Integrated Water Quality and Coral Reef Monitoring on Fringing Reefs of Tobago: Chemical and Ecological Evidence of Sewage-Driven Eutrophication in the Buccoo Reef Complex

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ABSTRACT

Land-based discharges of nutrients from deforestation, sewage and agricultural activities are a rapidly growing threat to Caribbean coral reefs and Marine Protected Areas (MPA's). To assess localized sewage problems in Tobago, we conducted an integrated water quality and coral reef monitoring program in the dry season between April and June, 2001. The study included a variety of fringing reef sites around Tobago, including the Buccoo Reef Complex (BRC) that was established as an MPA in 1973. The study involved:

i) measurement of water column dissolved inorganic nitrogen (DIN = ammonium plus nitrate plus nitrite), soluble reactive phosphorus (SRP), and chlorophyll-a (chl-a),
ii) digital video monitoring of benthic reef communities to quantify cover of hard corals, octocorals, macroalgae, turf algae, coralline algae, sponges, and
iii) determination of $\delta^{15}N$ ratios (= $^{15}N/^{14}N$) in benthic macroalgae at the reef sites to discriminate among natural versus anthropogenic nitrogen sources.

Low DIN:SRP ratios (< 5:1) throughout the study area indicated DIN rather than SRP-limitation of algal growth. DIN (~ 1 μM, mostly ammonium) and chl-a (up to 0.6 ug/l) within the BRC were high compared to more oligotrophic fringing reefs around Tobago and were indicative of eutrophication. Cumulative impacts of land-based nutrient enrichment in the BRC was also evidenced by relatively low cover of hermatypic (reef-forming) corals and high cover of macroalgae, turf algae, octocorals, and the zoanthid *Palythoa* that was physically overgrowing reef corals. Schools of mobile, herbivorous fishes (parrotfish, surgeonfish) were abundant in the BRC because of protection from reef fishing in this MPA. The $\delta^{15}N$ values of macroalgae in the BRC ranged from a high of +11.8 ‰ in Buccoo Bay near a sewage outfall to +5.3 ‰ at Coral Gardens on the outer reef, values within the range reported for macroalgae growing on sewage nitrogen. Elevated DIN and chl-a concentrations combined with relatively high $\delta^{15}N$ values of macroalgae at other fringing reef sites off southwest Tobago were indicative of sewage pollution from upland urban centers and tourist resorts around Scarborough, Crown Point, and Mt. Irvine. The lowest DIN and chl-a concentrations and $\delta^{15}N$ values (± 2.5 ‰) of macroalgae of the entire study were at Black Jack Hole off Little Tobago Island, a site characteristic of oligotrophic, background nitrogen sources and a lower degree of sewage pollution.

KEY WORDS: Coral reef, eutrophication, nitrogen

INTRODUCTION

Tropical coastal ecosystems, and coral reefs in particular, are suffering worldwide from the impacts of land-based nutrient pollution and eutrophication of coastal waters (NRC 2000). Pollution from land-based sources is considered the single most important threat to the marine environment of the Caribbean and an impediment to sustainable use of its resources (UNEP 1994). Sources of nutrient pollution known to impact Caribbean reefs include poorly treated sewage and grey-water, domestic and commercial (tourism) outfalls, fertilizers, deforestation, and top soil loss (Lapointe et al. 1990, Lapointe and Thacker 2001, Likens, 2001). Throughout the Caribbean SIDS (Small Island Developing States) inappropriate or non-existent wastewater treatment represents a major source of land-based nutrient pollution to not only coral reefs, but also to adjacent seagrass and mangrove ecosystems as well (NRC 2000).

One example of this problem can be found on the small island (300 km^2) of Tobago, located approximately 29 km northeast of Trinidad in the southeastern Caribbean. Approximately 70% of Tobago's coastal waters (along its eastern and Caribbean coastlines) are characterized by reef formations, of which the Buccoo Reef Complex (BRC) is the largest and the only Marine Protected Area (MPA) in the Republic of Trinidad and Tobago. Other major coral reef sites around Tobago include reefs at Speyside, Goat Island, Little Tobago Island, and Man-of-War Bay on the northeast; Culloden Bay, Arnos Vale, Englishman's Bay, and Three Sister's on the north coast; and Flying Reef, Diver's Thirst, Diver's Dream, Ketchup Reef, Grouper Ground, Kariwak Reef, Mt. Irvine Reef, and Stone Haven bay on the southwest coast (Laydoo 1991). These reefs are important to Tobago's tourism industry. Glass bottom boat tours use some of the reefs for reef viewing, snorkeling, and reef walking. The number of SCUBA divers visiting Tobago has increased to ~ 40 % of the total tourism market and currently supports 21 dive shops on the island. Conch, lobster, and fish are taken regularly from many of the reefs to support local restaurants and subsistence fishing. Pot and spearfishing are not encouraged on or near reef areas.

The BRC represents a classic example of a tropical fringing coral reef ecosystem that has been expressing symptoms of eutrophication from wastewater discharges for several decades (IMA 1994). The BRC encompasses an area of ~ 7 km^2 and was officially designated as a Marine Protected Area (MPA) in 1973. But, like most MPA's in the Caribbean, such designation has not protected these economically valuable coastal resources from water quality degradation. Most coastal dwellings (~ 80%) in the Buccoo Bay catchment area have septic tank or "soak-away" systems built in the carbonate-rich limestone that overlays the volcanic geology of Tobago. These sewage disposal systems provide little removal of nitrogen, which is highly mobile in carbonate-rich systems; the sewage liquor enters the water table and flows subsurface via groundwaters into downstream coastal waters (Lapointe et al. 1990, Costa et al. 2000, Lapointe and Thacker 2001). Inadequately, treated sewage (at best, secondary treatment only -- no nutrient removal) also enters Buccoo Bay and the Bon Accord Lagoon via several sewage treatment plants that service subdividions near Buccoo Village (Coral Gardens Estates) and Bon Accord. Sewage pollution in Buccoo Bay presents a significant risk to public health as indicated by consistently elevated concentrations of coliform bacteria and fecal streptococci (John 1996).

Although there has been a long history of both sewage pollution and research designed to assess its impact on the BRC, there remains little appreciation of the complex ecological consequences of elevated nutrients on the degradation of these biologically diverse coral reef communities. Consequently, no remedial actions have yet been implemented. Kenny (1976) provided one of the first qualitative studies of coral communities in the BRC but did not recognize a vital interrelationship between the inshore waters of Bon Accord Lagoon and the health of the outer coral reef communities; however, he noted that "care should be taken not to increase run-off from the adjacent land and to restrict the entry of pollutants". Laydoo and Heileman (1987) sampled effluents from sewage treatment plants servicing neighboring subdivisions that flow into coastal waters of the BRC. They detected deleterious effects from the sewage and recommended upgrading the treatment facilities on the Buccoo Reef watershed. In 1994, the Institute of Marine Affairs completed a management plan for the BRC (IMA 1994) that specifically recognized sewage impacts (i.e. fecal coliform contamination) to the inshore waters of Buccoo Bay but not chronic ecological impacts to the more offshore coral reef communities.

Like the BRC, fringing reefs around much of Tobago are receiving increasing nutrient loads from poorly or inadequately treated sewage effluents. Both large and small communities rely on "soak-aways" as on the BRC catchment. In some cases, attempts have been made to develop centralized collection and treatment systems for sewage. But, once again, the systems provide only secondary-level treatment at best (no nutrient removal) and are usually inadequate for the end-volume, resulting in BOD and nutrient-rich discharges into rivers or wetlands that eventually flow into coastal waters. To specifically assess the chemical and ecological impacts of sewage pollution in the BRC and other fringing reefs around Tobago, we initiated an integrated water quality and coral reef monitoring program in April 2001. The study involved measurement of ultra-low concentrations of water column dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP), and chlorophyll-a. Underwater video monitoring of benthic reef communities was used to quantify cover of hard corals, octocorals, macroalgae, turf algae, coralline algae, and sponges. Finally, determination of stable nitrogen isotope ratios ($\delta^{15}N$) in benthic macroalgae was used to discriminate among natural (N-fixation) versus anthropogenic (e.g. sewage, fertilizers) nitrogen sources fueling coastal eutrophication.

MATERIALS AND METHODS

Reef Sampling and Rationale

We sampled a total of four reef sites for water quality and biotic cover in the BRC along an inshore to offshore gradient between April 5 and 12, 2001. The sites included: Princess Reef and Buccoo Point Reef in the inner BRC and Coral Gardens and Outer Reef in the offshore areas of the BRC. In addition, samples were collected at Walkabout Reef and Nylon Pool in the middle of the BRC for the water quality variables and at a sewage outfall in Buccoo Bay for $d^{15}N$ in benthic macroalgae. We predicted that the inshore sites at the BRC would show the strongest evidence of nutrient pollution and advanced eutrophication from land-based runoff. In addition, a variety of fringing reefs around Tobago's Caribbean and Atlantic coasts were sampled for biotic cover, water quality, and $d^{15}N$ in benthic macroalgae between June 5 and 8, 2001, which included: Mt. Irvine "Wall", the Maverick (a sunken ship-artificial reef), Diver's Dream, Diver's Thirst, Culloden, Arnos Vale, Englishman's Bay, Three Sisters and, off Little Tobago Island, Kelliston Drain and Black Jack Hole. We predicted that evidence of nutrient enrichment and eutrophication would be relatively minimal off Little Tobago Island that is the site furthest offshore and flushed with oceanic "blue water" waters of the Guyana Current. This is especially true during the dry season when we conducted this study as the plume of the Orinoco River does impact much of Tobago's coastal waters during the wet season (July through November). Alternatively, we predicted greater evidence of impacts from nutrient enrichment and eutrophication on the fringing reef sites more directly impacted by land-based runoff, which includes sites at Mt. Irvine, the Maverick, Diver's Dream and Diver's Thirst that are hydrographically downstream of Scarborough or other urbanized watersheds on the southwest coast of Tobago.

Quantification of Reef Biota

SCUBA divers used an underwater digital video camcorder (Sony TRV 900 in an Amphibico Navigator housing, 100 degree spherical lens) to record imagery along two replicate 50 m long belt transects at each reef site. Divers obtained the imagery by holding the camcorder perpendicular to the reef surface (0.5 m off bottom, 0.4 m^2/image area) and slowly swimming along the transects to obtain clear, steady images. A second close-up oblique video transect was also recorded to allow identification of algal taxa and to distinguish among the fine-scale (1-5 cm) changes in biotic composition among these diverse and often multi-layered communities. The high resolution video images were anaylzed on a high resolution monitor using the random point-count method. This method provided a relatively unbiased estimate of the percent cover of hard corals, macroalgae (> 2 cm tall), algal turf (< 2 cm tall), coralline algae, sponges, and octocorals (Lapointe and Thacker 2002). Two independant scorers used the point-count method (with ten randomized dots superimposed over the video image) to score ten randomly selected images from each 50 m reef transect (200 point counts/reef site x 2 scorers = 400 total point counts per reef site).

Collection and Analysis of Seawater for DIN, SRP, and Chl-a

Divers used clean, one liter polyethylene Nalgene bottles to collect replicate (n = 4) seawater samples ~ 1 m off the bottom at the various reef sites. The water samples were held on ice in the dark in a cooler until return to shore where aliquots of the samples were filtered through a 0.45 µm GF/F filter and frozen. The samples were analyzed for DIN (= NH_4^+ plus NO_3^- plus NO_2^-) and SRP on a Bran and Luebbe TRAACS Analytical Console at Harbor Branch Oceanographic Institution's Environmental Laboratory in Ft. Pierce, FL. The methods for collection, handling, and processing of all nutrient samples followed a quality assurance/quality control protocol developed by HBOI's Environmental Lab. This plan prevented problems associated with sample contamination and excessive holding times. Salinity of the water samples was measured to ± 1.0 ‰ using a Bausch and Lomb refractometer. The GF/F glass fiber filters used for filtering the water samples were frozen and analyzed for chlorophyll-a (chl-a) as a measure of phytoplankton biomass. The filters were extracted for 30 minutes using 10 ml of dimethyl sulfoxide and then with an added 15 ml of 90% acetone at 5 °C overnight in the laboratory of Dr. Larry Brand, University of Miami, Miami, FL. The samples were measured fluorometrically before and after acidification for determination of chl-a and phaeopigment concentrations. Fluorescence measurements were made using a Turner Designs 10-000R fluorometer equipped with a infrared-sensitive photomultiplier and calibrated using pure chlorophyll a.

Collection and Analysis of Reef Macroalgae for $\delta^{15}N$

SCUBA divers collected samples of macroalgae from the various reef sites between April 10 and June 20, 2001 during the spring dry season. Water temperatures and depths at the reef sites were measured using Oceanic Datamax Pro Plus dive computers. Immediately following the collection, the macroalgae were sorted to species, cleaned of debris, and transferred to plastic zip-loc baggies in a cooler. Back on shore in the lab, the samples were identified, rinsed briefly in deionized water to further remove debris and then randomly sorted into two replicate composite samples per species (~ 3-6 plants per composite). The plants were placed in plastic drying dishes and dried in a lab oven at 65 °C for 48 hours. The dried macroalgae were ground to a fine powder using a mortar and pestle and stored in plastic vials until analysis. Samples of dried, powdered macroalgae were analyzed for stable nitrogen isotope ratios with a Carlo-Erba N/A 1500 Elemental Analyzer and a VG Isomass mass spectrometer using Dumas combustion (by Isotope Services, Los Alamos, New Mexico). The standard used for stable nitrogen isotope analysis was N_2 in air. $\delta^{15}N$ values, expressed as ‰, were calculated as $[(R_{sample}/R_{standard}) - 1] \times 10^3$, with R equal to $^{15}N/^{14}N$.

RESULTS

Quantification of Reef Biota

The four reef sites in the BRC showed a distinct offshore trend in % cover of macroalgae and hard corals. The highest % cover values for macroalgae, up to 40 %, occurred at the inner BRC sites (Princess Reef, Buccoo Point Reef) where blooms of *Halimeda opuntia*, *Bryopsis* spp., and *Caulerpa* spp. occurred in April (Figure 1). Coral cover was low on these two sites, < 10 %, compared to the more offshore sites (Coral Gardens, Outer Reef) that coral cover ranging from 20 to 40 % and comprised of the genera *Acropora*, *Montastrea*, *Diploria*, and *Siderastrea* (Figure 1). Algal turf was a major component of these reef communities with values ranging from up to ~ 50 % cover. The zoanthid *Palythoa* was a significant component of these reef communities and ranged up to > 20 % cover at Buccoo Point Reef where it was observed to be physically overgrowing the brain coral *Diploria* (Figure 1). The fringing reef sites around Tobago had the highest % cover value for hard corals (i.e. Culloden, > 50 % cover), lower % cover of macroalgae (< 10 % cover), high cover of coralline algae (up to ~ 30 % cover), and high cover of algal turf (> 50 % cover, Figure 1).

Seawater DIN, SRP and Chl-a

DIN concentrations were relatively high in the BRC, averaging ~ 1 - 1.5 µM on the outer reef sites and 0.7 - 0.9 µM at the inner reef sites (Figure 2). In contrast, SRP concentrations did not vary among inner and outer reef sites and averaged ~ 0.20 µM throught the BRC (Figure 2). Chl-a values were highest at the two inshore reef sites (0.25 to 0.65 µg/l) and < 0.10 µg/l at the two offshore reef sites (Figure 2).

In general, DIN concentrations were relatively low at the fringing reef sites around Tobago, with a few notable exceptions (Figure 3). DIN was lowest at Black Jack Hole off Little Tobago Island (< 0.20 µM) and highest at Arnos Vale and Culloden (~ 1.0 µM, Figure 3). In general, DIN values increased from Englishman's Bay to Culloden along Tobago's Caribbean coast although values decreased at Mt. Irvine and the Maverick off southwest Tobago where high chl-a concentrations occurred (Figure 3). Like the BRC, there were no significant patterns in SRP among the reef sites with average values ranging from 0.20 - 0.30 µM (Figure 3). Chl-a values increased significantly from the low background values (~ 0.1 µg/l) at Kelliston Drain and Black Jack Hole off Little Tobago Island to higher values at

Englishman's Bay (~ 0.3 µg/l), Mt. Irvine (~ 0.6 µg/l), and the Maverick (~ 0.6 µg/l, Figure 3).

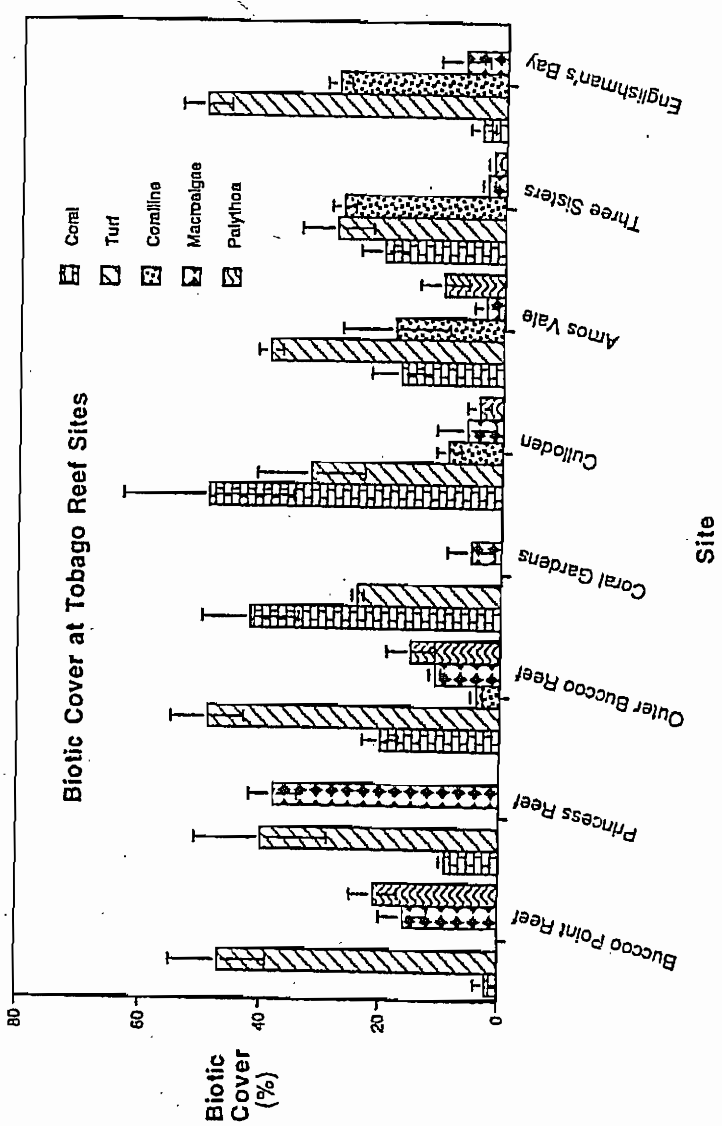

Figure 1. Biotic cover of four reef sites in the Buccoo Reef Complex (Buccoo Point Reef, Princess Reef, Outer Buccoo Reef, Coral Gardens) and four other reefs (Culloden, Amos Vale, Three Sister's, Englishman's Bay) on Tobago's Caribbean coast. Values represent means ± 1 SD (n = 2 replicate 50 m transects; a total of 400 point counts per reef).

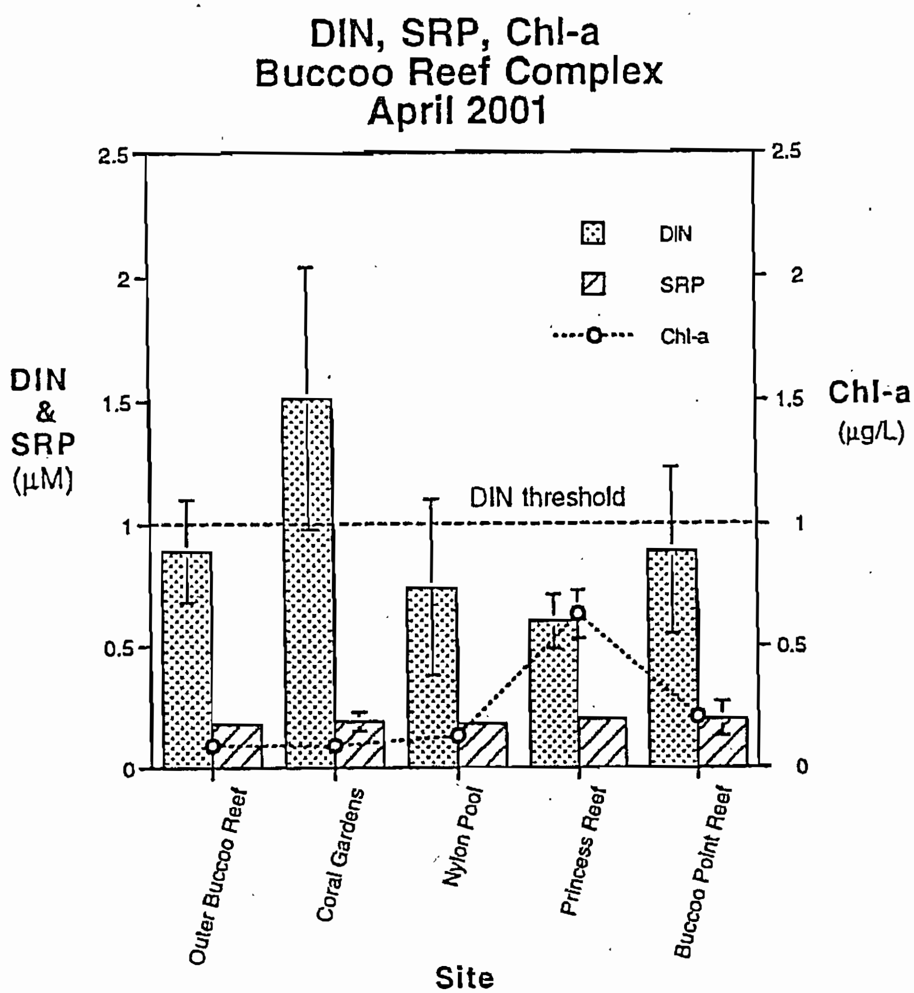

Figure 2. Water column dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP), and chlorophyll a (chl-a) concentrations at five sampling sites in the Buccoo Reef Complex. Values represent means ± 1 SD (n = 4).

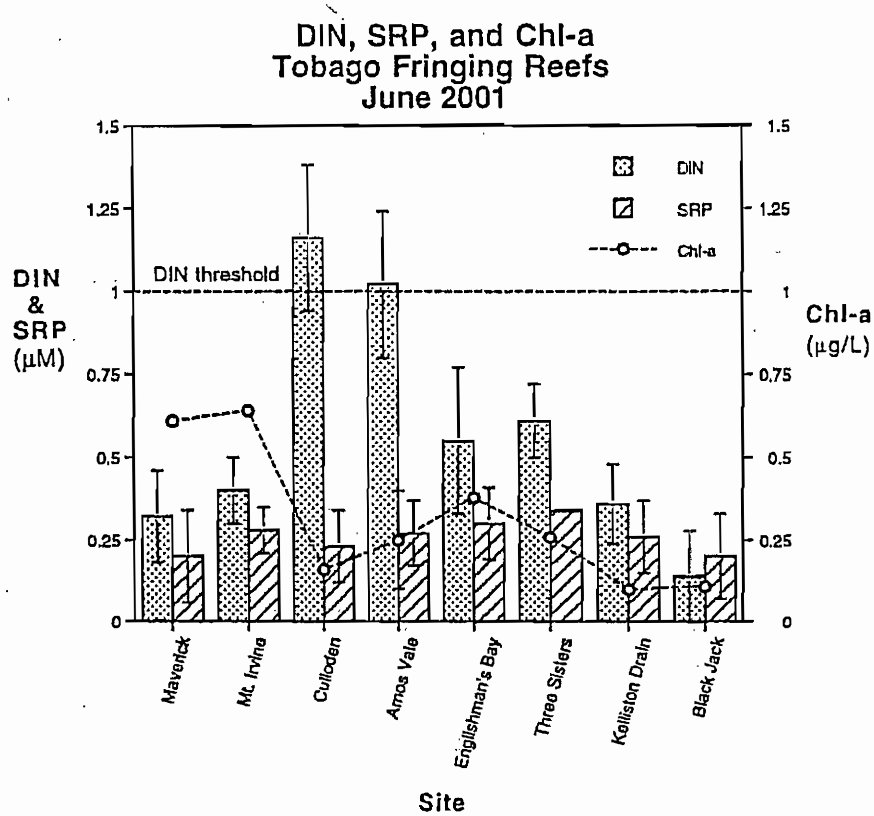

Figure 3. Water column dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP), and chlorophyll a (chl-a) concentrations at eight fringing reef sites around Tobago. Values represent means ± 1 SD (n = 4).

$\delta^{15}N$ of Reef Macroalgae

The mean $\delta^{15}N$ values of reef macroalgae on Tobago's reef ranged from a high value at the sewage outfall in Buccoo Bay to the lowest value at Black Jack Hole off Little Tobao Island (Figure 4). The $\delta^{15}N$ values of macroalgae in the BRC decreased with increasing distance from shore from a high of + 11.77 ‰ at the Buccoo Bay sewage outfall to + 6.98 ‰ at Princess Reef, + 6.42 ‰ at Buccoo Point Reef, + 6.22 ‰ at Walkabout Reef, + 6.24 ‰ at Outer Buccoo Reef, and + 5.30 ‰ at Coral Gardens (Figure 5). The average $\delta^{15}N$ value for macroalgae from the

Buccoo Bay sewage outfall was significantly (ANOVA, Fisher's PLSD test, $P < 0.0001$) higher than the average values for Princess Reef, Buccoo Point Reef, Walkabout Reef, Outer Buccoo Reef, Coral Gardens, and the other fringing reef sites around Tobago. In addition, the average $\delta^{15}N$ value of macroalgae from Princess Reef was significantly (ANOVA, Fisher's PLSD test, $P = 0.039$) higher than that of Coral Gardens (Figure 5).

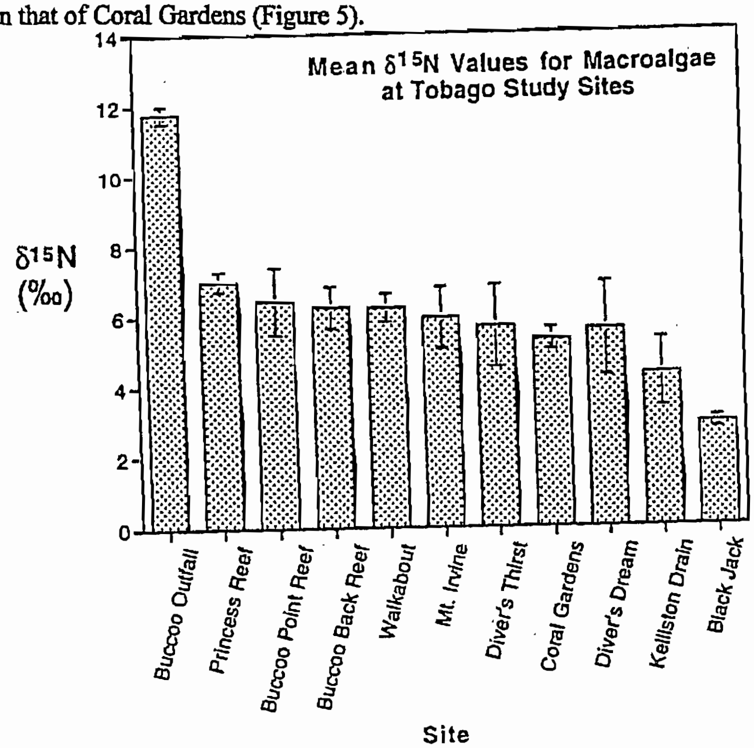

Figure 4. Mean $\delta^{15}N$ values for reef macroalgae from eleven reef sites, which includes six from the Buccoo Reef Complex (Buccoo Outfall, Princess Reef, Buccoo Point Reef, Walkabout Reef, Coral Gardens) and five other fringing reef sites around Tobago. Values represent means ± 1 SD ($n > 4$).

For the fringing reef sites around Tobago, the $\delta^{15}N$ values of macroalgae decreased from the highest value of + 5.93 ‰ at Mt. Irvine to + 5.66 ‰ at Diver's Thirst, + 4.58 ‰ at Diver's Dream, + 4.33 ‰ at Kelliston Drain and + 2.88 ‰ at Black Jack Hole (Figure 6). The average $\delta^{15}N$ value for macroalgae from Black Jack Hole was significantly (ANOVA, Fisher's PLSD test) lower than all other reef sites in the study, including Kelliston Drain ($P = 0.047$), Diver's Dream ($P = 0.037$), Diver's Thirst ($P = 0.0003$), Mt. Irvine ($P = 0.0003$), Coral Gardens ($P = 0.0083$), Outer Buccoo Reef ($P = 0.0002$), Walkabout Reef ($P < 0.0001$), Buccoo Point Reef ($P < 0.0001$), Princess Reef ($P < 0.0001$), and the Buccoo Bay outfall ($P < 0.0001$).

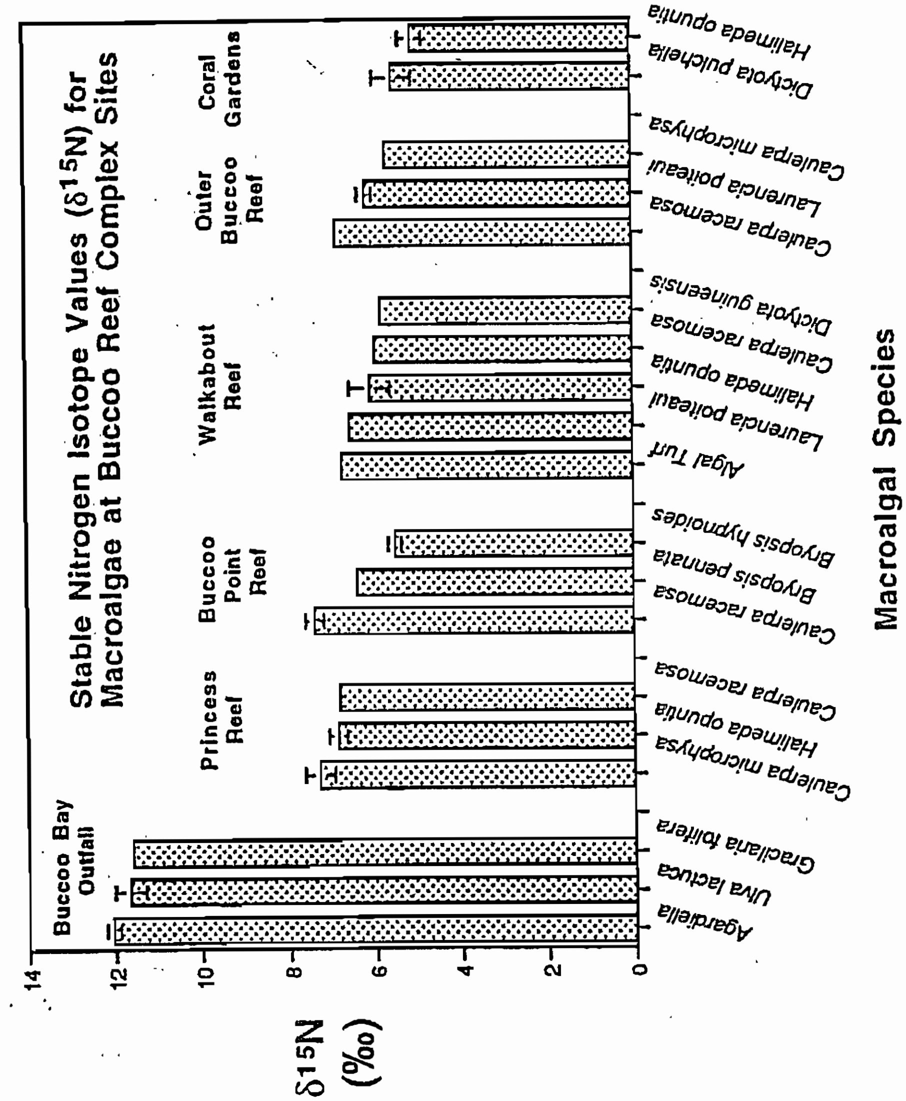

Figure 5. $\delta^{15}N$ values for reef macroalgae from six sites in the Buccoo Reef Complex (Buccoo Outfall, Princess Reef, Buccoo Point Reef, Walkabout Reef, Coral Gardens, Outer Buccoo Reef). Values represent means ± 1 SD (n = 2).

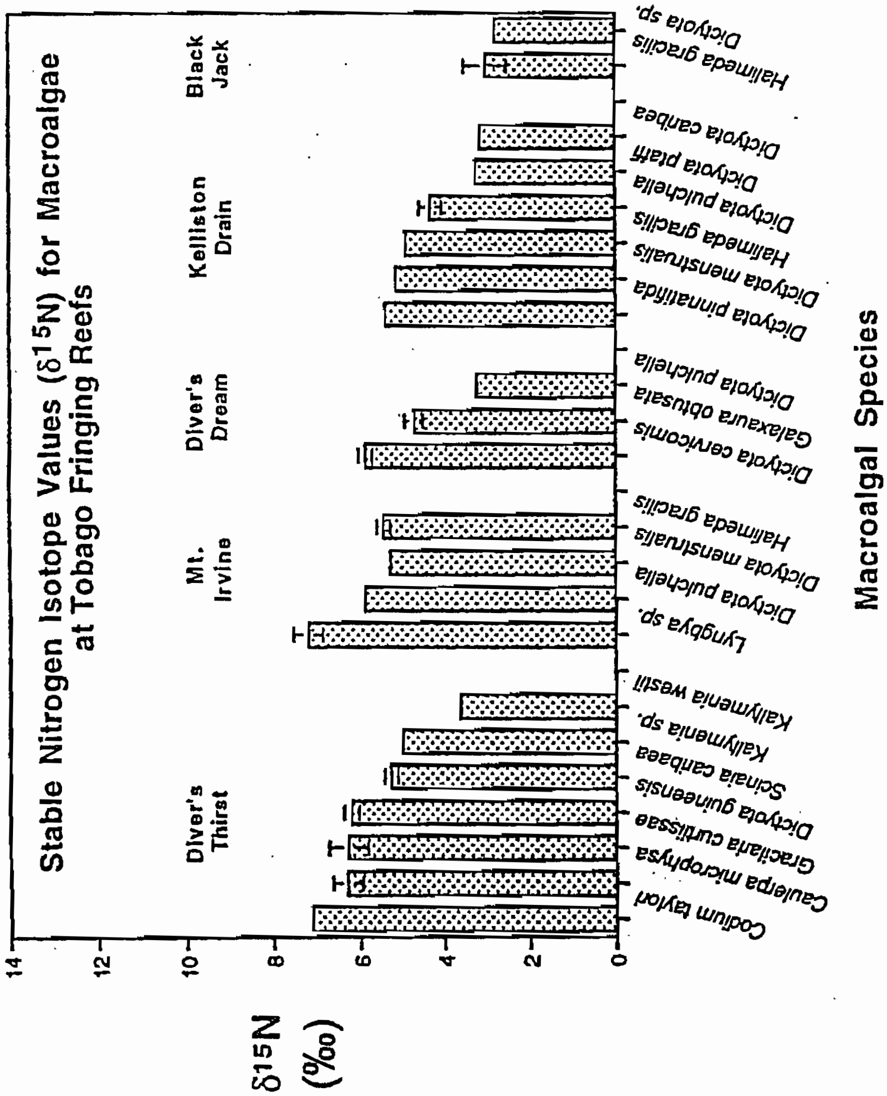

Figure 6. $\delta^{15}N$ values for reef macroalgae from five fringing reef sites around Tobago. Values represent means ± 1 SD (n = 2).

DISCUSSION

Our assessment of water quality and reef health on Tobago's fringing reefs is the first to document the primary role of land-based nitrogen runoff in fueling coastal eutrophication processes on these fringing coral reefs. Previous studies in the Republic of Trinidad and Tobago have emphasized the role of land-based phosphorus pollution from industrial (Kumarsingh et al. 1998) and domestic (Kumarsingh et al. 1998) wastewaters. However, the relatively high background SRP concentrations throughout the study area (~ 0.20 μM), combined with low DIN:SRP ratios (< 5:1), clearly indicate nitrogen rather than phosphorus limitation of primary production (Lapointe 1999). Such high background SRP concentrations, low DIN:SRP ratios, and tendancy towards DIN-limitation are indicative of a siliciclastic geology and contrasts with carbonate-rich environments found in Jamaica, the Bahamas, and the Florida Keys where low SRP concentrations and high DIN:SRP ratios tend towards SRP-limitation (Lapointe et al. 1992). Hence, the natural volcanic geology of Tobago may predispose its coastal waters for nitrogen rather than phosphorus limitation.

The strong DIN-limitation was evident from the inverse relationship between DIN concentration and phytoplankton biomass in the BRC and on fringing reefs along Tobago's Caribbean coast. In both cases, maximum phytoplankton biomass (chl-a) correlated with decreased DIN concentrations (but not SRP). This pattern results from rapid uptake of DIN – the primary limiting nutrient-- by phytoplankton "blooms" in coastal waters receiving land-based sewage pollution. These findings support previous observations in Kaneohe Bay, Hawaii (Laws and Redalje 1979) and the Florida Keys (Lapointe and Clark 1992) that chl-a provides a good "integrated" index of eutrophication in tropical and subtropical coastal waters. The generally low DIN concentrations on Tobago's fringing reefs (< 0.3 μM), especially off Little Tobago Island, not only limits phytoplankton biomass, but also the growth of macroalgae. Mean DIN concentrations > 0.5 μM are needed to support "blooms" of benthic macroalgae, such as those we observed on reef sites in the inner BRC. Classic "indicator species" of nutrient enrichment, including the macroalgae *Ulva*, *Halimeda*, *Bryopsis*, *Caulerpa*, and *Sargassum* were abundant on reefs in the BRC that had DIN concentrations > 0.5 μM. In contrast, macroalgae were less abundant on the fringing reefs around Tobago that had lower DIN concentrations.

The elevated $\delta^{15}N$ values of macroalgae in the BRC and other reefs around southwest Tobago are indicative of macroalgae growing in sewage polluted coastal waters. Several studies have shown that $\delta^{15}N$ values of macroalgae can be used to effectively discriminate among various natural and anthropogenic nitrogen sources. France et al. (1998) showed that 21 species of tropical macroalgae in coastal waters of southwestern Puerto Rico had a mean $\delta^{15}N$ of 0.3 ± 1.0 ‰, which is close to the atmospheric signature of 0 ‰ and indicative of nitrogen fixation as the source of nitrogen. For nitrogen derived from sewage, the macroalgae *Cladophora vagabunda*, *Gracilaria tikvahiae*, and *Enteromorpha sp.* from the Childs River estuary, which receives substantial N loading from septic tanks via submarine groundwater discharges, had elevated $\delta^{15}N$ values of 5.4, 7.6, and 8.4 ‰; even estuaries with relatively low rates of sewage N loading showed elevated $\delta^{15}N$ values in macroalgae (McClelland and Valiela 1998). Six species of macroalgae from Boston Harbor, which has been polluted by sewage for many decades, had a mean

$\delta^{15}N$ value of 6.5 ± 0.7 ‰ (France et al. 1998). In Negril, Jamaica, Lapointe and Thacker (2001) reported a $\delta^{15}N$ value of + 5.0 ‰ for human sewage from "soak-aways" and values of + 5.0 to + 6.5 ‰ for macroalgae on reefs adjacent to or downstream of sewage pollution. Based on this evidence, we suggest that the entirety of the BRC has been impacted by DIN derived from septic tank or "soak-away" sewage. Higher $\delta^{15}N$ values of +10.0 ‰ occur in secondarily-treated wastewater effluent (Lindau et al. 1989) and indeed, we observed similarly high values for macroalgae at the sewage treatment plant outfall in Buccoo Bay. Lower but elevated $\delta^{15}N$ values occurred in macroalgae at other reef sites in southwest Tobago, suggesting widespread sewage DIN enrichment on reefs downstream of urban and population centers. The lowest $\delta^{15}N$ values of + 2.5 ‰ for macroalgae at Black Jack Hole off Little Tobago Island were indicative of more oligotrophic and "natural" nitrogen sources, although these levels are still elevated above what would be expected for nitrogen-fixation alone (~ 0.5 ‰).

The loss of hard coral cover and replacement by macroalgal "blooms" on Jamaican coral reefs over the past two decades has been attributed simply to the "top-down" effects of overfishing (via fish traps) of herbivorous fish stocks (Hughes 1994). However, similar loss of hard corals and macroalgal blooms have occurred over the past two decades in the BRC, a MPA with abundant schools of parrotfish (including large adults), surgeonfish, and chubs. However, as described here, the BRC has also been polluted by land-based sewage inputs. The most sewage impacted inshore reef in the BRC (Princess Reef) not only had extensive macroalgal blooms (*Caulerpa, Halimeda*) but also had dense populations of reef urchins (*Echinometra viridis*). These observations point to "bottom-up" control (i.e. nutrients) of not only the macroalgal biomass, but the echinoid populations as well. Hunter and Price (1992) suggested that a "bottom-up template" is the most realistic approach for understanding trophic dynamics in ecosystems because plants have obvious primacy in food webs. We concur and suggest that sewage nitrogen subsidies over recent decades may have increased grazer populations (both echinoids and herbivorous fishes) in the BRC where growth is typically limited limited by dietary nitrogen (Lapointe 1999). Unfortunately, coral cover, biodiversity, and the economic value for tourism have all been reduced by sewage-driven eutrophication in the BRC despite abundant populations of grazers. These results support the conclusion of Agard and Gobin (2000) that the most important source of urban pollution in Trinidad and Tobago is domestic sewage, which appears to be impacting not only the BRC but also other fringing coral reefs "downstream" of Tobago's populated southwest coast.

LITERATURE CITED

Agard, J. B. R. and J.F. Gobin. 2000. The Lesser Antilles, Trinidad and Tobago. Pages 627-641 in: C. Sheppard (ed.) *Seas at The Millennium: An Environmental Evaluation.*

Costa, O.S., Z. M. A. N. Leao, M. Nimmo, and M.J. Attrill. 2000. Nutrification impacts on coral reefs from northern Bahia, Brazil. *Hydrobiologia* **440**:307-315.

France, R., J. Holmquist, M. Chandler, and A. Cattaneo. 1998. $\delta^{15}N$ evidence for nitrogen fixation associated with macroalgae from a seagrass-mangrove-coral reef ecosystem. *Marine Ecology Progress Series* **167**: 297-299.

Hughes, T. 1994. Catastrophes, phase-shifts, and large-scale degradation of a Caribbean coral reef. *Science* **265**:1547-1551.

Hunter, M.D. and P.W. Price. 1992. Playing chutes and ladders: heterogeneity and the relative roles of bottom-up and top-down forces in natural communities. *Ecology* **73**:724.

IMA 1994. The formulation of a management plan for the Buccoo Reef Marine Park. Volume 3. Biological investigations and water quality monitoring. Institute of Marine Affairs. Prepared for the Tobago House of Assembly. 58pp.

John, G.M. 1996. Quantitative characteristics of land-based sources of marine pollution in the vicinity of the Buccoo Reef Marine Park, Tobago. MS Thesis, University of the West Indies, Department of Biology. Cave Hill Campus, Barbados.

Kenny, J.S. 1976. A preliminary study of the Buccoo Reef/ Bon Acord Complex with special reference to development and Management. Department of Biological Sciences, University of the West Indies. St. Augustine. 123 pp.

Kumarsingh, K., L.A. Hall, A.M. Siunng-Chang, and V.A. Stoute. 1998. Phosphorus in sediments of a shallow bank influenced by sewage and sugar factory effluents in Trinidad, West Indies. *Marine Pollution Bulletin* **36**:185-192.

Kumarsingh, K., R. Laydoo, J.K. Chen, and A.M. Siunng-Chang. 1998. Historic records of phosphorus levels in the reef-building coral *Montastrea annularis* from Tobago, West Indies. *Marine Pollution Bulletin* **36**:1012-1018.

Lapointe, B.E., J.D. O'Connell and G.S. Garrett. 1990. Nutrient couplings between on-site sewage disposal systems, groundwaters, and nearshore surface waters of the Florida Keys. *Biogeochemistry* **10**:289-308.

Lapointe, B.E., M.M. Littler, and D. S. Littler. 1992. Nutrient availability to marine macroalgae in siliciclastic versus carbonate-rich coastal waters. *Estuaries* **15**:75-82.

Lapointe, B.E. 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. *Limnology and Oceanography* **42**:1119-1131.

Lapointe, B.E. 1999. Simultaneous top-down and bottom-up forces control macroalgal bloom on coral reefs. *Limnology and Oceanography* **44**:1586-1592

Lapointe, B.E. and K. Thacker. 2002. Community-based water quality and coral reef monitoring in the Negril Marine Park, Jamaica: Land-based nutrient inputs and their ecological consequences. Pages 939-963 in: J.W. Porter and K.G. Porter (eds.) *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys.* CRC Press. Boca Raton, Florida USA.

Laydoo, R.S. and L. Heileman. 1987. Environmental impacts of the Buccoo and Bon Accord Sewage Treatment plants, southwestern Tobago. A preliminary report. Institute of Marine Affaires and Crusoe Reef Society. 27 pp.

Laydoo, R.S. 1991. A guide to the coral reefs of Tobago. Institute of Marine Affairs and the Asa Wright Nature Centre, Republic of Trinidad and Tobago. 43 pp.

Lindau, C.W., R.D. Delaune, W.H. Patrick, Jr., and E.N. Lambremont. 1989. Assessment of stablenitrogen isotopes in fingerprinting surface water inorganic nitrogen sources. *Water Air Soil Pollutution* **48**:489-496.

Likens, G.E. 2001. Biogeochemistry, the watershed approach: some uses and limitations. *Marine and Freshwater Research* **52**:5.

McClelland, J. and I. Valiela. 1998. Changes in food web structure under the influence of increased anthropogenic nitrogen inputs to estuaries. *Marine Ecology Progress Series* **168**:259-271.

NRC (National Research Council) 2000. Clean coastal waters: understanding and reducing the effects of nutrient pollution. National Academy Press, Washington, DC.

UNEP 1994. Regional overview of land based sources of pollution in the wider Caribbean region, in *Caribbean Environment Program Technical Report* # 33, UNEP Caribbean Environment Program. Kingston, Jamaica.