality sampling occurred at all six sites within each zone. Nutrient and total suspended solids (TSS) samples were taken simultaneously at a depth of approximately 1 m below the water's surface following previous methodology (Honisch, 2012). Salinity, temperature, dissolved oxygen, pH, turbidity, and chlorophyll were also simultaneously measured using a Conductivity, Temperature, and Depth (CTD) sensor lowered approximately 1 m below the water's surface (Seabird 25 Sealogger CTD, Sea-Bird Electronics, Bellevue, WA, USA). Nutrient samples were analyzed using an autoanalyzer (Astoria Analyzer, Astoria-Pacific, Clackamas, OR, USA) for nitrite, nitrate,