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Investigating Bermuda's pollution history through stable isotope analyses of modern and museum-held gorgonian corals

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ABSTRACT

For centuries, Bermuda has been challenged with wastewater management for the protection of human and environmental health. By quantifying the $\delta^{15}N$ of the common sea fan *Gorgonia ventalina* sampled from 30 sites throughout Bermuda we show that sewage-derived nitrogen is detectable on nearshore coral reefs and declines across the lagoon to the outer rim. We also sampled gorgonians from two museum collections representing a 50y time-series (1958–2008). These samples revealed an increase in $\delta^{15}N$ of >4.0‰ until the mid-1970s, after which $\delta^{15}N$ values slowly declined by ~2.0‰. A $\delta^{15}N$ chronology from a gorgonian skeleton exhibited a similar decline over the last 30–40 years of approximately 0.6‰. We conclude that policies have been effective in reducing sewage impacts to Bermudian reefs. However, significant sources of sewage pollution persist and are likely have a strong impact on harbor and nearshore coral communities and human health.

1. Introduction

With its relative isolation within the oligotrophic Gulf Stream currents of the North Atlantic gyre, Bermuda has been a valued station for global environmental monitoring. Specifically, the accreted skeletons of Bermudian corals and sponges have been useful in reconstructions of past ocean chemistry and sentinels of global change (Goodkin et al., 2007). However, relatively little attention has been given to coral-derived records of local impacts resulting from over 200 years of intensive human colonization. Corals are useful recorders for local anthropogenic impacts. Recently, corals from Bermuda have revealed increasing levels of heavy metal contamination from landfills over the last 30 years (Prouty et al., 2013). Yet, coral records have not been utilized for revealing the past and present impacts of residential and urban sewage inputs. This is a significant problem for the island as the majority of Bermuda's wastewater infrastructure is relatively unchanged since colonial times, while modern centralized wastewater treatment is prohibited by the island's geology. As such, Bermuda produces ~20×10^6 L of sewage per day, which is discharged with minimal treatment mostly from residential on-site sewage disposal systems (OSDS; typically cess-pits) into the coastal marine environment and four deeper water outfalls along the north and south shore (Jones et al., 2011). The South Shore outfall discharges the bulk of Bermuda's wastewater into deeper oceanic waters.

The ecological impacts of sewage pollution in Bermuda have not gone unnoticed. In the 1970s, Bermuda experienced widespread blooms of the green macroalgae *Cladophora prolifera* throughout inshore waters and harbors which led to benthic hypoxia (Bach and Josselyn, 1978). Although initially thought to be exploiting open niche space as an exotic species, Lapointe and O'Connell (1989) revealed that *C. prolifera* was co-limited by N & P availability, and that the 25-year persistence of the algal bloom was likely driven by groundwater nutrient inputs. Indeed, Bermuda's groundwater contamination by sewage is pronounced with nitrate concentrations exceeding 700 μM (Simmons, 1997). Sewage impacts from offshore outfalls have been documented on corals as well. Juvenile recruitment and density of *Diploria* spp. correlated with higher macroalgal density surrounding the Hungry Bay sewage outfall along Bermuda's south shore (Webster and Smith, 2002). Recently, Jones et al. (2011) surveyed microbial and sedimentary biomarkers from sites throughout the Great Sound complex of Bermuda. They concluded that up to 30% of the sites surveyed are affected by sewage but that the problem is largely isolated to a few "hotspots" and that sewage pollution is relatively "quite low".

While microbes are useful indicators of water quality, particularly for protecting human health in recreational waters, they are poor indicators for a major stressor to corals: nitrogen (Paul et al., 1995; Baker et al., 2010a). Wastewater containing high concentrations of

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ammonium and nitrate seep through porous limestone into harbors, bays, and nearshore habitats. Whereas microbes may settle (Fries et al., 2006) and/or experience mortality from light and osmotic stress, nutrients like nitrogen are more labile and can move further through the environment affecting areas more distant from the source. Moreover, owing to lower density sewage plumes from outfalls often immediately rise to the surface and later deposit sediment and nutrients elsewhere depending on prevailing surface currents. Therefore, large areas of benthic habitat can be affected by these inputs over time. Corals tend to be nitrogen-limited and are capable of assimilating nitrogen from inorganic sources such as ammonium and nitrate (Yellowlees et al., 2008). Thus, corals take up sewage-derived nitrogen readily and utilize this nutrient for growth (Baker et al., 2010a). Subsequently, the coral creates a record of the nitrogen source through its stable isotope value, δ^{15}N.

Today, δ^{15}N analysis of reef biota is routinely used to assess sewage pollution (Risk, 2009; Risk et al., 2009). Gorgonian octocorals are dominant members of Bermuda's coral reef community and are found from the outer reef slope across the lagoon and within harbors and bays. Unlike hard corals, gorgonians accrete proteinaceous skeletons and therefore contain substantial amounts of nitrogen (Goldberg, 1976). The nitrogen in the skeleton is derived from the surrounding environment primarily from dissolved inorganic sources like nitrate found in seawater (Baker et al., 2010a). By measuring the ratio of the heavy (^{15}N) relative to the light (^{14}N) stable isotope (δ^{15}N), one obtains information regarding the provenance of the nitrogen assimilated by the coral (Risk, 2009). As coral reefs are generally nitrogen-limited additional sources of nitrogen from anthropogenic sources are readily assimilated and easily detected by stable isotope methods. The method, when applied to gorgonian corals has been successful in identifying point and non-point sources of nitrogen pollution including sewage and agricultural fertilizers in the Caribbean over the last century (Baker et al., 2010b).

Given Bermuda's long history as a developed island, and the rapid decline of coral reefs worldwide, the goal of this research was to establish a baseline measurement for stable isotope ratios of gorgonian corals around Bermuda from which future development and environmental remediation efforts can be assessed.

2. Methods

2.1. Regional sampling

In August of 2010, 30 sites within the northern lagoon of Bermuda including nearshore, patch, and barrier reefs were visited by boat (Fig. 1, Table 1). 3 to 5 samples of the common sea fan *Gorgonia ventalina* were taken using snorkel or SCUBA. A sample consisted of a small, 2 cm^2 fragment taken from the colony edge. This area likely represents the most recent (~1 yr) of growth (Yoshioka and Yoshioka, 1991; Baker et al., 2011). At four harbor sites (1, 2, 4, 6; Table 1), few or no *G. ventalina* were found so branch tips from the gorgonian *Pseudoplexaura porosa* were sampled instead. At two of these locations (4, 6) the species co-occurred and we were able to compare δ^{15}N values. We found no significant difference between the species (mean ‰ ± s.d.; GVEN = 8.6 ± 0.4 vs. PPOR = 8.3 ± 0.1, $n = 2$ per species) so the data were pooled for subsequent analysis. A total of 158 samples were collected from 7 offshore, 6 lagoon, 9 nearshore, and 8 harbor sites (Fig. 2). We also sampled along 2 nearshore - offshore transects perpendicular to the north shore, which outlined the marine protected area. All samples from harbor, nearshore, and mid-lagoon sites were sampled while snorkeling to 1–3 m depth. Offshore, samples were taken while on SCUBA at depths between 5 and 10 m, however the resulting isotope values were not corrected for depth dependent fractionation as this had little impact on subsequent analyses (Heikoop et al., 1998; Baker et al., 2011).

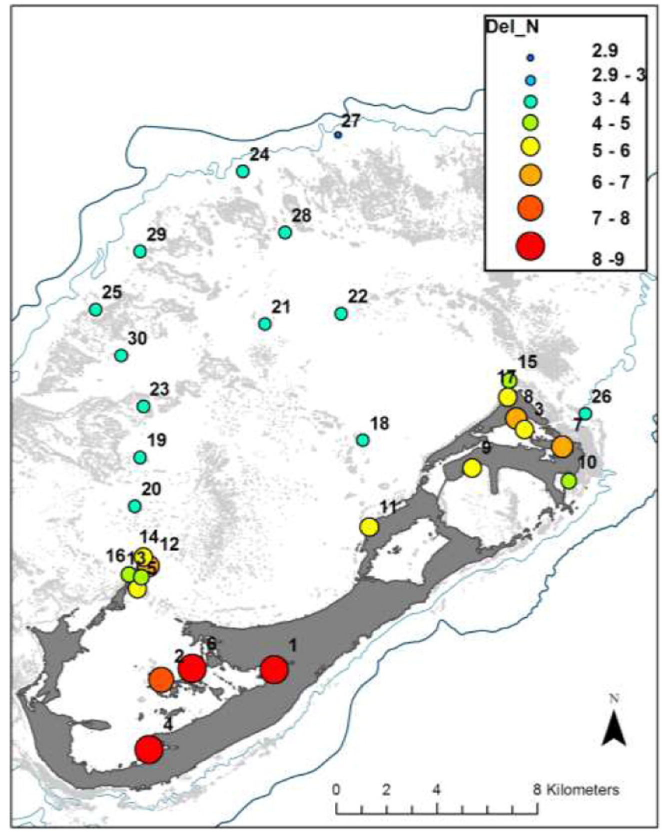

Fig. 1. Map of Bermuda depicting sites of sample collection. The circle color and size signifies the average δ^{15}N at each site.

2.2. Targeted high spatial resolution sampling

We investigated the Navy Dockyard area along the NE portion of Ireland Island where non-point sources of sewage pollution from the North Basin marina live-aboards and a cruise ship dock along the King's and Heritage wharves were suspected (Fig. 2). A ~300 m transect was laid parallel to shore along Commissioner's Point and *G. ventalina* were sampled where they occurred every 7 to 30 m at approximately 2 m depth while snorkeling.

2.3. Time-series reconstructions of δ^{15}N histories

A large >50 yr (estimated) old holdfast from a deceased colony of *Pseudoplexaura* sp. was found in an area adjacent to the airport runway. The colony base was removed from the hard bottom, oven dried, sectioned and polished to resolve the banding pattern. The bands were counted and the outer layers were peeled away using forceps and a scalpel. Small pieces of the outer bands were shaved off using a scalpel for isotope analysis. The harder interior bands were sampled using a NewWave Research Microdrill with a ~ 250 μm burr-tipped drill bit with a penetration depth of 100 μm. For both sampling methods each sample likely represented 2–3 years of growth.

Finally, 10 museum specimens were sub-sampled from the Bermuda Aquarium Museum & Zoo (BAMZ). They represented 3 species of gorgonians collected between 1973 and 2000, *Pseudopterogorgia acerosa, P. americana,* and *Gorgonia ventalina*. Museum specimens of these species have been previously used for historical reconstructions of δ^{15}N Caribbean-wide (Baker et al., 2010b). Additionally, 8 museum specimens of *G. ventalina* were sub-sampled from the Smithsonian Institution's National Museum of Natural History (NMNH; Table 2).

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