Land-based nutrient enrichment of the Buccoo Reef Complex and fringing coral reefs of Tobago, West Indies

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A B S T R A C T

Tobago’s fringing coral reefs (FR) and Buccoo Reef Complex (BRC) can be affected locally by wastewater and stormwater, and regionally by the Orinoco River. In 2001, seasonal effects of these inputs on water-column nutrients and phytoplankton (Chl a), macroalgal C:N:P and δ15N values, and biorocover at FR and BRC sites were examined. Dissolved inorganic nitrogen (DIN, particularly ammonium) increased and soluble reactive phosphorus (SRP) decreased from the dry to wet season. Wet season satellite and Chl a data showed that Orinoco runoff reaching Tobago contained chromophoric dissolved organic matter (CDOM) but little Chl a, suggesting minimal riverine nutrient transport to Tobago. C:N ratios were lower (16 vs. 21) and macroalgal δ15N values higher (6.6‰ vs. 5.5‰) in the BRC vs. FR, indicating relatively more wastewater N in the BRC. High macroalgae and low coral cover in the BRC further indicated that better wastewater treatment could improve the health of Tobago’s coral reefs.

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1. Introduction

Coral reefs are biologically diverse, economically valuable ecosystems that provide an array of ecological services to coastal communities. Coral reefs flourish in tropical and subtropical oligotrophic waters and are susceptible to eutrophication as a result of low level nutrient pollution (Johannes, 1975; NRC, 2000). Early studies in Kaneohe Bay, Hawaii, showed that reef corals can be overgrown by macroalgae when small increases in nutrient concentrations (nitrogen and/or phosphorus) occur as a result of sewage pollution (Banner, 1974; Smith et al., 1981). In the Caribbean region, pollution from land-based sources is considered one of the most important threats to the marine environment and to the sustainable use of its resources (UNEP, 1994). Sources of nutrient pollution include sewage outfalls, septic tanks, stormwater, and regionally by the Orinoco River. In 2001, seasonal effects of these inputs on water-column nutrients and phytoplankton (Chl a), macroalgal C:N:P and δ15N values, and biorocover at FR and BRC sites were examined. Dissolved inorganic nitrogen (DIN, particularly ammonium) increased and soluble reactive phosphorus (SRP) decreased from the dry to wet season. Wet season satellite and Chl a data showed that Orinoco runoff reaching Tobago contained chromophoric dissolved organic matter (CDOM) but little Chl a, suggesting minimal riverine nutrient transport to Tobago. C:N ratios were lower (16 vs. 21) and macroalgal δ15N values higher (6.6‰ vs. 5.5‰) in the BRC vs. FR, indicating relatively more wastewater N in the BRC. High macroalgae and low coral cover in the BRC further indicated that better wastewater treatment could improve the health of Tobago’s coral reefs.

Like many marine protected areas in the Caribbean region, creation of the BRMP has not protected the area from water quality degradation. Many coastal dwellings in the adjacent Buccoo Village area, for example, have septic tanks and “soak-away” systems dug into the porous limestone that overlies the island’s volcanic foundation. This rudimentary sewage disposal technology provides little removal of nitrogen, which is highly mobile in carbonate-rich systems and is transported via groundwater into coastal waters (Lapointe et al., 1990; Costa et al., 2000; Lapointe and Thacker, 2002). Similarly, secondarily treated sewage, a technology that does not remove dissolved nutrients sufficiently to protect coral reef ecosystems, enters Buccoo Bay and the Bon Accord Lagoon from several sewage treatment plants servicing subdivisions near Buccoo Village (Coral Garden Estates) and Bon Accord. Sewage pollution in Buccoo Bay presents a significant risk to public health as indicated by chronically elevated coliform bacteria and fecal streptococci counts (John, 1996).

There has long been concern about sewage pollution in the BRC, but little study of how it drives the eutrophication and degradation
of these coral reef communities. Kenny (1976) provided one of the first qualitative studies of coral communities in the BRC and noted that “care should be taken not to increase runoff from the adjacent land and to restrict the entry of pollutants”. Laydoo and Heileman (1987) sampled effluents from sewage treatment plants servicing subdivisions on the watershed of the BRC and recommended upgrading the treatment facilities throughout the Buccoo Reef watershed. In 1994, the Institute of Marine Affairs completed a management plan for the BRMP (IMA, 1994) that specifically recognized sewage impacts (i.e. fecal coliform contamination) in the inshore waters of Buccoo Bay, but the plan did not address the chronic ecological impacts of nutrient pollution on the coral reef communities.

Like the BRC, other fringing reefs around Tobago’s coast could be receiving increasing nutrient loads from inadequately treated sewage effluent. Both large and small communities rely on “soak-aways”, as on the BRC watershed, or on centralized sewage collection and treatment systems that provide, at best, secondary treatment (no nutrient removal) and are usually undersized, resulting in nutrient-rich effluent discharges into rivers or wetlands, which eventually flow into coastal waters.

To specifically assess the chemical and ecological impacts of sewage pollution in the BRC and on the fringing reefs around Tobago, we undertook a water quality and coral reef monitoring project in 2001. The project involved two rounds of sampling – April–June (dry season) and September–October (wet season) – to allow monitoring of seasonal effects, including that of the Orinoco River floodwater plume, which impacts Tobago’s coastal waters during the wet season (Laydoo, 1991; Risk et al., 1992). Measured variables included: water-column dissolved inorganic nitrogen (DIN; ammonium and nitrate + nitrite), soluble reactive phosphorus (SRP), and chlorophyll a (Chl a); macroalgal tissue carbon (C), nitrogen (N), phosphorus (P), and stable N isotope (δ¹⁵N) ratios; and benthic biotic cover (hard corals, octocorals, macroalgae, turf algae, coralline algae, and sponges). δ¹⁵N in benthic macroalgae was used to discriminate among natural (N-fixation) and anthropogenic (e.g. sewage) N sources fueling algal blooms and eutrophication in the study area.

2. Materials and methods

2.1. Study sites and sampling rationale

To assess the effects of land-based nutrient discharges on near-shore benthic community structure, six reef sites in the BRC were sampled along an inshore to offshore gradient (Fig. 1). In the inner BRC nearest shore were Princess Reef, just offshore of the house where Princess Margaret once honeymooned, and Buccoo Point near Buccoo Village, where a sewage outfall is located; in the mid-BRC were Walkabout Reef, where glass-bottom boat tour operators allow people to disembark and walk on the back reef (Fig. 2A), and Nylon Pool, where seagrasses have recently invaded (Fig. 2D); and in the outer BRC farthest from shore were Coral Gardens and Outer Buccoo Reef (Fig. 1). We predicted that the inner BRC sites would show the strongest evidence of nutrient enrichment from land-based runoff and that there would be decreasing impact with increasing distance from shore. In addition, a variety of fringing reefs (FRs) around Tobago’s Caribbean and Atlantic coasts were sampled, including some well known dive sites: Mt. Irvine “Wall”, the Maverick (a sunken ship artificial reef), Diver’s Dream, Hilton Reef (offshore of what is now the Tobago Vanguard Hotel), Diver’s Thirst, Culloden, Arnos Vale, Englishman’s Bay, Three Sisters, and two sites off Little Tobago Island: Kellistin Drain and Black Jack Hole (Fig. 1). We hypothesized that nutrient enrichment would be relatively minimal off Little Tobago Island, the site farthest offshore, in the oceanic “blue water” of the Guyana Current. Conversely, greater nutrient enrichment would occur on the
FRs more directly impacted by land-based runoff from the urbanized areas of southwest Tobago, including the six sites in the BRC as well as Hilton Reef, Mt. Irvine, the Maverick, Diver’s Dream and Diver’s Thirst. All sites were sampled in both the dry and wet seasons of 2001 (see rainfall data, Fig. 3) to assess the effects of stormwater runoff on the seasonal variability of nutrient concentrations, $\delta^{15}$N, and benthic community structure.

2.2. Analysis of seawater for DIN, SRP, and Chl a

SCUBA divers collected water samples from the various reef sites between April 10 and June 20, 2001 (dry season), and between September 24 and October 23, 2001 (wet season). Water temperatures and depths at the reef sites were measured using Oceanic Datamax Pro Plus™ dive computers. Divers used clean, 0.5 L HDPE Nalgene bottles to collect replicate ($n = 4$) seawater samples ~0.5 m off the bottom at each reef site. Water samples were held on ice in the dark until return to shore where aliquots were filtered through 0.45 μm Whatman GF/F filters. Loaded filters and filtered samples were then frozen for shipment to analytical labs where they were analyzed within 30 days of collection. Water samples were analyzed for ammonium, nitrate + nitrite (hereafter referred to simply as nitrate), and SRP at one of two labs: dry season samples were analyzed at the Harbor Branch Environmental Laboratory (HBEL) in Fort Pierce, FL, whereas wet season samples were analyzed at Nutrient Analytical Services, Chesapeake Biological Laboratory, University of Maryland System, Solomons, MD.

Fig. 2. (A) “Reef walking” in the BRC; (B) blooms of Caulerpa racemosa and Halimeda opuntia at Princess Reef in the inner BRC; (C) expansion of the zoanthid Palythoa caribaeorum on outer Buccoo Reef; (D) Nylon Pool, showing underwater dark patches where turtle grass, Thalassia testudinum, has recently invaded; and (E) aerial view of coastal riverine discharges from Tobago during the wet season, 2001.

Fig. 3. Monthly rainfall at Crown Point, Tobago, 2001.
2.3. Analysis of macroalgae for C:N:P and $^{15}$N

SCUBA divers collected replicate ($n = 2$) composite macroalgae samples from each reef site in nylon mesh bags. For each species sampled, 3–6 separate plants were collected for each composite sample to ensure representativeness. Immediately following collection, macroalgae were cleaned of debris and transferred to plastic zipper-lock bags and held in a cooler above ice in the dark for transport to the lab. In the lab, the samples were identified, rinsed briefly (3–5 s) in de-ionized water to remove salt and remaining debris, and placed in plastic dishes for drying in a lab oven at 65 °C for 48 h. Dried macroalgae were ground to a fine powder, using a mortar and pestle, and stored in sealed plastic vials for shipment. $^{15}$N (‰) analyses were performed at Isotope Services, Los Alamos, NM, using a Carlo-Erba N/A 1500 Elemental Analyzer and a VG Isomass mass spectrometer, using Dumas combustion; $N_2$ in air was the standard. $^{15}$N (‰) values were calculated: $^{15}$N = $[$[R$_{\text{sample}}$/R$_{\text{standard}}$] − 1] × 10$^3$, where $R = ^{14}$N/$^{15}$N. Dry season macroalgal tissue C, N, and P (‰) analyses were performed at NAS-CBL, where C and N were measured on an Exeter Analytical, Inc., CBL, where C and N were measured on an Exeter Analytical, Inc., and P was measured following the methodology of Asplia et al. (1976) using a Technicon Auto-Analyzer II (D’Elia et al., 1997).

2.4. Benthic biotic cover

At each site, SCUBA divers used an underwater digital video camcorder (Sony TRV 900 in an Amphibico Navigator housing, 100° spherical lens) to record imagery along two, replicate, 50 m belt transects by holding the camcorder perpendicular to the reef surface (0.5 m off bottom, 0.4 m² image area) while slowly swimming along the transects. A second, close-up, oblique video transect was also recorded to facilitate algal taxa identification and to resolve fine-scale (1–5 cm) changes in biotic composition in these diverse and often multi-layered communities. The digital video images were analyzed on a high resolution color monitor using the random point-count method. This method provides a relatively unbiased estimate of the benthic cover (%) of hard corals, macroalgae (>2 cm tall), algal turf (<2 cm tall), coralline algae, sponges, and octocorals (Lapointe and Thacker, 2002). Two independent scorers used the point-count method (with 10 randomized dots superimposed over the video image) to score ten randomly selected images from each 50 m reef transect (200 point counts/reef site × 2 scorers = 400 total point counts per reef site).

2.5. Satellite remote sensing

Tobago is not isolated, but is affected by the Orinoco and Amazon rivers (Hu et al., 2004b). To help determine whether the study sites were primarily impacted by local discharges or by the Orinoco River plume, data from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument onboard the satellite Terra (1999–present) were analyzed. Level-1 data for 2001 were obtained from the NASA Goddard Space Flight Center (GSFC), and processed using the default algorithms in the software package SeaDAS (version 5.1). Calibrated radiance data were corrected for atmospheric effects and solar/viewing geometry, then used in a blue/green band-ratio algorithm (O’Reilly et al., 2000) to estimate surface water Chl a concentrations (mg m⁻³). The underlying assumption was that the blue light was modulated primarily by phytoplankton. However, because most (>80–90%) of the blue-light absorption was due to chromophoric (colored) dissolved organic matter (CDOM) in the Gulf of Paria and adjacent waters (especially in the Orinoco River plume; Odriozola et al., 2007), such derived “Chl a” was only used as a color index to show the spatial patterns of the different water masses, including the Orinoco River plume. In contrast, the MODIS fluorescence line height (FLH) product, derived from the red bands using a baseline subtraction algorithm (Letelier and Abott, 1996), was nearly immune to CDOM influence (Hu et al., 2005). Hence, FLH was used as a better index to show spatial biomass patterns.

2.6. Statistical analyses

Statistical analyses were performed in SPSS 11 for Mac (www.spss.com) using the Generalized Linear Model (GLM; Type III sum of squares) and Tukey’s HSD (THSD) post hoc test. The GLM ANOVA was used to assess differences between samplings (df = 1) and between the BRC and FR groups (df = 1), and to determine if significant differences existed among sites (df > 1). If differences among sites were determined by GLM to be significant, then THSD multi-comparison tests were performed to identify the source(s) of the difference(s). Differences were considered significant if $p < 0.05$.

3. Results

3.1. Seawater DIN, SRP, Chl a, and Salinity

DIN concentrations (Fig. 4) averaged $1.6 ± 1.1$ μM ($n = 107$) overall and varied both temporally ($p < 0.001$) and spatially ($p = 0.005$) among the sites. Mean DIN (sites pooled) was lower ($p < 0.001$) in the dry season (0.7 ± 0.5 μM; $n = 51$) than in the wet season ($2.4 ± 0.7$ μM; $n = 56$). The seasonal DIN increase was mostly the result of a 4-fold ammonium increase ($p < 0.001$) from the dry season (0.4 ± 0.2 μM; $n = 51$) to the wet season ($1.6 ± 0.6$ μM; $n = 56$). Nitrate increased ($p = 0.001$) 3-fold from the dry season (0.3 ± 0.4 μM; $n = 51$) to the wet season (0.9 ± 0.5 μM; $n = 56$) but was a relatively minor component of the DIN pool compared to ammonium in both seasons, as indicated by consistently low f-ratios (0.32–0.35). The mean DIN in the BRC was higher ($p = 0.012$) than at the FRs in the dry season (0.9 ± 0.5 μM vs. 0.5 ± 0.4 μM) but not in the wet season (2.4 ± 2.5 μM). Lowest mean concentrations of both DIN (1.0 ± 1.1) and ammonium (0.7 ± 0.7) occurred at Buckaloo Point, whereas the highest DIN (2.4 ± 0.7 μM) and ammonium (2.0 ± 0.9 μM) occurred at Buckaloo Point in the inner BRC.

SRP concentrations (Fig. 5) averaged $0.23 ± 0.15$ (n = 107) overall and varied temporally ($p = 0.034$) and spatially ($p < 0.001$). The mean SRP concentration (sites pooled) was higher ($p = 0.011$) in

(NAS-CBL). The HBEL samples were analyzed on a Bran and Luebbe TRAACS 2000 Analytical Console (nitrate + nitrite) and an Alpkem nutrient auto-analyzer (ammonium, nitrite, SRP), with detection limits of 0.08 μM for ammonium, 0.05 μM for nitrate + nitrite, 0.003 μM for nitrite, and 0.01 μM for SRP. The NAS-CBL samples were analyzed on a Technicon Auto-Analyzer II (nitrate, SRP) and a Technicon TRAACS 800 (ammonium, nitrite), with detection limits of 0.21 μM for ammonium, 0.01 μM for nitrate + nitrite, 0.01 μM for nitrite, and 0.02 μM for SRP (D’Elia et al., 1997). A modified f-ratio (nitrate/DIN) was used to gauge the relative abundance of nitrate vs. ammonium in the DIN pool (McCarthy et al., 1975; Harrison et al., 1987). Salinity was measured to within ±1% using a Bausch and Lomb refractometer. The GF/F filters used for filtering the water samples were analyzed for Chl a by extraction in 10 ml of dimethyl sulfoxide for 30 min, then overnight at 5 °C with an added 15 ml of 90% acetone. Sample extracts were measured fluorometrically, before and after acidification, to determine Chl a concentration. Fluorescence measurements were made using a Turner Designs 10-000R fluorometer equipped with an infrared-sensitive photomultiplier, calibrated using a pure Chl a standard.
and varied both temporally and spatially. Overall, the mean occurred at Black Jack Hole (0.18 ± 0.09 or during the dry or wet seasons. The lowest SRP concentrations were not significantly different than those at the FRs, either overall during the 2001 dry (April–June) and wet (September–October) seasons. Values represent means ± 1 SD (left) and on the FRs (right) during the 2001 dry (April–June) and wet (September–October) seasons. Values represent means ± 1 SD (n = 4 site−1 sampling−1).

Fig. 4. Ammonium, nitrate, and DIN concentrations (µM), and f-ratios in the BRC (left) and on the FRs (right) during the 2001 dry (April–June) and wet (September–October) seasons. Values represent means ± 1 SD (n = 4 site−1 sampling−1).

Fig. 5. Soluble reactive phosphorus (SRP) concentrations (µM) and DIN:SRP ratios in the BRC (left) and on the FRs (right) during the 2001 dry (April–June) and wet (September–October) seasons. Values represent means ± 1 SD (n = 4 site−1 sampling−1).

DIN:SRP ratio was higher (p < 0.001) in the wet season (14 ± 4; n = 56) than in the dry season (3 ± 3; n = 51). The DIN:SRP ratio was higher (p < 0.001) in the BRC (4 ± 3; n = 20) than on the FRs (2 ± 3; n = 31) in the dry season. However, wet season DIN:SRP was higher (p = 0.008) on the FRs (15 ± 4; n = 44) than in the BRC (12 ± 4; n = 26).

Chl a (Fig. 6) averaged 0.32 ± 0.19 µg/l at all stations throughout the study and varied temporally (p = 0.038) and spatially (p = 0.0031). Overall, Chl a averaged 0.28 ± 0.02 µg/l (n = 51) in the dry season and 0.35 ± 0.17 µg/l (n = 70) in the wet season (sites pooled). The lowest value was at Coral Gardens (0.09 ± 0.02 µg/l) in the dry season and the highest was in the Bon Accord Lagoon (1.13 ± 0.16 µg/l) in the wet season. Dry season Chl a values were similar between the BRC (0.23 ± 0.02 µg/l) and the FRs (0.31 ± 0.12 µg/l), whereas wet season Chl a was higher (p = 0.031) in the BRC (0.41 ± 0.24 µg/l) than on the FRs (0.32 ± 0.10 µg/l).

Salinity varied spatially and seasonally throughout the study. In the dry season, salinity in the middle and outer BRC ranged 36–37‰, with lower values at Buccoo Point reef ranging 33–36‰; on the FRs, salinity ranged 36–37‰. In the wet season, salinity in the BRC ranged 32–36‰, and on the FRs salinity stratification was evident, with lower salinities of 34–36‰ in the surface layer compared to 36–38‰ in the near-bottom layer at most sites.

3.2. C:N:P and δ15N in macroalgae

Macroalgae in the BRC were enriched in N but not P compared to the FRs during the dry season (Table 1). The mean C:N (16 ± 6; n = 16) in the BRC was lower (p = 0.014) than on the FRs (21 ± 7; n = 24), in contrast to the mean C:P values, which were statistically similar (770 ± 294 in BRC vs. 759 ± 385 on the FRs). There was also a higher (p = 0.002) N:P ratio in the BRC (50 ± 16; n = 16) compared to the FRs (35 ± 12; n = 24). The lowest C:N ratio (8) occurred at Buccoo Point in the BRC, the highest (26) at Black Jack Hole off Little Tobago Island. The lowest C:P (444) also occurred at Buccoo Point but the highest (1238) occurred at Coral Gardens in the outer BRC. The lowest N:P (28) occurred at Killistown Drain off Little Tobago Island, the highest (62) at Coral Gardens in the BRC.

Macroalgal δ15N values (Fig. 7) averaged +5.9 ± 1.2‰ (n = 174) throughout the study and varied temporally, spatially, and by taxa. The mean δ15N in the dry season (+5.5 ± 1.2‰; n = 82) was lower than the wet season (+6.1 ± 1.2‰; n = 92). Overall (sites pooled) mean δ15N was lower (p < 0.001) in the FRs (+5.5 ± 1.3‰; n = 94) than it was in the BRC (+6.2 ± 1.1‰; n = 80). The lowest δ15N values among reef sites occurred at Black Jack Hole (+2.5‰) and the highest were at Princess Reef (+7.3‰) in the inner BRC. Among taxa, the highest δ15N values (+12%) were found in the chlorophytes Ulva lactuca and in the rhodophytes Gracilaria.
and Agardhiella subulata, nutrient indicator species collected adjacent to the sewage outfall near Buccoo Point (Fig. 7; Table 1). \( \delta^{15}N \) values varied significantly \( (p < 0.001) \) among macroalgal classes (divisions), with highest values in the rhodophytes \( (+7.0 \pm 2.3\% ; \ n = 30) \), followed by the chlorophytes \( (+6.2 \pm 1.3\% ; \ n = 82) \), and the phaeophytes \( (+5.5 \pm 1.2\% ; \ n = 54) \).

### Table 1

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</tr>
<tr>
<td></td>
<td></td>
<td>Caulerpa opuntia</td>
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<td>26</td>
<td>1379</td>
<td>52</td>
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<td></td>
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<td>Bryopsis hypnoides</td>
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<td>0.23</td>
<td>8</td>
<td>447</td>
<td>54</td>
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<tr>
<td></td>
<td></td>
<td>Bryopsis pennata</td>
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<td>3.9</td>
<td>0.16</td>
<td>8</td>
<td>441</td>
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</tbody>
</table>

3.3. Benthic biotic cover

The inner BRC sites had distinctly higher macroalgal cover and lower coral cover than elsewhere in the study area (Fig. 8). The highest macroalgal cover (up to 40%) occurred at Princess Reef and Buccoo Point where blooms of *Halimeda opuntia*, *Bryopsis* spp., and *Caulerpa* spp. occurred (Fig. 2B; Table 1). Coral cover was <10% at these two sites, compared to 20–40% cover at the outer BRC sites (Coral Gardens, Outer Reef), which was comprised of the genera *Acropora*, *Montastrea*, *Diploria*, and *Siderastrea*. Algal turf was a major component of reef communities in the BRC, with cover ranging up to >50%. The zoanthid *Palythoa caribaeorum* was another significant component of the BRC reef communities and ranged up to >20% cover at Buccoo Point where it overgrew dead coral.
slope that we observed in the wet season. Relatively high N:P ratios are characteristic of many carbonate-rich coastal waters around the Caribbean and result in primary limitation by P rather than N (Lapointe et al., 1992; Corredor et al., 1999). The reduced "limestone" effect at the FRs, relative to the BRC, results in lower DIN:SRP and N:P ratios, and a shift to more N-limited primary production.

Multiple lines of evidence from our study indicate that Buccoo Point – directly impacted by wastewater discharges from the adjacent upland watershed – was the most nutrient impacted site during our study. The highest water-column DIN, ammonium, and SRP concentrations of the entire study occurred there, which, along with the lowest salinities, macroalgal C:N and C:P ratios, demonstrates the impacts of elevated water-column DIN and SRP concentrations on reef biota. These observations are consistent with previous research using cylindrical cores of the coral M. annularis, in the BRC vs. Culloden reef, to compare historical trends in P availability (Kumarsingh et al., 1998b). Those researchers found higher fractions of organic P in the coral cores in the BRC than Culloden reef, and, that temporal patterns of increase in both total and organic P in the BRC coral cores correlated positively with human activities on the watershed. Our results also support previous findings by the Institute of Marine Affairs, Trinidad (IMA, 1996) that the highest nutrient concentrations in southwest Tobago occurred in Buccoo Bay and the Bon Accord Lagoon, both of which have experienced increasing wastewater nutrient loadings in recent decades.

The effects of elevated nutrient concentrations and high DIN:SRP ratios in the BRC were evidenced in increased biomass and elevated tissue N and P contents of macroalgae in the BRC compared to the FRs. Macroalgae in the BRC, enriched in N compared to the FRs, had lower C:N (15 vs. 21) and higher N:P (50 vs. 35) ratios as a result. The lower C:N ratios reflect reduced N-limitation of growth and explains the overall higher macroalgal biomass in the BRC compared to the FR. The relatively high N enrichment in the BRC drives the macroalgae to greater P-limitation, as evidenced by the higher N:P ratio of macroalgae in the BRC compared to the FRs. Blooms of the chlorophytes Bryopsis spp., Caulerpa spp., and H. opuntia were observed overgrowing reefs in the BRC (Fig. 2B), a phenomenon that was not observed at any of the FRs. Turtle grass, Thalassia testudinum, invaded the carbonate sands at Nylon Pool (Fig. 2D) over a decade ago, another symptom of sewage-driven eutrophication in oligotrophic coral reef regions (Bell, 1992). The phenomenon by which high N:P inputs from the watershed drive macroalgal blooms (and seagrass growth) on coral reefs towards increased P-limitation has been reported for other carbonate-rich waters in the Caribbean, including the Florida Keys (Lapointe, 1987; Lapointe and Clark, 1992; Lapointe et al., 2004), southeast Florida (Lapointe et al., 2005a), Jamaica...
The identification of wastewater as the source of DIN enrichment in the BRC was apparent from the elevated macroalgal δ¹⁵N in the BRC compared to the FRs. Numerous studies have shown how macroalgal δ¹⁵N values faithfully discriminate among various natural and anthropogenic nitrogen sources (see Risk et al., 2009 for a review). For example, France et al. (1998) showed that 21 species of tropical macroalgae in coastal waters of southwestern Puerto Rico had a mean δ¹⁵N of +0.3 ± 1.0‰, a value close to the atmospheric signature of 0‰ and indicative of N-fixation. In contrast, macroalgae exposed to varying degrees of urban wastewater pollution in Negril, Jamaica (Lapointe and Thacker, 2002), southeast Florida (Lapointe et al., 2005b), the Florida Keys (Lapointe et al., 2004), and Moreton Bay, Australia (Costanzo et al., 2001) all reported δ¹⁵N values ranging from −3 to +15‰, with values

Fig. 9. MODIS/Terra imagery showing near-shore waters of Tobago under the influence of the Orinoco River plume during the wet season (August–October), which is mostly CDOM rather than chlorophyll a (Chl a). Left panels show MODIS “Chl a” concentrations (mg m⁻³) derived from the color ratio between the blue (443 or 488 nm) and green (551 nm) bands. Because both Chl a and CDOM strongly absorb the blue light, Chl a values actually represent a combined effect of the two. Right panels show the MODIS chlorophyll fluorescence line height (FLH, mW cm⁻² μm⁻¹ sr⁻¹), which is much less affected by riverine CDOM. Despite significant noise (striping, cloud-edge effect, sun glint effect), the spatial patterns of FLH and their contrast to the left panels suggest that most of the river plume signal near Tobago are due, not to Chl a, but to riverine CDOM.
>8% in close proximity to wastewater sources. This pattern is consistent with our results, where the highest $^{15}$N values ($\sim+12\%$) were observed in the “nutrient indicator” species (Ulva lactuca, G. tikvahiae, A. subulata) near the wastewater outfall in Buccoo Bay. Lower mean values of +7.3% for Princess Reef, in the inner BRC, and +6.2% for macroalgae throughout the BRC would be expected from dilution of wastewater N from the inner to the outer BRC. These $^{15}$N data support the hypothesis that the entirety of the BRC has been significantly impacted by wastewater DIN from submarine groundwater discharge (SGD) of leachate from “soakaways” and from direct sewage outfall discharges. Lower, but relatively elevated $^{15}$N values occurred in macroalgae at other reef sites in southwest Tobago, especially at Hilton Reef, downstream of Scarborough, indicating widespread sewage DIN enrichment downstream of urban areas. The lowest $^{15}$N value, (+2.5%), measured during the dry season at Black Jack Hole, off Little Tobago Island, was more characteristic of an oligotrophic system less impacted by human activity although, even there, $^{15}$N values increased significantly during the wet season as a result of more widespread dispersion of land-based sewage pollution via increased stormwater runoff and SGD.

Elevated Chl $a$ concentrations during the wet season provides further evidence of watershed-driven eutrophication in the BRC. In the dry season, maximum Chl $a$ correlated with decreased DIN concentrations, but not with SRP. This pattern results from rapid uptake by phytoplankton of DIN, the primary limiting nutrient in coastal waters subject to sewage pollution. These findings support previous observations in Kaneshe Bay, Hawaii (Laws and Redalje, 1979) and the Florida Keys (Lapointe and Clark, 1992) where Chl $a$ provided a good “integrated” index of eutrophication in tropical and subtropical coastal waters. During the dry season, generally low DIN concentrations on Tobago’s fringing reefs (<0.3 $\mu$M), especially off Little Tobago Island, not only limits phytoplankton biomass, but also the growth of macroalgae. Mean DIN concentrations >0.5 $\mu$M are needed to support “blooms” of benthic macroalgae (Lapointe, 1997), such as those we observed on reef sites in the inner BRC. Classic “indicator” species of nutrient enrichment, including the rhodophytes G. tikvahiae and A. subulata, and the chlorophytes U. lactuca, H. opuntia, Bryopsis spp., and Caulerpa racemosa were abundant on reefs in the inner BRC where DIN concentrations were >0.5 $\mu$M, especially near the sewage outfall in Buccoo Bay. In contrast, macroalgae were generally less abundant on the fringing reefs around Tobago that had lower DIN concentrations. Similar macroalgal zonation patterns resulting from land-based nutrient gradients have been noted on other islands in the Caribbean region, including Jamaica (Lapointe, 1997; Lapointe and Thacker, 2002), the Florida Keys (Lapointe et al., 2004) and the Turks and Caicos Islands (Goreau et al., 2008).

The MODIS image series added additional evidence to differentiate the origin of elevated nutrients and phytoplankton biomass. The synoptic water circulation patterns in the color imagery often revealed land-reef connectivity that could complement the in situ data (e.g., Andréfouët et al., 2002; Hu et al., 2004a; Soto et al., 2009). Fig. 9 shows several examples of the MODIS “Chl $a$” and FLH images during both the dry and wet seasons. While the “Chl $a$” images clearly showed the influence of the Orinoco River plume in the near-shore waters of Tobago (the green–yellow–red colors) during the wet season, the corresponding FLH images suggested that this influence was primarily through DOM, as opposed to phytoplankton biomass. The absence of elevated phytoplankton biomass in the Orinoco River plume near Tobago suggests that riverine nutrients were depleted by the time the plume reached Tobago. Similarly, Ryther et al. (1967) compared Amazon outflow water with surrounding seawater and reported very low levels of dissolved nutrients and phytoplankton in this lower salinity plume. Hence, we conclude that the elevated nutrient and Chl $a$ concentra-

In summary, our results support the conclusion of Siung-Chang (1997) for the Caribbean region, and of Agard and Gobin (2000) for Trinidad and Tobago, that the most important source of marine pollution 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.

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